Active and Passive Microwave Technologies

Working Group Report

NASA Earth Science Technology Office

June 2004

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NASA EARTH SCIENCE TECHNOLOGY OFFICE
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EXECUTIVE SUMMARY

The NASA Earth Science Technology Office (ESTO) recently formed a technology working group in the area of active and passive microwave technologies in order to identify detailed technology requirements for implementing the NASA Earth Science Enterprise (ESE) research objectives. The results of this roadmapping activity have been captured in this report.

The working group consisted of five technology subgroups focused on the topics of active antennas, passive antennas, active electronics, passive electronics and data processing. The requirement definition process began with a set of quantitative science requirements defined by NASA/HQ program scientists and their communities. The science requirements encompassed the six enterprise science focus areas of atmospheric composition, carbon cycle and ecosystems, climate variability and change, Earth surface and interior, water and energy cycle, and weather. For each science requirement, one or more measurement scenarios were developed and technology challenges corresponding to each scenario were identified. Measurement scenarios included an array of active sensing instruments (e.g. synthetic aperture radar or SAR, interferometric SAR, atmospheric real aperture radar, scatterometers, altimeters, and radio occultation and GPS instruments), and passive sensing instruments (e.g. real aperture radiometers, real aperture sounders, and synthetic thinned array radiometers or STARs). The technology challenges for each scenario were studied in detail and a capability breakdown structure was developed for each of the challenges. The group then developed roadmaps for acquiring the required technologies.

In developing the technology roadmaps, the group considered three main prioritization criteria: science value, candidate scenario value, and technology value.

The science value was determined by the importance of a particular measurement (rated by NASA HQ program managers) and the measurement timeliness (determined by ESE science roadmaps or other relevant documents).

The candidate scenario value was determined by scenario uniqueness (an indication of unique capabilities that a particular scenario offers to meet the science requirements) and scenario relevance (i.e. whether the scenario meets or exceeds the threshold and goal science requirements).

The technology value was determined by two factors: the technology criticality, meaning whether the technology is enabling (i.e. needed to enable a new measurement capability) or enhancing (i.e. allowing incremental performance improvement or cost enabling), and technology utility (i.e. the number of measurement parameters that are served by a given technology).

Combining all three priority criteria, it is concluded that for the science priorities of ESE, InSAR, SAR, and STAR technologies provide the highest return on investment. Based on this analysis, the following requirement priorities were established in each of the technology areas:

In the area of active antennas, lightweight, large antenna structure technologies, deployable and inflatable technologies, reflector and phased array structure technologies, and adaptive waveform sensing and correction technologies yield the highest return. Low cost phase array technologies and multiple beam technologies also provide medium payoff.

In the area of passive antennas, lightweight, low insertion loss array feeds, lightweight structures and structural elements and active and passive feeds/systems technologies provide the highest return on investment. Antenna metrology, trade studies (e.g. spinning vs. non spinning real aperture) and thermal control technologies provide medium return.

In the area of active electronics, large aperture SAR technologies focusing on electronics for lightweight electronically scanned array (ESA), particularly L-band and Ku-band, provide the highest returns. Highest priority technologies in this area are T/R modules, rad-hard, low power chirp generators and digital receivers, components required for wavefront sensing and control, and lightweight, reliable signal distribution. Ku, Ka-band interferometer technologies focusing on developing electronics for phase-stable ESA also provide high returns. Millimeter wave ESA (Ka, W, G-band) technologies benefit single-pass interferometer missions and atmospheric radar missions. Technology priorities are phase stable T/R modules and MMIC devices.

In the area of passive electronics, MMIC/Miniature plus low mass/power radiometers, MEMS filters and RF switches, and analog RFI mitigation technology provide the highest return. Calibration subsystems for correlation radiometers, on-board RF signal distribution, combined active/passive system design, 3- and 4-Stokes polarimetric receiver design, and ultrastable low loss radiometers provide the next highest return. High frequency LNAs operating at frequencies higher than 160 GHz, LO sources operating at frequencies higher than 50 GHz, down conversion techniques operating at frequencies higher than 900 GHz, and mmW/smmW detectors provide medium return.

In the area of data processing, technologies required to enable STAR instruments (low precision A/D converters, massively parallel 1-bit cross correlators, high bandwidth data links and on-board high-rate digital distribution) as well as high performance radiation hard processors were deemed to provide the highest return. Large on-board data storage, high performance on-board A/D digital receivers, real time on-board processing, digital RFI mitigation, and high-speed, high-resolution digital spectrometers for sounding provide high returns. Processing algorithms were deemed to be of medium or lower importance.

Detailed integrated active and passive technology roadmaps are discussed in Chapter 4. Technology roadmaps corresponding to each of the ESE science focus areas appear in Chapter 5.

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1. Introduction

The NASA Earth Science Enterprise (ESE) has recently developed a set of science roadmaps in six specific science focus areas. The roadmaps are in the area of Atmospheric Composition, Carbon and Ecosystems, Climate Variability and Change, Earth Surface and Interior, Water and Energy Cycle, and Weather. The roadmaps (as of March 2004) appear in Appendix 1.A. These roadmaps characterize the ESE science objectives to be achieved in the next decade. The letter "T" in each roadmap identifies technology areas that require future investments in order to accomplish the Enterprise science objectives.

In order to identify detailed technology requirements for implementing the Earth science research objectives, the Earth Science Technology Office (ESTO) has assembled a technology working group specifically focused in the area of active and passive microwave technology. The working group membership has been by invitation only and was comprised of members from NASA centers, academia, FFRDCs, and industry. Dr. Azita Valinia (NASA/ESTO) served as the working group lead. Drs. Waleed Abdalati (NASA/GSFC) and M. Craig Dobson (NASA/HQ) served as the science lead and technology lead, respectively. A list of working group members appears in Appendix 1.B.

Focusing on active and passive microwave technologies only, the working group's charter was to develop a decadal technology implementation plan and technology roadmaps for enabling the ESE science roadmaps. The roadmaps are intended to guide ESTO's investment strategy for future technology developments.

This working group report is the first in a series of technology implementation plans and roadmaps developed to address needed technologies for enabling the ESE science objectives. Other volumes to follow will focus on active and passive optical, IR, and UV techniques.

Technology Requirement Definition Process

In order to give the community the opportunity to provide direct input in this technology roadmapping activity, the working group members invited the community to an open forum on January 8, 2004, held in Washington, DC. Input from the community was accepted for both science and technology requirements. Inputs were accepted via an electronic input submission website which was open for approximately 4 weeks. The community was also invited to give oral presentations at the forum. A list of forum participants appears in appendix 1.C.

ESTO had also sponsored a comprehensive technology planning workshop in March of 2003. During that workshop, technology requirements were derived and validated by the community in all technology thrust areas (sensors and platforms). These requirements are available in searchable format on the Earth Science Technology Integrated Planning System

(ESTIPS) database. The final report of the workshop is also available on the database at http://esto.nasa.gov/estips.

In this planning activity, focusing on active and passive microwave technologies, the working group started from the ESTIPS data, incorporated the community's input, and did extensive research to add many layers of detail to the top level requirements available on ESTIPS.

The working group consisted of 5 technology subgroups focused on the topics of active antennas, passive antennas, active electronics, passive electronics and data processing. Subgroup membership appears in appendix 1.D. There were also 5 science subgroups. Appendix 1.E shows the science subgroup membership. The working group members met four times in the Washington, DC area. The kickoff meeting occurred on November 4, 2003. The subsequent meetings took place on January 8, February 3, and February 27, 2004. Working group members worked independently in between the meetings and used the scheduled meetings to give progress reports and define the next set of milestones to be delivered at the subsequent meetings.

An overview of the requirement definition process appears in Figure 1.1.

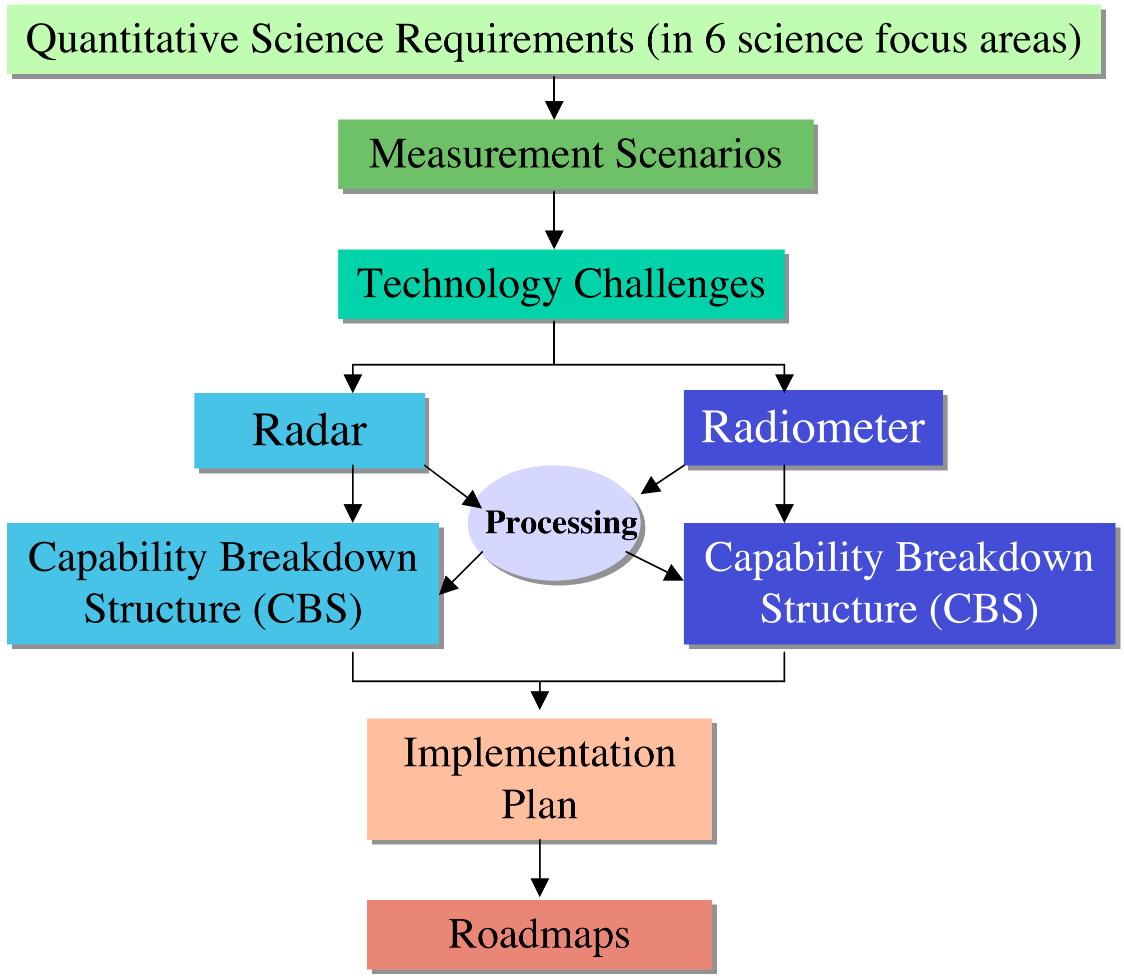


Figure 1.1: Overview of the technology requirement definition process

Chapter 2 of this document describes the ESE quantitative science requirements and their relevance to microwave measurement techniques. Chapter 3 reviews all microwave measurement scenarios considered by the working group. Chapter 4 describes the technology challenges for the scenarios discussed in chapter 3 and gives the capability breakdown structure for each of the required technologies. Technology roadmaps corresponding to the ESE science focus areas are presented in chapter 5. Finally, an analysis and summary of the prioritized technology requirements are given in chapter 6.

2. THE SCIENTIFIC BASIS FOR THE TECHNOLOGY DEVELOPMENT PROGRAM

The frontier of Earth system science is to: (1) explore interactions among the major components of the Earth System - continents, oceans, atmosphere, ice, and life, (2) distinguish natural from human-induced causes of change, and (3) understand and predict the consequences of change. To examine these complex processes, the Earth Science Enterprise is organized into the six focus areas discussed below. Roadmaps have been developed to articulate the activities needed to achieve the long-term goals for each of the focus areas (Appendix 1A).

Microwave remote sensing is a powerful tool for enhancing our knowledge and understanding of a wide variety of environmental phenomena related to the atmosphere, oceans, land surface, and ice cover, and ultimately to life. The scientific basis for the microwave remote sensing technologies proposed for development by NASA's Earth Science Technology Office is presented in this chapter. The goals of each science focus area, and the roles that microwave remote sensing can play in achieving those goals, as well as the benefits to society of making the proposed measurements, are all discussed below.

Most of the remote sensing technologies that are proposed in this report are satellite-based. There are a number of reasons why environmental phenomena are often best observed from satellites, rather than from UAVs (Unmanned Airborne Vehicles), manned aircraft, or *in situ* networks of sensors. Satellites afford large-area synoptic coverage. Satellites in a polar orbit can provide global access (which is especially important in remote areas such as the South Pacific). Microwave instruments on two satellites in suitably phased orbits can provide global coverage in approximately 12 hours, if they have suitably wide swath widths on the ground. The availability of such routine monitoring is important for parameters that are highly variable in space and time. Satellites can provide data with fixed spatial resolution from a circular orbit, which simplifies data analysis compared to that from an airborne platform. The stability and repeatability of satellite orbits compared to aircraft trajectories is important, for example in interferometric SAR (Synthetic Aperture Radar). Satellites do not have the human restrictions imposed by manned aircraft. Finally, by international agreement, satellites have no overflight restrictions. But the disadvantages of satellites are that the orbits are inflexible in time and space, the revisit frequency for any given spot on the Earth is limited to a minimum value, and the achievable spatial resolution is limited by distance. Instrument repair is not possible at the orbital altitudes used for remote sensing. Spaceborne instruments must be space qualified, which typically involves long and costly development programs. But the benefits of spaceborne platforms for the monitoring of global phenomena distinctly outweigh their disadvantages in the majority of cases.

Active and passive microwave (radar and radiometer) observations provide specific atmospheric, oceanographic, terrestrial and cryospheric (ice) parameters that are directly relevant and critical to meeting the goals of the six focus areas. The potential for microwave remote sensing to contribute to the measurement of environmental phenomena related to the six science focus areas is summarized in Table 1. Entries are made only where a particular environmental measurement parameter is part of a particular focus area. The entry “P” indicates where microwave remote sensing is the primary contributor [compared to electro-optical (E-O) remote sensing in the ultraviolet through infrared portion of the spectrum]. A “C” indicates that microwave remote sensing complements E-O remote sensing, but is secondary. The entry “E-O” indicates cases where microwave remote sensing makes no contribution. Special cases where neither contributes, namely the measurement of the Earth’s gravity and magnetic fields, contain special notations. A particular advantage of microwave over E-O techniques is the relative insensitivity of microwave observations to cloud cover and weather conditions, especially at the lower microwave frequencies.

The complete set of validated science requirements for the six focus areas is shown in Tables 2a – 2f. In addition to a description of each environmental measurement requirement and the source of its validation, the required horizontal resolution, vertical resolution, revisit rate, and measurement accuracy are given. In these four columns, in all cases where there are two numbers separated only by a semicolon, the first number is the threshold requirement, which represents the minimum required performance, and the second number is the goal or objective, which represents the maximum desired performance. The measurement accuracy is the one-sigma rms random noise (where the bias is assumed to be indistinguishable from zero).

Atmospheric Composition

The Atmospheric Composition science focus area addresses the gaseous molecular species and aerosols that comprise the Earth’s atmosphere. Aerosols are suspended droplets and particles; examples include volcanic sulphates and black carbon. The specific science questions answered through this focus area are:

- Is the ozone layer changing as expected?
- What are the roles of upper tropospheric water vapor, aerosols and ozone in climate change?
- What are the sources of tropospheric pollutants?
- Do we understand the transport of gases within the stratosphere and between the stratosphere and the troposphere?

Microwave remote sensing can be used to measure many atmospheric-composition-related environmental measurement parameters that are of interest to NASA, as indicated in Table 1. Water vapor, aerosols, ozone, certain trace species, and cloud particle properties can all be measured using microwave techniques. The importance of measuring these parameters is clear. Stratospheric ozone depletion is one of the most important climatological problems. Monitoring stratospheric ozone and the molecules that lead to its depletion, including trace species such as chlorine and bromine oxides ($C^{l}O$ and BrO), can lead to a quantitative understanding of ozone depletion. It can also contribute to the prediction of stratospheric ozone recovery in the Antarctic, as well as to the assessment of the potential for future ozone depletion in the Arctic. Monitoring tropospheric ozone can help lead to a quantitative understanding of this important pollutant. The evolution, composition and properties of atmospheric aerosols need to be better understood, because they are one of the two most poorly understood factors in the global change equation. The energy balance of the Earth-atmosphere system is subtle and nonlinear, and our understanding of aerosols remains grossly inadequate to model climate change. Water vapor is actually the most powerful greenhouse gas, so understanding its changes and improving our ability to do predictions is very important. Understanding the long-range transport of atmospheric pollutants such as CO is important for the operational prediction of air quality. Finally, monitoring atmospheric composition will contribute to the development of integrated climate/chemistry models, which are vital to our ability to understand and predict climate change.

The societal benefits of the observation of atmospheric composition are many. The stratospheric ozone layer is all that protects us from the damaging effects of solar UV radiation, so the monitoring, understanding, and prediction of ozone are all extremely important in predicting the levels of surface UV radiation. Lower in the atmosphere, tropospheric ozone and CO are damaging to human health when ingested. Improvements in monitoring, understanding and prediction of regional air quality would have significant health benefit. Finally, improved climate forecast accuracy would benefit a wide range of human activities.

The observations that NASA intends to perform would advance our understanding of atmospheric composition and chemistry, and thus our ability to predict ozone depletion and recovery, regional pollution, and climate change. Improved observations would yield improved understanding, thus improvements in global and regional forecast capability. The microwave remote sensing instruments proposed by NASA have an especially significant ability to contribute to the measurement of trace species that are related to ozone depletion.

Quantitative science requirements appear in Appendix 2A.

Carbon and Ecosystems

The Carbon and Ecosystems science focus area aims to characterize and model the cycling of carbon through the Earth system, and to determine the reliability and accuracy of the models in predicting the future concentrations of atmospheric carbon dioxide and methane. The Earth's carbon cycle influences and is influenced by several parameters and state variables such as atmospheric CO_2 and other trace gas fluxes, above- and below-ground vegetation biomass, land-cover and land-use state and change, surface and deep soil moisture, and ocean carbon fluxes. The specific science questions answered through the Carbon and Ecosystems focus area are:

- How are global ecosystems changing?
- What changes are occurring in global land cover and land use, and what are their causes?
- How do ecosystems respond to and affect global environmental change and the carbon cycle?

- What are the consequences of land cover and land use change for the sustainability of ecosystems and economic productivity?
- What are the consequences of climate and sea level changes and increased human activities on coastal regions?
- How well can cycling of carbon through the Earth system be modeled, and how reliable are predictions of future atmospheric concentrations of carbon dioxide and methane by these models?

Currently, there are large uncertainties in the knowledge of various components of the carbon cycle, notably in biomass (vegetation above- and below-ground, and ocean) and gas fluxes. Furthermore, characterization and modeling of interannual variability and disturbance recovery are far from sufficient. The chief goal of the carbon cycle focus area in the next decade is to develop predictive models with the ability to quantify subregional sources and sinks reliably and to produce realistic interannual variability estimates. The development of such models necessitates systematic observations of terrestrial primary productivity (vegetation index), biomass, land cover, and various supporting oceanic and climatic observations. Observations on local, regional, continental, and global scales are required to develop and validate such models with confidence in reduced uncertainty levels, ultimately leading to reliable climate predictions.

A number of microwave remote sensing measurements have key roles in producing the observations needed for development, fine-tuning, and validation of these carbon/climate models. Specifically, radar measurements at various frequencies are needed to provide reliable, repeatable, above-ground biomass estimates at local to global scales. This includes estimates of vegetation recovery from disturbance. Delineating disturbed areas, for instance due to fire, as well as quantifying fire fuel is another place where radar observations can contribute. Radar can be used extensively to map land cover types, particularly wetlands, which often act as carbon sinks and play a significant role in the cycling of nutrients. Both passive and active microwave measurements are powerful tools, and perhaps the only feasible means, for estimating soil moisture, which is an interface between the water and carbon cycles. Soil moisture at the root zone beneath vegetation canopies is a key limiting factor in determining the carbon uptake/release by the trees, and can only be feasibly estimated by using lower-frequency radars. Passive microwaves at L-band are also used to determine ocean salinity, another variable required in carbon cycle models.

Carbon is important as the basis for the food and fiber that sustain human populations, as the primary energy source that fuels human economies, and as a major contributor to the planetary greenhouse effect and the potential for climate change. Carbon dioxide and methane concentration have been increasing in the atmosphere, primarily as a result of human use of fossil fuels and land clearing. Rising atmospheric carbon dioxide concentration and its potential impact on future climate is an issue of global economic and political significance. The need to understand how carbon cycles through the Earth system is therefore critically important to our ability to predict any future global change. Recent policy debates have demonstrated the need for a comprehensive, unbiased scientific understanding of sources and sinks of carbon dioxide on continental and regional scales, and how sinks might change naturally over time or be enhanced by human activities.

Quantitative science requirements appear in Appendix 2B.

Climate Variability and Change

The Climate Variability and Change science focus area addresses the understanding and prediction of time-varying interactions between the components of the global climate system and the effect of human activity on this system from seasonal and annual to decadal timescales. This involves the quantification of certain forcings and feedbacks to characterize recent and future climate change. An important element of this comprehensive end-to-end program is to produce the global and regional observations in support of this effort. The specific science questions answered through this focus area are:

- How is the global ocean circulation varying on interannual, decadal, and longer time scales?
- What changes are occurring in the mass of the Earth's ice cover?
- How can global climate variations induce changes in the global ocean circulation?
- How is global sea level affected by natural variability and human induced changes in the system?
- How can predictions of climate variability and change be improved?

The goals through 2014 are to characterize and reduce uncertainties in long-term climate prediction, to provide routine forecasts of precipitation, temperature, and soil moisture, and to improve prediction of sea-level rise. The broad suite of observations required to meet these goals includes systematic measurements of certain greenhouse gases, atmospheric temperature and moisture, sea surface topography, sea surface salinity, ocean vector winds, clouds, aerosols, precipitation, surface temperatures, ice cover, snow cover, soil moisture, energy balance, and solar irradiance, most of which can be addressed with microwave techniques. The required techniques include altimetry, interferometry, polarimetry, and sounding. In all cases, the complexities and the technological challenges in the implementation of remote sensing systems to measure these parameters are outlined in the following sections.

While satisfying the goals of understanding physical climate and change, the measurements are also important in related focus areas (Table 1). Climate variability and change profoundly influence social and natural environments throughout the world, with consequent impacts on natural resources and industry that could be large and far-reaching. For example, climate fluctuations strongly affect the success of agriculture, the abundance of water resources, and the demand for energy, while long-term climate change may alter agricultural productivity, and land and marine ecosystems. Advances in climate science and observations will provide information for decision makers and resource managers to better anticipate and plan for potential impacts of climate variability and change and to enable more scientifically informed decisions across a broad array of climate-sensitive sectors.

Quantitative science requirements appear in Appendix 2C.

Earth Surface and Interior Structure

The Earth Surface and Interior Structure science focus area addresses the Earth's solid surface and its evolution, as well as geologic processes within the Earth's interior including earthquakes, volcanoes, and other phenomena that contribute to our notion of a "restless planet." The specific science questions answered through this focus area are:

- What is the nature of deformation at plate boundaries and what are the implications for earthquake hazards?
- How do tectonics and climate interacts to shape the Earth's surface and create natural hazards?
- What are the interactions among ice masses, oceans and the solid Earth and their implications for sea level change?
- How do magmatic systems evolve and under what conditions do volcanoes erupt?
- What are the dynamics of the mantle and crust and how does the Earth's surface respond?
- What are the dynamics of the Earth's magnetic field and its interactions with the Earth system?

Important parameters of interest to solid earth scientists that can be studied from space include high resolution topography, displacements and stress in the Earth's solid surface, the thermal signature of the surface, and changes in the Earth's rotation rate and pole position (terrestrial reference frame). The Earth's gravitational and magnetic fields are also important, but cannot be measured with microwave remote sensing techniques.

High resolution topography of the solid earth is important to a large variety of studies, for example the water cycle, plant and animal distribution, geologic processes such as mountain building and volcanism, and geologic hazards such as volcanic eruption and earthquakes. High resolution topography provides an important background data set for interferometric SAR. While there are several techniques for acquisition of space-based topographic data, those involving the microwave spectrum have the best chance of achieving full global coverage, because of its nearly-all-weather capability, at high spatial resolution.

Short-term changes in the Earth's solid surface at the centimeter level can also be detected by interferometric SAR. These changes are important for understanding earthquakes and longer-term deformation, for studying subsidence of the surface due to the extraction of fluids such as oil, natural gas, and water, for studying volcanic processes, and for assessing volcanic hazard. Many volcanoes inflate by measurable amounts prior to eruption.

These processes are responsible for the long-term evolution of the Earth, and appropriate observations promote better understanding of the planet on which we live. From a more practical standpoint, improved understanding of geologic processes allows mitigation of natural hazards, for example due to earthquakes, volcanic eruptions, and tsunamis.

Changes in Earth orientation are important in part for their intrinsic scientific merit. This includes changes in the Earth's rotation rate, which are related to global atmospheric cycles and are affected by seasonal hemispheric water balance, El-Nino events, and global warming. Changes in Earth orientation are also critical because they provide the dynamic reference frame information that is essential for space observations such as tracking interplanetary satellites using ground-based antennas, and techniques such as interferometric SAR that require high geometric fidelity. Changes in the Earth's surface at the centimeter level cannot be measured unless the spacecraft location is known to comparable accuracy. Earth orientation measurements require a mix of ground and space-based observations, including microwave techniques such as VLBI (Very Long Baseline Interferometry) and GPS (Global Positioning System) methods.

Quantitative science requirements appear in Appendix 2D.

Water and Energy Cycle

The Water and Energy Cycle focus area addresses the exchange of water and energy between the oceans, atmosphere, terrestrial waters and terrestrial ice stores. The specific science questions answered through this focus area are:

- How are global precipitation, evaporation, and the cycling of water changing?
- What are the effects of clouds and surface hydrologic processes on Earth's climate?
- How are variations in local weather, precipitation and water resources related to global climate variation?

Microwave remote sensing can be used to measure many relevant environmental measurement parameters that are of interest to NASA, as indicated in Table 1. Water vapor, clouds, precipitation, soil moisture, snow cover, snow water equivalent and wetness, surface freeze/thaw transition, river stage height and discharge rate, and other parameters of relevance can all be measured using microwave techniques. The importance of measuring these parameters is clear. Improved measurement techniques would lead to improved models, resulting in improved forecasts of precipitation, snowmelt, soil moisture and runoff, and floods and droughts. Better knowledge of the water budget at subcontinental and seasonal scales would help lead to higher-resolution weather and climate models. Improved measurements would improve our understanding of the effects of cloud feedback on climate change. River stage height and discharge rate are the parameters that connect the land and the ocean water budgets.

Water dominates human society through its importance to the very existence of terrestrial life, through its impact on the world's food supply, and also as a natural or human-induced hazard through river flooding. Better understanding of the water and energy cycle will greatly improve human preparedness for disaster management of river flooding, and more importantly improve the water resources management of food supply. It will also provide better understanding of the link between human activity and climate change. As a resource, amounts of water can be managed to maximize benefits to society. As an example, the untimely presence of snow and its rapid melt can cause significant damage to life and property. Better management through a better understanding of the water and energy cycle will help to reduce damage and costs from water-related hazards and will enable the better global management of water resources for global communities.

Quantitative science requirements appear in Appendix 2E.

Weather

Weather refers to the state of the atmosphere and its variability on time scales of minutes to months. A complete characterization includes not only the state of the atmosphere, but also the temperature and moisture characteristics of the atmosphere-Earth surface interface, since these parameters are drivers of the weather. The specific science questions answered through this focus area are:

- How are variations in local weather, precipitation and water resources related to global climate change?
- Is the global water cycle through the atmosphere accelerating?
- How well can weather forecasting be improved by new global observations and advances in data assimilation?

Microwave remote sensing can be used to measure many weather-related environmental parameters that are of interest to NASA, as indicated in Table 1. Atmospheric temperature and water vapor, clouds, aerosols, storm cell properties, precipitation, soil moisture, snow, ocean surface winds, sea surface salinity, and sea ice can all be measured using microwave techniques. The importance of measuring weather-related environmental parameters is clear. The most poorly understood factors in the global change equation are clouds and aerosols. The energy balance of the Earth-atmosphere system is subtle and nonlinear, and our understanding of the properties of clouds and aerosols is still grossly inadequate to model climate change with the fidelity that is required. The atmospheric temperature profile is an indicator of global change, particularly the mesospheric temperature profile, which is observable with microwave sounders. With regard to the atmospheric moisture profile, water is actually the most important greenhouse gas. Improved knowledge of precipitation, including snow, light rain, and frozen hydrometeors, will lead to new and improved retrieval schemes at middle and high latitudes, and improved simulations of precipitating storms. Soil moisture, snow, ice, and surface temperature serve as boundary conditions on the weather, in terms of heat, moisture, and reflectivity.

The societal benefits of weather observation are many. Improved weather prediction would yield savings in life, property, and infrastructure. Improved prediction of severe weather, such as thunderstorms, tornados, hurricanes, and winter storms, would be particularly valuable. Aviation safety could be improved through better knowledge of cloud ice content. Transportation costs could be reduced through better knowledge of the sea surface wind and sea ice for ship routing. Improved knowledge of precipitation (rain, snow, and frozen hydrometeors) is important for transportation and for making many economic decisions. More accurate weather predictions could result in significant savings for the energy industry, so that they do not, for example, generate excess energy that goes unused on warmer days. Construction planning could benefit from improved weather forecasts. Better forecasts are important in planning disaster assessment and emergency response. The commodities market could also benefit from improved weather forecasts.

The observations that NASA intends to perform would advance our understanding of the weather, and thus our ability to predict the weather. Improved observations, assimilated into NWP models, would yield quantitative improvements in global and regional forecast capability. Improvements in regional forecasting of rain and snow, forecasting of winter storms on the local level, hurricane landfall accuracy, tornado lead time, and prediction of thunderstorm occurrence could all be expected.

Quantitative science requirements appear in Appendix 2F.

Table 1. Microwave Remote Sensing Contribution to Science Focus Areas

	Water & Energy	Weather	Climate	Atmosphere Composition	Carbon	Solid Earth
Atmosphere						
Atmospheric Temperature		P	P			
Atmospheric Water Vapor	P	P	P	P		
Cloud System Structure	P	P	P			
Cloud Particle Properties (incl. liquid & ice water path)	P	P	P	P		
Tropospheric Winds		E-O				
Lightning Rate		E-O				
Storm Cell Properties		P				
Total Aerosol Amount (incl. Volcanic Gas & Ash)				C**		
Stratospheric Aerosol Dist		C**	C**	C**		
Aerosol Properties				E-O		
Total Column Ozone			C**	C**		
Ozone Vertical Profile			C**	C**		
with CFCs			E-O	E-O		
with ClO and BrO				P**		
with nitrous oxide (N_2O)				C**		
Troposph. Ozone & Precursors				E-O		
with CO				E-O		
Total Solar Irradiance		E-O	E-O	E-O		
Solar UV Irradiance		E-O				
Earth Radiation Budget	E-O		E-O			
Trace Gas Sources (& total CO_2)			E-O		E-O	
CO_2 and Methane (incl. Profiles)			E-O	E-O	E-O	
Global Precipitation	P	P	P			P
Atmos. Properties in Tropopause (covered by other parameters)						
Land						
Soil Moisture	P	P	P		P	P
Terrestrial Primary Productivity (incl. vegetation index)	C	C			C	C
Land Cover and Land Use	C			C	C	C
Biomass			C		C	
Fire Occurrences and Extent					C extent	
Fuel Quantity and Quality					C	
Land Surface Temperature		C				C
Snow Cover	P	P	P			
Snow Water Equivalent & Wetness	P	P	P			

	& y	er	te	sphere osition	n	Earth
Freeze-Thaw Transition (incl. Growing Season Length)	P	P	P		P	
River Stage Hgt/Discharge Rate	P					
Surface Deformation and Stress						P
Land Surface Topography	P					P
Earth Surface Composition/Chemistry					C	
Earth Gravity Field	GRACE					GRACE
Earth's Magnetic Field						magnet's
Terrestrial Reference Frame						P (VLBI)
Motions of Earth's Interior****						C
Oceans						
Ocean Surface Winds	P	P	P			
Sea Surface Temperature	C	C	C		C	
Ocean Surface Topography			P			P
Sea Surface Salinity		P	P		P	
Marine Primary Productivity (incl. Coastal Region Prop's)			E-O		E-O	
Ocean Surface Currents			P			
Deep Ocean Circulation***						
Cryosphere						
Sea Ice Extent (incl. Melt Extent & Seasons, Shore-fast Ice)		P	P			
Sea Ice Thickness			P			
Snow Depth on Sea Ice			P*			
Sea Ice Motion (small&lrg scale)			P			
Sea Ice Surface Temperature			C			
Sea Ice Meltpond Fraction			C			
Sea Ice Velocity			P			
Polar Ice Sheet Velocity			P			
Polar Ice Sheet Surface Topo			P			
Polar Ice Sheet Bed Topography			P*			
Accumulation on Polar Ice Sheet			P			
Polar Ice Melt Extent & Seasons			P			

Legend:
P = microwave primary (contributes at least as much as E-O)
C = microwave complementary (secondary to E-O contribution)
E-O = electro-optical (no microwave contribution)
* specifically airborne
** microwave limb sounder
*** modeled, not sensed
**** modeled using gravity, magnetics, InSAR & VLBI

3. MEASUREMENT SCENARIOS (INSTRUMENT CONCEPTS)

In order to meet the science requirements that are outlined in Chapter 2, the first step is to develop concepts for microwave remote sensing instruments that address those requirements. The candidate measurement scenarios that have been developed by ESTO are summarized in this chapter. At the end of this chapter is a summary of how the following measurement scenarios relate to the six science focus areas.

Each measurement scenario has been assessed with regard to its potential to meet the thresholds and goals associated with the various science requirements, as presented in Appendices 2A-F. This assessment is indicated by a letter in parentheses at the end of each paragraph describing a given scenario. That letter may be interpreted as shown in Table 3.

Table 3. Measurement Scenario Assessment Designation

T - scenario just meets all the threshold science requirements (horiz res, vertical res, revisit, and accuracy)
E - scenario meets all thresholds and exceeds one or more
G - scenario meets all thresholds and meets one or more of the goals/objectives (in those cases where goals are stated)
P - scenario fails to meet one or more of the stated thresholds

The scenarios are organized according to instrument type. The passive microwave remote sensing measurement scenarios are presented first: real-aperture radiometers and sounders, synthetic aperture radiometers, and one scenario involving VLBI (Very Long Baseline Interferometry). The active microwave remote sensing measurement scenarios are presented next: SAR (Synthetic Aperture Radar), InSAR (interferometric SAR), real-aperture atmospheric radars, scatterometers, altimeters, and three radio occultation and GPS-related scenarios.

For the detailed spreadsheets related to these scenarios, the reader is referred to the online ESTIPS database (www.estips.gsfc.nasa.gov).

Passive Microwave Remote Sensing Measurement Scenarios

Real-Aperture Radiometers

Real-aperture microwave radiometers have a long history of application to Earth remote sensing. They are frequently called "imagers" or "imaging radiometers" instead of "radiometers." In concept, an antenna (typically involving a reflector) physically scans the Earth, intercepts the microwave radiation from a portion of the scene, and focuses it onto one or more frequency-and-polarization-sensitive feedhorns (or equivalent devices). The captured radiation is detected as an electrical signal at the front end, amplified, digitized, and recorded for various frequencies and polarizations (typically linear; occasionally circular). Real-aperture imagers typically employ a conical scan pattern, such that they scan the Earth with a constant angle about nadir, which has advantages with regard to data analysis and interpretation, especially as regards polarization/emissivity effects. Real-aperture radiometers are limited in aperture by how large a solid dish antenna can fit in a launch vehicle fairing and be accommodated on a spacecraft, or by how large a folded or unfurlable antenna can be similarly accommodated. Such a sensor cannot be called a radiometer unless it is calibrated. Typically, a warm load of known temperature and emissivity and a cold space mirror are located such that they are viewed by the feedhorns once per rotation, when the antenna is looking off the Earth. These provide the basis for a two-point radiometric calibration. Other calibration techniques involve the use of switched internal passive or active sources, intercomparisons with other instruments, and the use of geophysical references ("vicarious" calibration). In practice, a combination of these techniques may be used. Note that with apertures larger than a meter or so, a true end-to-end calibration is impractical before launch, so for example, pre-launch calibration would not include the antenna, and a full end-to-end calibration can be done only on-orbit.

Unlike visible imagers, microwave radiometers are not limited by considerations of day or night. Unlike visible or infrared imaging radiometers, microwave radiometers can operate through most (but not all) weather conditions. The single most significant limitation of microwave radiometers is spatial resolution. Quite large antennas must be constructed to achieve spatial resolutions below 10 km at typical microwave frequencies, resulting in very large and heavy solid antennas, or large and complex deployable/inflatable antennas. One solution is the Synthetic Thinned Array Radiometer (STAR) approach that uses a partially filled aperture, reducing mass at the expense of more complex image-generation processing, calibration, and signal distribution considerations. Note that the STAR technique provides spatial resolution equivalent to a real aperture instrument with an antenna size the same as the outer dimensions of a STAR aperture. The STAR approach does not dramatically improve resolution the way SAR techniques do with radars; this is because radiometers fundamentally operate on incoherent signals. Mechanically-scanned real aperture instruments may have limited dwell time per pixel, especially if the footprint size is small. One variation of a real-aperture imager is the pushbroom configuration in which multiple feedhorns are clustered to image adjacent pixels on the ground. This can be applied to address dwell time considerations in rotating or non-rotating configurations. Another variation is a radiometer with a beamforming array antenna (as long as image generation is not done using STAR techniques). Real-aperture radiometers have the longest space flight history, beginning in the 1970's. They are arguably the best-understood, most-straightforward type of radiometer. All currently-existing spaceborne passive microwave geophysical retrievals were developed and still operate using real-aperture radiometers.

Measurement scenario 106 is for a conically scanning microwave radiometer operating at 19 and 37 GHz (V and H pol) with 5 km spatial resolution or better, to measure snow water equivalent. A large (> 6 m) folding-rigid, folding mesh, or inflatable/rigidizable antenna could be used to accomplish this from LEO (low Earth orbit). Because GEO (geosynchronous) altitude is over 40 times that of a typical LEO orbit, the antenna would have to be over 40 times as large to achieve the same resolution, so a LEO orbit is most appropriate for this concept. There is significant heritage with instruments having up to approximately 2 m diameter solid antennas. The inflatable/rigidizable technology, however, is in its infancy. (T)

Measurement scenarios 111 and 38 incorporate a rotating ~25 m diameter offset parabolic deployable antenna with a 40 degree incidence angle beam and will provide 10 km spatial resolution (and 1 km from a co-flown SAR) in a conical scan pattern. Alternatively, a parabolic torus containing a focal plane array with more that 100 elements will be designed to pushbroom image the scene without the need to rotate the system. In response to measurement scenario 111, this instrument is designed to measure surface soil moisture, i.e., less than 5 cm depth using L-band (1.41 GHz). The radiometers will need a stability and accuracy of 0.4 K for this measurement. An L-band (1.26 GHz) SAR will be used to produce the 1 km spatial resolution images. The radiometers will also need to measure the third Stokes polarization parameter to correct for the ionospheric rotation. The instrument will have a 900 km swath width and will provide global coverage every 3 days. This concept uses multiple feeds and radiometers to keep the rotation rate < 5 rpm. In response to measurement scenario 38, this instrument will also measure ocean salinity with a 40 km spatial resolution and 0.1 - 0.2 psu accuracy. The radiometers will need a stability of 0.1 K over periods of 2-5 days to measure salinity to an accuracy of 0.2 psu. An L-band (1.26 GHz) polarimetric scatterometer would be co-flown to correct for ocean surface wind effects. Adding an X-band channel will enhance this instrument for many other applications such as high-resolution global precipitation measurements and sea ice extent. This instrument may be flown in tandem (sub-cycle orbit) with a UHF/VHF SAR to measure soil moisture at depths from 1 to 5 m, although it is completely scientifically viable without such a radar. Due to its long wavelength and low spatial resolution, only a LEO orbit is reasonable. Possible antenna technologies include meshes and inflatables, although inflatable technology is in its infancy. (T for salinity, E for soil moisture)

Measurement scenario O1 involves a rotating ~7 m diameter deployable antenna with a 53 degree incidence angle beam, and will provide ~18 km spatial resolution at 6 GHz in a conical scan pattern. Two frequencies would be used for Sea Surface Temperature retrieval: 6 GHz V&H and 10 GHz V&H. The former is the best overall frequency, while the latter is better in warmer waters. Additional frequencies would be used to measure other quantities required in the analysis (sea surface wind speed and atmospheric water content): 18, 21 and 37 GHz. From low Earth orbit (~800 km altitude) the instrument would have a swath width of ~1700 km, and a refresh rate in the neighborhood of one day, depending on the orbit particulars and swath overlap near the equator. Due to the long wavelength and low spatial resolution, only a LEO orbit is reasonable. Possible antenna technologies include meshes and inflatables, although inflatable technology is in its infancy. (T)

Measurement scenario 143 involves a sub-mm wave/far IR radiometer designed to measure cloud properties, especially ice cloud microphysics. The instrument uses multi-frequency scattering and absorption by cloud ice particles of microwave emission from moist air below for characterization of ice particle density and size. This instrument uses an advanced 1 THz oscillator to combine both sub-mm wave and far IR bands into a single instrument. Relevant parameters are:

- sub-mm microwave radiometer: 183, 325, 448, and 621 GHz; and
- far-Infrared radiometer: 20-22, 27-32, 44-46, 118-120 cm^{-1} channels;
- with a 2 km nadir FOV (Field of View) and a 0.9 m antenna. Technology development of 1 THz oscillators would allow combination of microwave sub-mm and far-infrared sub-mm sensors into a single instrument. (T)

Real-Aperture Sounders

Passive microwave and millimeter wave sounders are radiometers that estimate the vertical profile of atmospheric constituent gases from measurements of their natural thermal emission. Sounders can be generally classified into two types. Nadir sounders have antenna-pointing geometries with beams that terminate at the Earth surface. They rely on the pressure broadening of resonant gaseous emission to identify the pressure (and hence the altitude) of the source of the emission. At very high altitudes, there is little molecular interaction and the spectrum of emission is narrowly concentrated around “line center” frequencies that correspond to quantized energy transition levels. At lower altitudes and higher pressures, where molecular interactions are more pronounced and energy transition levels are statistically broadened, the spectrum of emission is itself broadened to include frequencies further from a line center. Thus, upwelling atmospheric emission at frequencies near line center tends to originate from very high altitudes while upwelling at frequencies further from a line tends to originate from lower altitudes. A nadir sounder requires measurements by a spectrometer with frequencies that cover the range of altitudes of interest. The second major class of instruments is limb sounders. Limb sounders have antenna-pointing geometries with beams that are tangent to the Earth surface. The point of closest approach of the antenna beam to the Earth surface determines the “tangent height” of the geometry. The tangent height is also the altitude from which the atmospheric emission makes the greatest contribution to the measurements, provided the measurements are also made at a frequency appropriate for that altitude with respect to the pressure broadening phenomenon. Profiles are generated by mechanically scanning an antenna to different tangent heights. In general, limb sounders tend to have superior vertical resolution over the nadir sensors, owing to the fact that they can leverage both the pressure broadening effect and the tangent viewing geometry to identify the source of the emission. Nadir sounders tend to have superior horizontal resolution, owing to the fact that their antenna beams form a cone that terminates on the Earth. Historically, nadir sounders have tended to be used more for tropospheric measurements. This is in part due to the refractive bending complications that arise with the limb geometry at near-surface tangent heights and in part because horizontal variability is so much larger in the troposphere.

The Advanced Microwave Limb Sounder (AMLS) is intended to address measurement scenario #140. The science objective is to investigate the relationship between ozone distribution, water vapor, aerosols, temperature and trace constituents in the tropopause. Of particular importance are the technological advances needed to enable limb sounding with horizontal resolution of 50 km, versus the ~200 km that is the current state-of-the-art. This is achieved by a novel azimuth-scanning technique, which provides complete global coverage, with no inter-orbit gaps and nominal horizontal resolution of 50 km (which can be achieved in both directions by views from orthogonal directions on adjacent orbits). Other related enabling technologies are cryo-coolers, to reduce measurement noise and integration time requirements, an increase in the maximum frequency coverage of the radiometer front ends, and an increase in the bandwidth of the back end spectrometers. With the proposed technological advances, the AMLS is projected to just meet the threshold horizontal resolution requirement of 50 km. Other key requirements (vertical resolution and measurement precision) are already met by current state-of-the-art limb sounders. (T)

The real aperture Geosynchronous Sounder is intended to address measurement scenario #176. The science objective is to make continuous measurements of atmospheric temperature, water vapor, and rainfall. This is achieved using a mechanically scanning microwave radiometric sounder in geosynchronous orbit. The instrument is intended to operate at geosynchronous altitude to provide images over the visible hemisphere every 30 minutes. This instrument combines the functions of Aqua AMSU and HSB. Ideally, this instrument augments the GOES infrared sounder for nearly all-weather capability. The instrument will operate near 50 GHz and 183 GHz with 10% bandwidths. The instrument will be a 4-m diameter scanning offset parabolic reflector with a scanning subreflector. The noise equivalent delta temperature (NEDT) of the image will be < 1 K with an accuracy of < 1 K. The platform must have capability to compensate for the scanning motion of the large antenna and subreflector. Momentum compensation systems will need to compensate for mechanical scanning with pointing accuracy of 10% to 20% of the smallest beam width. Given these technological advances, the real aperture Geosynchronous Sounder is projected to just meet the critical threshold image refresh rate of 30 minutes. (T)

Synthetic Thinned Array Radiometers (STAR)

The concept of aperture synthesis was advanced in the field of radio astronomy as a means to achieve the finest resolving power with an antenna array that uses a relatively small number of individual elements. The intent of using this technique was to achieve the best resolution possible for a fixed amount of available dollars. A prime example is the Very Large Array (VLA) in New Mexico, which uses a “Y” configuration of elements to achieve the resolution of a filled array whose diameter is equal to that of the circle that encloses the “Y”. Because the cost of microwave and digital components has continually decreased, antenna complexity can now be transformed to signal processing complexity to obtain resolution. Indeed, radio telescopes utilizing aperture synthesis and very long baseline interferometry (VLBI) rival, and even exceed, the resolution achieved by some of the best earth-based optical telescopes.

As more geoscientists are becoming accustomed to passive microwave satellite data, demand is developing for both better spatial resolution and for the addition of frequencies as low as 1.4 GHz. Both of these demands now place the technologist in a similar quandary to that faced by radio astronomers 50 years ago: at some size, large, mechanically scanned filled apertures are just too costly to adequately operate in orbit. The ground rules for Earth observations are, however, somewhat different than those for radio astronomy. The spacecraft moves forward at 7 km/s, so that processing must be done more rapidly. The Earth is an extended source, whereas astronomical sources are embedded in a cold cosmic background, which influences signal-to-noise ratios. These and other issues have been addressed over the past decade, and have led to an airborne demonstration unit (the ESTAR) and several spacecraft designs.

The VLA and ESTAR, respectively, represent 2-D and 1-D aperture synthesis techniques. In 2-D aperture synthesis, flood beam antenna elements are sparsely arranged, and the element design is straightforward. In essence, the engineering complexity is transferred to the electronics, which requires N^2 correlators to synthesize the image of the scene, where N is the approximate size of the antenna in wavelengths. For a 20-meter aperture, N is on the order of 100 at L-band; hence, a 2-D synthetic requires several thousand correlations. The 1-D array, such as ESTAR, develops pushbroom imaging by combining conventional real aperture imaging in the along-track direction, and aperture synthesis in the cross-track direction. In this configuration, circuit complexity is reduced by virtue of only requiring N correlations; however, antenna design of the thinned array of linear elements becomes more of a technical challenge. The 1-D STAR can be configured to operate either in a conical or a cross-track scan mode.

The STAR is a microwave radiometer, and as such, offers the same advantages as a conventional radiometer fed by a filled aperture. The STAR, particularly at the long wavelengths, can operate through almost all weather conditions, and at nighttime. However, unlike conventional filled aperture systems, significant thinning can be done as a means to considerably reduce the size and weight of the payload that is launched into space, at considerable cost savings.

Measurement scenarios 34 and 177, respectively, specify a 2-D and a 1-D STAR operating at 1.4 GHz to measure soil moisture and oceanic salinity. The 2-D system will incorporate H and V polarization, and the 1-D version will have H polarization and will scan cross-track to the direction of spacecraft motion. The 1-D system will consider the use of a slotted membrane waveguide. Both systems will operate from LEO. (G)

Measurement scenarios 107 and 108 also respectively utilize 2-D and 1-D aperture synthesis for measurement of snow water equivalent. The required frequencies are 18 and 37 GHz, and the required resolution is 5 km. The 1-D version will incorporate conical scan and both H and V polarizations. (G)

Scenario 67 is a thinned array radiometer operating at 50 and 183 GHz. It uses a single polarization in GEO and is designed to profile atmospheric temperature and to measure the water vapor burden and precipitation. (P)

Measurement scenario H1 (P) will measure the freeze-thaw transition at high latitudes; scenario H2 (G) will measure snow-water equivalent (SWE) and snow wetness; and scenario

H3 (G) will measure soil moisture. All of these scenarios (H1, H2, H3) will utilize a 25 m L-Band "Y" configured thinned array radiometer to achieve 10 km resolution from LEO.

Measurement scenario C2 requires a 19 and 37 GHz conically scanned thinned array radiometer. It measures snow cover over sea ice with 5 km resolution from LEO. (G)

Scenario A1 is a pushbroom or STAR imager in LEO, intended to measure global precipitation with spatial resolution of 5 km using frequencies of 10 and 37 GHz. Scenario A2 is a STAR in LEO that operates at discrete channels over 4 to 10 GHz in order to decouple emission due to ocean surface winds and the overlying column of precipitation. The target resolution from LEO is 15 km. (G for both)

Very Long Baseline Interferometry (VLBI)

The rotation rate of the Earth is constantly changing, due to exchange of angular momentum between the atmosphere and the solid Earth, the oceans and the solid Earth, the fluid core and the solid Earth, and other effects. The location of the Earth's rotation axis is also constantly wandering. The combination of these two problems is referred to as UTPM (Universal Time and Polar Motion), or alternatively as polar motion and length of day (LOD). The terrestrial reference frame with respect to inertial space must be known very accurately in order to analyze altimeter and interferometric SAR measurements.

The solution to this problem is to use a technique borrowed from radio astronomy, as discussed above, namely Very Long Baseline Interferometry (VLBI).   The Deep Space Network (DSN) of JPL is routinely used to monitor UTPM by very accurately measuring the observed positions of distant quasars as a function of time, using an interferometric technique. In this case, the baseline is comparable to the diameter of the Earth. Scenario 53 involves the use of this technique, which requires improvement to reach the measurement accuracy goals. (T)

Active Remote Sensing Scenarios
Synthetic Aperture Radar (SAR)

Synthetic aperture radar (SAR) systems are active remote sensing instruments, which take advantage of elegant physical and signal processing concepts to achieve high resolution with relatively small antennas. The SAR is a pulsed system, whose operation is based on synthesizing an effective antenna aperture from a smaller physical aperture by accurately keeping track of the pulse-to-pulse timing as well as the location of the physical antenna as it moves along onboard an airborne or spaceborne platform. The resolution of a SAR in the cross-track direction is related to the bandwidth of the transmitted pulses, which are typically FM chirps: the larger the bandwidth, the higher the resolution. The along-track resolution limit is determined by the physical antenna size, such that the best achievable along-track resolution is equal to half of the antenna length. In principle, then, the resolution of a SAR system is independent of the operating center frequency, which (relatively speaking) allows high resolution at low frequencies with small antennas as long as the pulses have sufficient bandwidth. Practical considerations such as fading and signal-to-noise ratio at different frequencies may limit the resolution further. SAR systems may have polarization diversity on both transmit and receive, which makes their data information content very rich in terms of scene/target structural and geometrical properties. The reason is that differently polarized signals scatter differently from differently oriented targets or part of the same target.

SAR systems offer unique measurement capabilities not achieved by any other remote sensing system. Polarimetry, as stated above, is among them. With proper calibration of polarimetric SAR data, quantitative information about scene electrical scattering properties can in principle be obtained. For complex scenes such as forested areas, multilayer ice, or multilayered soil covered with vegetation, SAR data with multiple frequencies can be used to characterize the scatterers successively at different depths. The reason is that higher frequencies are scattered from the upper layers of scatterers and are attenuated and absorbed through the underlying layers. In contrast, lower frequencies can travel deeper into targets and carry scattered signals back to the radar receiver from underlying layers. As such, polarimetric SAR at single or multiple frequencies finds applications in diverse disciplines such as hydrology (soil moisture, water resources), ecology and the carbon cycle (biomass, vegetation moisture and density), and snow and ice (ice thickness, snow water equivalent). Several of these measurements have been demonstrated through ground-based, airborne, and/or spaceborne systems. However, they still require significant improvements and more sophisticated, low-cost measurement systems before they can be of significant benefit to their respective science disciplines. To this end, a number of measurement scenarios and associated new technologies have been identified, which are discussed below.

Measurement Scenario 19 is for a polarimetric P-band (60-70 cm wavelength) SAR to estimate vegetation biomass. Addition of lower frequencies would also be desirable to achieve biomass retrievals of higher than 200 tons/ha. Required estimation accuracy is 5 tons/ha, and required resolution is 25-50 m with semi-annual repeat global mapping. An antenna of size 10 m X 3 m is therefore sufficient, and no scanning is required. A larger antenna of size 12 m X 5 m will allow faster coverage and better system performance. A minimum bandwidth of 6 MHz is needed. This mission is possible with current technology, except that new technologies to reduce cost and mass are needed to make it feasible. New technologies needed are lightweight, low-stow-volume antennas, and high efficiency T/R modules. Feasible antenna configurations include phased array and reflector+feed configurations. The latter will be significantly lighter, whereas the former may be able to offer more flexible pattern design options. (T)

Measurement Scenario 22 is an L-band dual polarization (HH+HV) SAR designed to measure freeze/thaw state, which requires a wide swath to enable 2-3 day repeat observations. The bandwidth required is on the order of 10 MHz. This system has strict calibration requirements of no worse than 0.5 dB relative accuracy and 1dB absolute. Also, electronic beam scan is needed for ScanSAR to achieve a minimum 700 Km swath with a 10 m X 3 m antenna, otherwise one needs a 50 m X 1 m antenna, which is a significant technology challenge to be addressed. As with the P-band mission, this one can be done with today's technology except that the instrument (antenna) mass would be cost prohibitive. (T)

Measurement Scenario 112 is a UHF/VHF SAR designed to penetrate vegetation and measure soil moisture at root zone depth (1 to 5 m below the surface). This instrument could be flown in tandem (subcycle orbit) with an L-band radar/radiometer for surface soil moisture measurements if needed, or it could include a radiometer which utilizes the existing large antenna aperture. The bandwidth at both frequencies is 1 MHz, and the repeat observation period is 7-10 days, requiring a swath of 300-430 km. The soil moisture measurement accuracy is 4% absolute and 1% relative (change). The technology challenge here is the 30 m antenna length required to achieve the wide swath. This is achieved by subilluminating a 30 m lightweight mesh reflector with a custom dual-frequency feed to synthesize two effective widths of 3 m and 11 m for UHF and VHF bands, respectively. The TRL for both the feed and the mesh reflector is expected to be at 5 by the end of 2004. (E/G)

Measurement Scenario 105 is a Ku-band polarimetric SAR plus C-band polarimetric SAR designed to obtain snow water equivalent (SWE) and snow wetness to 3 cm height accuracy for SWE >0.3 m or 10% height accuracy for SWE <0.3 m, 10% snow wetness accuracy and state of soil beneath snow (wet, frozen, etc). It requires global coverage with 3-day revisit (>500 km swath) and <100 m spatial resolution. To accommodate both the C-band SAR antenna plus Ku-band Interferometric SAR requires very lightweight antenna technologies with 5-8 kg/sq-m mass density, which are deemed feasible in 3-5 years. (Note that this scenario originally called for L- and Ku-band, but that a recent algorithm study indicates that C- and Ku-band provide a superior set of frequencies for this measurement.) (E/T)

Measurement Scenario 161B is aimed at direct measurement of sea ice thickness with a precision of 20 cm and accuracy of 10% for thicknesses ranging between 50 cm and 8 m. It requires an ultra-wideband radar operating over the frequency range from 50 to 250 MHz and 300-1300 MHz, and possibly using multiple formation-flying platforms for bistatic operation. UAVs are the platform of choice for this scenario, since: (1) such ultra- wideband systems are not feasible for space operations; and (2) the wideband VHF band signals can interfere with conventional aircraft navigation systems, which is not as much of a concern for UAVs. This system operates as a synthetic aperture radar in the azimuth direction, and as a multi-angle sounder in the cross-track direction. The main technology requirements here are wideband antennas, and UAVs that can be flown at altitudes at or below 500 m with payload capability of about 50 kg and power of 200 W. (E)

Measurement Scenario 161C is for direct measurement of thickness of snow over sea ice. It requires an ultra-wideband radar operating over the frequency range from 1-8 GHz, possibly using multiple formation-flying platforms for bistatic operation. UAVs are the platform of choice for this scenario, since such ultra-wideband systems are not feasible for space operations, and UAVs may offer an economical airborne option. This system operates as a synthetic aperture radar in the azimuth direction, and as a multi-angle sounder in the cross-track direction. The main technology requirements here are wideband antennas, and UAVs that can be flown at altitudes at or below 500 m with payload capability of about 50 kg and power of 200 W. This scenario is a higher-frequency version of 161B. (E)

Measurement Scenario 162 is an L-band SAR, 0.25 m wavelength, quad-pol (HH, HV, VH, VV), with antenna size 15 x 3 m. Its goal is to characterize land cover types, including wetlands type/extent/dynamics, and vegetation characteristics such as moisture, density, and height, using polarimetric SAR. Interferometric SAR enhances accuracy of products. Spatial resolution is 25 m, with a 15 day repeat cycle to capture some of the wetlands dynamics. As in the first two scenarios above, this mission could be accomplished with today's technology but at a cost that may not be acceptable. Technology development in the areas of lightweight antennas and array-mounted electronics will enhance this mission (E).

Measurement Scenario C1 is a dual-pol C-band SAR (HH+VV) with wide swath capability to map the Arctic and Southern Ocean every 3 days. This is used for derivation of ice motion and deformation from time-sequential data. The instrument has a horizontal resolution of 5-25 m with operation at C-band. This SAR has a swath width of 450-500 km, which requires a ScanSAR implementation, for example via an electronically scanned antenna (ESA) of size on the order of 15 m X 3 m using a modular ESA, rigid fold-up, or other lightweight technology and structure. The required bandwidth is 10 MHz, peak transmit power is larger than 4KW, and the required T/R module efficiency is at least 60%. (T)

Interferometric SAR (InSAR)

Interferometric Synthetic Aperture Radar (InSAR) has been under development for application to Earth and planetary remote sensing since the mid 1970s. The technique exploits traditional SAR imagery from two antennas, combining the phase information coherently to determine the relative phase between the two observations. Each SAR observation is an image comprised of complex pixels representing the backscatter brightness of the surface (pixel magnitude), and the phase delay associated with the propagation distance from the phase center of the antenna to the phase center of the pixel (pixel phase). Interfering two observations pixel by pixel involves multiplying one pixel by the complex conjugate of the other. The resulting interferogram records the phase difference between the two observations.

If the observations are made with two antennas separated in space perpendicular to the SAR flight direction, the interferometric phase encodes primarily the difference in path length to the surface. This triangulation phase, coupled with knowledge of the position of the interferometer antennas, allows accurate reconstruction of the topography of the surface.

If the observations are made with two antennas separated in space along the SAR flight direction, a paired snapshot of a rapidly changing surface can be made. In this case the interferometric phase records the movement of the surface from one time to the next. A special case of this approach is implemented with one antenna incorporating a moving phase center held fixed in space as the antenna moves. The antenna is referred to as a displaced phase center antenna (DPCA), and is typically used to detect moving discrete objects otherwise obscured by the surface return.

If the observations are made with a single antenna repeating a flight path two or more times, the interferometric phase from any pair again records the movement of the surface over the elapsed time, typically slow moving processes such as volcanoes and glaciers. This technique is sometimes referred to as “coherent change detection”. If the repeat track has a cross track separation, then the interferometric phase will be a combination of topographic phase and surface change, if any. These effects can be separated using additional repeat pass measurements or with independent knowledge of the topography, for example, using a fine resolution digital elevation model (DEM). In general, repeat-pass methods for estimating topography are limited by random changes in the surface scatterers over time (scene decorrelation), and by refractive anomalies in the radar line-of-sight direction, which vary over time. Two-aperture simultaneous InSAR is the preferred technique for topographic mapping applications.

InSAR has become an accepted standard for fine-resolution automated mapping of topography and surface change over wide areas. Stereo techniques can provide accurate topographic information under the right observational circumstances (sufficient parallax and brightness contrast in the image) but remains less automatable, and generally less accurate, than a correspondingly capable InSAR system.

The critical technology challenges for InSAR are related to the ability to control and calibrate the system as an interferometer. This implies that a system must be incorporated for knowing the interferometric baseline (separation of the phase centers of the antennas) and the relative phase of the two receivers. For the two-aperture simultaneous interferometer, this generally implies the need for a metrology system for measuring the physical vector separation and orientation of the apertures, structural control or measurement of the surface of the apertures, and electrical calibration schemes to track the phase of a reference signal from the receive aperture surfaces through the feed networks and receiver chains for each antenna.

For repeat-pass systems, knowledge of the baseline is equally important, but must either be determined from accurate orbit determination and attitude reconstruction (e.g. with differential GPS for orbit and use of Inertial Navigation Unit/gyros for lever arm attitudes). Aperture shape control/knowledge is still important here as it affects the phase center of the antenna. Tracking the receiver phase variation over the orbit, including tracking phase cycle slipping, becomes a calibration driver. In addition, for repeat pass systems, control of the orbit to a small fraction of the maximum allowable baseline (a function of resolution, incidence angle, range, and wavelength) is important to ensure interferometric integrity of each and every repeated observation. This implies a mission operations scenario with sufficient propellant and adequate modeling of drag on the spacecraft. Surface decorrelation can be a limiting factor in the ultimate accuracy of repeat-pass interferometry systems, and longer wavelength radars are generally less susceptible to these effects.

The technology challenges for the basic radar system comprising the interferometer increase as the aperture area or linear dimension increases and the orbital altitude increases. For large apertures, maintaining surface flatness and reducing mass density (to enable cost-effective development) are the critical challenges to affordably fielding the constellations of radars in the NASA science roadmaps. Generally, as the orbital altitude increases, the apertures must be larger to maintain measurement sensitivity, and in addition, the electronics must be able to sustain more stressing radiation conditions. Issues of mass density become all the more critical, as one of the fundamental methods of addressing radiation is to add massive shielding. In addition, power and cost can increase considerably with altitude. In the case of SAR, the power required to maintain image quality increases with the cube of the range. Phased array technology is required for many of these observations, particularly those requiring very wide swaths employing ScanSAR. Phased arrays can eventually become prohibitively expensive due to the large number of elements required (unless used only in a feed in a reflector antenna).

Following is a list of the measurement scenarios that utilize interferometric techniques (Table 4), with the exception of scenarios 29 and 93 that are treated in the Altimeter section on the following page.

Table 4. Measurement Scenario Assessment Table

Scenario Description
Measure polar ice sheet velocity using a repeat-pass L-band InSAR in low Earth orbit (LEO). The relevant technology is affordable, lightweight, L-band active array technology. The mission must provide sufficient coverage and repeat frequency.
Infer sea ice thickness by measuring sea ice freeboard (height above ocean surface) using an InSAR altimeter in LEO. The relevant technology is a Ka-band interferometer looking near nadir.
Provide direct measurement of sea ice thickness, with precision of 20 cm, and accuracy 10% of thickness within the range between 1- 8 m of ice, from LEO.
Measure water storage in wetlands and lakes, river stage height and discharge rate using a Ka-band InSAR in LEO. The InSAR here is both two-apertures cross-track for topography and two apertures along track for velocity determination.
Measure snow water equivalent (SWE) and snow wetness using a Ku/C-band two-aperture cross-track polarimetric InSAR in LEO.
Measure land surface deformation using one (or more) repeat pass InSARs in LEO.
Measure land surface topography using two formation flying SARs operating as a two-aperture cross-track interferometer in LEO.
Measure land surface topography and deformation with high temporal resolution using a constellation of SARs in Medium Earth Orbit (MEO). The MEO option provides improved temporal coverage and accessibility relative to LEO orbit.
Measure land surface topography and deformation using an airborne repeat-pass InSAR.
Measure land surface topography using X-band two-aperture cross-track InSAR from low Earth orbit.
Determine vegetation characteristics, primarily height, and secondarily density profile, using two-aperture cross-track InSAR from airborne platform.
Determine vegetation characteristics, primarily height, and secondarily density profile, using two-aperture cross-track InSAR from LEO.
Measure land surface topography and deformation with high temporal resolution using a constellation of SARs in geosynchronous orbit. This scenario option provides near continuous temporal coverage and accessibility.

Atmospheric Real-Aperture Radars

The Precipitation Radar on board the US/Japanese TRMM satellite is the first, and so far the only, spaceborne atmospheric radar. Inspired by the detailed 3-D images of severe storms that ground weather radars can produce, atmospheric scientists hope to use spaceborne atmospheric radars to study the fine-scale vertical structure and dynamics of clouds, snow and rain over oceans, and to monitor systematically the changes in structure and dynamics around the globe. Indeed, while IR imagers can provide a coarse estimate of cloud-top height at a relatively high horizontal resolution, and while microwave imagers can provide a somewhat less coarse estimate of bulk cloud and rain concentrations, at relatively low horizontal resolution, only a radar can be directly sensitive to the vertical distribution of water, at high resolution in the horizontal (an antenna issue) as well as the vertical (a bandwidth issue).

The first challenge in designing such instruments is that, in order to maintain sufficient horizontal resolution to resolve the fine-scale vertical variability (which can change drastically over 5 kilometers horizontal), and because of weight and size restrictions, current technology does not allow one to consider frequencies much below Ku band. But liquid water attenuates microwaves significantly above X band, and it does so in a way that depends on the total amount of water as well as on the variable size of the drops or droplets. This attenuation can be so large as to drive the lower-atmosphere echoes below the noise even in moderately strong weather systems, the attenuation rate increasing with frequency. Furthermore, the relation between attenuation and drop volume is sufficiently non-linear to make the interpretation of the echoes detectable below the melting level quite difficult. Thus, the liquid-water attenuation must be taken into account in the specification of the sensitivity and the dynamic range.

The second challenge in designing atmospheric radars is the limitation on their sampling capability, due to surface clutter and to the three-dimensional nature of the echoes. Because the surface is orders of magnitude brighter than clouds and all but the heaviest rain, the further off-nadir a radar points, the larger the vertical portion of the atmosphere that gets occluded by the surface. For a low Earth orbit, this limits the width of the radar's swath quite severely. A further constraint for LEO scenarios is that, unlike imaging radars, atmospheric radars are expected to collect the echoes from each vertical range bin above a given "pixel" at the surface, and to do so before the platform has moved too far in order to avoid horizontal "gaps" in the instantaneous coverage. Thus, the surface clutter and the sheer volume of measurements constrain the sampling frequency to such an extent that these instruments have so far been considered mostly as research tools for the systematic three-dimensional study of cloud- and sub-cloud-size structures, rather than as global sampling tools.

Measurement scenario 142 is for a LEO single-frequency (94 GHz) nadir-pointing cloud profiling radar. With sufficient sensitivity, such a radar could profile the vertical distribution of liquid-water as well as ice concentrations. With sufficiently high pulse repetition frequency (PRF) and a sufficiently narrow beam, it could also estimate vertical motion profiles. (P)

Measurement scenario 156 is for a balloon-borne single-frequency (94 GHz) nadir-pointing cloud-and-aerosol profiling radar. Similar to the radar of scenario 142, the stratospheric balloon platform would increase the horizontal and vertical resolutions ten-fold over spaceborne designs, using less power, and it would allow studies above fixed remote sites over continuous extended periods of time. The instrument would be recoverable and hence re-usable after each measurement campaign. (T)

Measurement scenario 159 is for a LEO dual-frequency (94 and 140 GHz) scanning cloud profiling Doppler radar. The dual frequency design would allow the vertical profiling of mean cloud particle size as well as cloud water concentrations, and improve the accuracy of the latter over that of a single-frequency cloud radar. The Doppler capability would allow the estimation of mean vertical motion near nadir. With enough sensitivity, this instrument could also improve the accuracy of the retrieved vertical distribution of light precipitation, at rain rates below the sensitivity of lower-frequency rain-profiling radars. (T)

Measurement scenario 75 is for a LEO dual-frequency (14 and 35 GHz) scanning Doppler+polarization rain radar. The dual-frequency design should allow the vertical profiling of mean drop size as well as rain rate with relatively high accuracy. The Doppler capability should allow the profiling of the vertical component of the wind. A 5.5 x 5.5 m parabolic cylindrical antenna with an active array feed should allow the use of an adaptive scanning technique, increasing the high-vertical-resolution coverage to rainy areas within a 520-km-wide swath from a nominal 450 km orbit. The polarization capability would allow the precise detection of precipitation-size frozen hydrometeors. High sensitivity in both frequency channels would extend the measurement accuracy from snow and drizzle to heavy rain. (T)

Measurement scenario 154 is for a LEO closely-spaced-dual-frequency (both at Ka band) rain radar. The two frequencies would share a single transmitter. The difference in attenuation rates at the two frequencies could be used to improve the accuracy of rain profile retrievals relative to single-frequency rain radars. (P)

Measurement scenario 76 is for a LEO tri-frequency (14, 35 and 94 GHz) LEO rain-and-cloud radar. This is an “augmentation” of scenario 75, the addition of a matched-beam 94-GHz channel allowing for an increased range of detectable water concentrations, an increased accuracy in the measurement of light precipitation, and a systematic study of the spatial correlations between rain and clouds. (G)

Measurement scenario 160 is for a GEO single-frequency (35 GHz) spiral-scanning Doppler rain radar with a 30 m antenna. In a geostationary orbit, such a radar would measure vertical profiles of rainfall intensity and vertical wind at a horizontal resolution of about 12 km, with unprecedented temporal sampling frequency within a 55 degree longitude/latitude box, making it exceptionally useful for the study of severe weather systems such as hurricanes within the tropics, especially as no other scheme has yet been proposed to study tropical convection at fine temporal scales. (T)

Finally, measurement scenario 155 is for a UAV-borne multi-frequency (10, 14 and 94 GHz) scanning Doppler+polarization rain and cloud radar, capable of vertically profiling precipitating and cloud water concentrations as well as vertical wind. The UAV platform would allow high horizontal and vertical resolutions and longer observation periods than conventional aircraft. (G)

Scatterometers

Scatterometers are active radar instruments whose primary function is to make measurements of the radar backscattering coefficient of distributed terrestrial targets. The radar backscattering coefficient (σ^0) of a statistically homogeneous distributed target, such as a random rough surface or a random volume composed of randomly oriented scatterers, is the ensemble average of the radar cross section (RCS) of the target per unit area. The radar backscatter coefficient of a target is a function of both target physical parameters, such as the surface roughness and dielectric constant of a random surface, and scatterometer system attributes such as frequency, polarization and incidence angles. Ground-based, airborne, and spaceborne scatterometer systems have long been used for a wide variety of remote sensing applications, ranging from basic feasibility studies to specific operational missions, all with the goal of retrieving bio-physical parameters of targets of interest. The first spaceborne, Earth observing scatterometer system was launched aboard the Seasat spacecraft by NASA/JPL on June 28, 1978.

Depending upon the complexity of the relationship between target parameters and the radar backscattering coefficient, the number of influential target parameters, and sensitivity of $\sigma°$ to the target parameters, scatterometer systems with multi-look angle, multi-polarization, and/or multi-frequency must be considered. For example, the ERS-1 satellite, carrying a C-band scatterometer with three independent antennas pointing in directions of 45°, 90°, and 135° to the right of the satellite track, is used for measuring sea surface wind magnitude and direction. Basically, a spot on the sea surface is illuminated three times, by the fore, mid, and aft beams, respectively, to provide three independent $\sigma°$ values used in the retrieval algorithm.

Spaceborne scatterometer systems are often used in imaging mode by scanning the antenna in the cross-track direction. Imaging scatterometers make use of relatively large antenna aperture in order to achieve a moderate resolution proportional to Rl/D, where R is range to the target, l is the wavelength, and D is the antenna diameter. Because of their poor resolution, scatterometers are most appropriate for remote sensing of targets with large physical and homogeneous extents such as oceans, sea ice, vast prairies, and forests, etc. Their large footprint allows for scanning a large swath, and therefore global images can be acquired often with a relatively short duration. Use of high gain antennas mitigates high transmit power requirements often encountered with SAR systems. The low data rate nature of scatterometer data and very low data processing requirements keeps the satellite's power consumption low and allows for on-board processing capability.

Radiometric calibration of scatterometers for measuring the absolute values of $\sigma°$ is an important step that directly affects the quality of the estimated physical parameters obtained from the scatterometer measurements. Internal and external calibration methods must be considered and implemented. Internal calibration can take care of short-term and long-term system instabilities such as level of transmitted power, amplifier gains, etc. External calibration is used to examine the overall system performance as a function of time and performing radiometric calibration. This is usually done using active ground-based transponders with very large RCS values and radar returns over stable ground targets such as the Amazon rain forest.

Coherent scatterometers, which are capable of measuring both the magnitude and phase of the radar backscatter and are frequency agile, can be used in a dual-frequency correlation mode. These radars are referred to as D-k radars in the literature. The Doppler spectrum of the radar backscatter contains information about the radial velocity of the target motion, such as ocean surface currents, which can be used in retrieving the target parameters. The cross correlation of the Doppler spectra obtained from the scattered microwave signals at the two frequencies contains distinct sharp peaks located at frequencies proportional to radial velocity of target motion. A more advanced form of the D-k radar is known as the frequency correlation radar, where instead of two frequencies, the radar is capable of transmitting and receiving coherent radar backscatter at many frequencies.

Measurement scenario 61 requires a specialized scatterometer that can measure near-surface wind velocity (both speed and direction) under all weather and cloud conditions over the Earth's oceans. The measurement is made using modulation of microwave backscatter from the ocean surface due to roughness. Global measurements are made of ocean surface winds with 2 m/s wind speed and 20 deg wind direction accuracy using a Ku-band polarimetric scatterometer in low Earth orbit. Currently, systematic ocean surface wind measurements are being provided by the NASA QuikSCAT and SeaWinds scatterometers. Measurements are feasible with present technology, but new technology will reduce mass, power, and volume, using an antenna aperture diameter of about 1 m. Measurement scenario 148 is similar to scenario 61 with the exception of Earth orbit operation. For scenario 148 the Ku-band scatterometer needs to operate in MEO orbit and will require a 3-10 m antenna aperture. (E for both)

Scenario 90 needs a Ku-band scatterometer to measure sea ice extent and ice motion with daily coverage and wide swath (approx. 1600 km) aboard a LEO satellite in a polar orbit. This sensor option is a dual polarization real aperture or Doppler beam sharpening Ku-band scatterometer which monitors daily ice motion and ice edge position twice daily (complete coverage every 12 hours) or more with a spatial resolution of 3-5 km. For this scenario, edge detection accuracy of 1 km, ice concentration accuracy of better than 5%, and snow depth accuracy of smaller than 5 cm are needed. (T)

Measurement scenario 102 also makes use of a Ku-band scatterometer in LEO orbit for monitoring snow cover with high temporal resolution over a global scale. The Ku-band frequency is needed to enhance volume scattering and to achieve high sensitivity to snow. An ultra wide swath is needed for twice-daily (day/night) coverage over cold land regions (>35 deg latitude). The system will measure freeze/thaw transition and ecosystem dynamics at 1-3 km spatial resolution. The instrument may be a real aperture scatterometer or a Doppler beam sharpening scatterometer. The radar will be configured as fully polarimetric with an scanning antenna to achieve a swath width of 2000 km and a resolution of less than 1 km. (T)

For scenario O2 a dual-frequency scatterometer system operating in D-k mode at X- or Ku-band from geostationary orbit is considered. The radar receives resonant scattering from capillary waves whose ocean wavelengths are one-half the electromagnetic difference wavelength transmitted by the radar. Ocean surface current is retrieved from the well known dispersion relationship between the frequency and wavelength of the gravity waves. The D-k radar can also measure the ocean wave spectrum and the wind vector. Geostationary orbit is required so that platform velocity will not mask a Doppler frequency measurement range of only a few Hz. A 10 m antenna is required to achieve horizontal resolution of 100-150 km. (T)

Altimeters

A radar altimeter measures the distance between the sensor and the illuminated surface to derive a topographic map of the surface. Since it operates at microwave frequencies, the measurement is much less affected by weather conditions. As an application of a radar altimeter, the geostrophic (balance between pressure and the Coriolis force) component of the circulation can be estimated by measuring sea surface topography. In order to be successful, centimetric accuracy is required in the determination of sea surface height (SSH). The circulation of the oceans plays a major role in determining the Earth's climate and energy balance.

The first instrument to demonstrate decimetric precision was the Seasat altimeter. Subsequently, the TOPEX altimeter, launched in 1992, refined the instrument suite and demonstrated measurements of global scale circulation that included making significant contributions to the study of El Nino, Rossby waves, and tides, among other phenomena. TOPEX introduced what has become the standard suite for ocean altimeter systems. It consists of a dual frequency (Ku and C band) altimeter with an effective pulse width of ~50 cm (320 MHz bandwidth). The two radar frequencies are used for removal of the ionospheric delay. The instrument operates using a real aperture and full-deramp range compression for reduction of data rate. A three-frequency radiometer (18 GHz, 21 GHz, and 35 GHz) is used to estimate wet tropospheric delays. The orbit determination is accomplished using GPS receivers and a DORIS (Doppler ORbitography and geopositioning Integrated by Satellite) transponder. Subsequent to TOPEX, the Jason-1 mission was launched in 2001, carrying essentially the same instrument suite, but with more refined components.

Measurement scenario 28 is for a synthetic aperture altimeter operating at Ka-band in low Earth orbit with 5 – 10 km resolution. In order to study sea-level rise and coastal phenomena, there has been a desire to improve the height accuracy of conventional altimeters and the along-track resolution. A concept that could meet these requirements is the Delay Doppler (Synthetic Aperture) Altimeter. The conventional altimeter's onboard processing is changed by coherent processing to synthesize and correct for range migration waveforms obtained from different Doppler bins. These changes, which are implemented through the inclusion of an FPGA (Field Programmable Gate Array) azimuth processor prior to range compression, improve the along track resolution by synthesizing a larger antenna aperture. It also improves the height accuracy by providing a sharper waveform to track and additional incoherent looks. The expense of this technique is the required increase in pulse repetition frequency and power for the onboard processing. The concept was demonstrated under funding by the NASA Instrument Incubator Program. The expected height accuracy is 1 cm.

The antenna size is 1.5 m and the transmit power is 1 W using a SSPA (Solid State Power Amplifier). The bandwidth is 600 MHz and the PRF (Pulse Repetition Frequency) is about 10 KHz. For precise orbit determination, a Doppler Beacon Receiver, GPS receiver, and laser reflector array are required. A multiple frequency microwave radiometer is required to determine atmospheric water vapor. This scenario meets the measurement goals except the cross-track sampling. Using multiple satellites, this scenario can satisfy the cross-track sampling and the revisit time goals. (G)

Measurement scenario 29 is for an interferometric radar operating at Ku-band to measure ocean eddy structure and two-dimensional ocean circulation. A TOPEX-class altimeter is not sufficient for mapping ocean mesoscale phenomena (e.g., ocean eddies), which are responsible for most of the kinetic energy in the ocean and for the mixing of hot and cold water masses. The limitations of conventional nadir altimetry for mesoscale ocean mapping are due to the small (~2 km) swath of nadir altimeters and to the requirement that the repeat cycle be on the order of 10 days. A different method of overcoming the swath limitations, known as WSOA (Wide Swath Ocean Altimeter), is employed. This instrument requires a 10 m interferometric baseline in a low Earth orbit. The 10 m mast must provide the short-term stability and the radar electronics must be phase-stable (0.01 degrees after the cross-over calibration). This instrument uses Ku-band TWTAs to generate the 500 W transmit power. Light weight antennas (5 m x 0.5 m) are implemented using reflectarray technology to produce different polarization swaths located symmetrically about the nadir altimeter track. The bulk of the interferometric processing occurs onboard using FPGAs, in order to reduce data rate substantially. The expected accuracy is 1 cm. For precise orbit determination, a Doppler Beacon Receiver, GPS receiver, and laser reflector array are required. A multiple frequency microwave radiometer is required to determine atmospheric water vapor. This scenario meets all the measurement goals. The specific orbit will determine the revisit time. (G)

Measurement scenario 93 is for an interferometric, synthetic aperture radar operating at Ku-band to measure the absolute elevation and surface relief of ice sheet and glaciers. The instrument is the next generation of the ICESat mission. It will produce ice sheet topography accurate to 1 cm and provide a complete mapping of the polar regions at a spatial resolution of 1 km. The main application of this instrument is to continue the monitoring of polar ice balance started by ICESat at higher spatial sampling and resolution. The interferometric baseline is formed by a 10 m mast. The antenna size is 5 x 0.5 m and the peak transmit power is 500 W. A highly precise metrology is required to measure the interferometric baseline formed by the two antennas and a mast. However, the metrology system can be replaced by the use of cross-over adjustments for calibration. The radar must be phase-stable (0.1 degrees over 1 minute). This instrument meets all thresholds (E).

Radio Occultation and GPS-Related Scenarios

The Navstar, or Global Positioning System (GPS), constellation consists of at least 24 satellites (plus several spares) operating in 12-hr circular orbits at an altitude of approximately 20,000 km. Between 6 and 12 GPS satellites are in view almost all the time globally at 5 deg or higher elevation, and even more satellites can typically be tracked from a low-Earth satellite carrying a GPS flight receiver. GPS signals are transmitted at two L-band frequencies (1.2 GHz and 1.6 GHz), enabling correction for ionospheric signal propagation delays. The US Air Force, which manages and operates the GPS, tracks the satellites from a ground network of 5 sites and estimates the GPS orbits and clocks to a level of about a few meters. The GPS ephemeris and clock information are periodically (several times per day) uploaded to the satellites. When a user with a GPS receiver can see range (technically referred to as "pseudorange" because the relative transmit and receive clocks are not known a priori) data from 4 GPS satellites, the user can assume that the GPS clocks and positions are all "known" and thus can solve for the user clock and three position coordinates with those four range (pseudorange) measurements.

In practice, this technique permits user positioning at the level of several to 10 meters. However, for geodetic and high-precision applications, user positioning at the 1-cm or even few-mm level is required. To achieve this, a larger network of ground receivers is used and more accurate solutions for the GPS orbits and clocks are obtained. For instance, JPL and other analysis centers use data from the more than 250 GPS ground receivers in the International GPS Service (IGS) to determine GPS orbits to about 5-cm. With this type of system, which requires many sophisticated algorithms and processing enhancements over "standard GPS," user positioning at the few-mm level is possible, after the fact. This capability is referred to as "static positioning" in the below discussion of scenario 51. With the advanced JPL real-time version of this system, real-time user accuracy can reach about 10-cm presently (compare this to the "standard GPS" real-time user accuracy of a few meters). Such real-time systems are also discussed in scenario 51.

Measurement scenario 68 is an atmospheric occultation scenario in which a signal transmitted by one LEO satellite is received by another LEO satellite. The geometry of the two LEO orbits forms a rising or setting pair with a link through the Earth's atmosphere, thereby providing vertical profiles of various atmospheric constituents through absorption, depending on the frequencies of the transmitted signal. A constellation of at least two counter-rotating satellites is required, with orbits optimally chosen to maximize occultations globally or over selected regions.

Vertical profiles of water vapor and isotopes, and ozone, in the lower troposphere, upper troposphere and lower stratosphere with 1 km vertical resolution, horizontal resolution of 200 km and accuracy of a few percent or better, can be achieved with frequencies 10-22 GHz, 183 GHz, 195 GHz, and higher. GPS L1 and L2 would add traditional occultation capabilities, in which the GPS carrier phase data is exploited.

To allow for the complete characterization of the absorption line shape, a microwave/mm-wave sounder capable of generating a set of 5 or more tones unevenly distributed around the resonance frequency of the species being measured is required. For the lower (10-22 GHz) frequencies only, the requirements for tone generation and amplification are met by current technologies. For higher frequencies, there is a need for a technology to produce 10 mW output per tone, suitable for radiation by a 30 cm diameter antenna. The main system tradeoff is between amplification and antenna size, and hence gain and beam width, to achieve voltage signal-to-noise ratio of 1000 or better. (P)

Measurement scenario 30 is one in which the instrument determines ocean surface height by measuring the difference between direct and ocean-reflected GPS/GNSS (GPS/Global Navigation Satellite System) signals. The instrument may also be able to measure ocean surface wind velocity and eddy scale ocean topography from GPS/GNSS reflections. This instrument is a type of bistatic radar; the transmitters are the existing GPS satellites and not part of the observing system being designed here. Although one single receiver is sufficient to perform this measurement, accuracy and horizontal resolution improve as the square root of the number of platforms.

Measuring ocean surface reflections of the GPS signal requires high-precision, steerable, multi-beam antenna systems. To achieve 5 cm accuracy over a 25 km x 25 km cell in ten days, required for eddy-monitoring-quality topography measurements, steerable, high-gain (~30 dB), and ~10-beam antennas will be required. A dual-frequency software-driven GPS receiver is required, with FPGA architecture to handle thousands of correlators with channel synchronization, the ability to process multiple GPS antenna inputs, and process large data volumes. The ability to upload changes to the flight software during flight is essential. (P)

In measurement scenario 51, the instrument is an advanced GNSS receiver for use on the ground. Its data will help estimate earthquake potential, identify active blind thrust faults, and test models of compressional tectonics. It can also be used to measure local variations in strain rate that might reveal the mechanical properties of earthquake faults. In the event of an earthquake, an array of these instruments would measure permanent crustal deformation not detectable by seismographs, as well as the response of major faults to the regional change in strain. This instrument is also used to measure terrestrial reference frame components of position and velocity for a point on the Earth's crust.

The requirement is < 5 cm real-time kinematic positioning in all spatial dimensions, with a 1 cm goal. (This could be achieved, for example, by the ability to accept real-time corrections from NASA's global differential GPS system together with sufficiently comprehensive in-receiver GPS analysis software.)

For static positioning, daily precision of < 0.5 mm in horizontal components and < 1 mm in vertical components (approximately 5x improvement over current state of the art) is required. To achieve this, the receiver may need to be reconfigurable to allow measurement of new (GPS III) signals, as well as the Russian GLONASS GNSS and/or the European Galileo GNSS. An all-in-view capability may be highly desirable. The receiver/antenna may need to track dual frequency carrier phase down to < 5 degree elevation with < 1 cm multi-path error to help separate the tropospheric parameter from vertical location and clock synchronization parameters.

A robust version of this receiver for rapid deployment (within 24 hr), via ballistic drop from aircraft, for example, is also desirable. Less-stringent positioning requirements (comparable to current state-of-the-art) could be tolerated in this version. (G?)

Relationship of the Measurement Scenarios to the Science Focus Areas

A summary of which measurement scenarios support which science focus areas is presented in Table 5. It is clear from this table that advanced microwave remote sensing techniques can make significant and wide-ranging contributions to the Earth science goals of NASA. It is also clear that active and passive remote sensing techniques both have much to contribute. The technologies required to develop implement these measurement scenarios are discussed in detail in the next chapter.

Table 5. Mapping from Measurement Scenarios to Science Focus Areas

Scenario Description	ID	Water& Energy	Weather	Climate
Passive Techniques				
• Real-Aperture Radiometers				
- snow water equivalent radiometer	106	X	X	X
- L-band 25 m mesh antenna	111	X	X	X
- dual L-band 25 m radiometer/scatt	38	X	X	X
- sea surface temp 7 m radiometer	O1	X	X	X
- sub-mm/far-IR cloud radiometer	143	X	X	X
• Real-Aperture Sounders				
- advanced Microwave Limb Sounder	140			X
- 4 m scanning geosynch sounder	176	X	X	X
• Synthetic Thinned Array Radiometers				
- 2-D STAR soil moisture & salinity	34	X	X	X
- 1-D STAR soil moisture & salinity	177	X	X	X
- 2-D STAR snow water equivalent	107	X	X	X
- 1-D STAR snow water equivalent	108	X	X	X
- temp profile, moisture, precip	67	X	X	X
- 25 m L-band freeze-thaw transition	H1	X	X	X
- 25 m L-band snow water & wetness	H2	X	X	X
- 25 m L-band soil moisture	H3	X	X	X
- conscan STAR for snow over sea ice	C2	X	X	X
- global precipitation	A1	X	X	X
- ocean surface winds & precipitation	A2	X	X	X
• VLBI				
- VLBI for Earth rotation/polar motion	53			
Active Techniques				
• Synthetic Aperture Radar (SAR)				
- P-band biomass	19			X
- L-band freeze/thaw transition	22	X	X	X
- UHF/VHF deep soil moisture	112	X	X	X
- Ku & L-band snow water & wetness	105	X	X	X
- UAV ultra-wideband, sea ice thick	161B			X
- UAV ultra-wideband, snow on sea ice	161C			X
- L-band SAR quad-pol for land cover	162	X		
- C-band wide swath ice monitor	C1			X

Scenario Description	ID	Water& Energy	Weather	Climate
Active Techniques				
• Interferometric SAR				
- L-band polar ice sheet velocity	92			X
- InSAR altimeter sea ice freeboard	97			X
- sea ice thickness	161A			X
- wetlands, lakes & rivers	100	X		
- snow water & wetness	105	X	X	X
- land surface deformation	44A			
- land surface topography	44B	X		
- MEO const. for deformat'n & topo	45	X		
- GEO const. for deformat'n & topo	46	X		
- airborne repeat-pass land surf topo	47	X		
- X-band land surface topography	163	X		
- UAV vegetation height & density	157			X
- LEO vegetation height & density	158			X
• Atmospheric Real-Aperture Radars				
- 94 GHz LEO cloud profiler	142	X	X	X
- 94 GHz balloon-borne cloud profiler	156	X	X	X
- 94/140 GHz LEO Doppler cloud radar	159	X	X	X
- 14/35 LEO Doppler/pol rain radar	75	X	X	X
- dual freq Ka-band LEO rain radar	154	X	X	X
- 14,35,94 GHz LEO rain & cloud radar	76	X	X	X
- 35 GHz GEO Doppler rain radar	160	X	X	X
- UAV Doppler & pol cloud & rain radar	155	X	X	X
• Scatterometers				
- LEO sea surface wind velocity	61	X	X	X
- MEO sea surface wind velocity	148	X	X	X
- LEO sea ice extent & ice motion	90		X	X
- LEO snow cover, freeze/thaw trans.	102	X	X	X
- Delta-k radar ocean surface current	O2			X
• Altimeters				
- LEO synthetic aperture altimeter	28			X
- LEO interf. wide swath altimeter	29			X
- LEO synthetic ap. interf. alt for ice	93			X
• Radio Occultation & GPS Scenarios				
- RF occultation radiometer	68	X	X	X
- GPS reflectometer	30			X
- GPS in situ network surface deform'n	51			
• Surface Rover				
- E-M induction & acoustics	151	X	X	X

4. TECHNOLOGY REQUIREMENTS

Introduction

In this chapter technology requirements are defined and discussed. The chapter is divided three major sections: Active Instruments (radars), Passive Instruments (radiometers) and On-board Processing Technology. The active and passive instrument sections each discuss both antennas and electronics. In each section the required technical capabilities and technical challenges are discussed and summarized as a guide to the decision maker. Two distinct figures of merit are employed in each section to gauge the potential utility of each candidate technology; the number of scenarios addressed by the technology and the number of types of measurements supported the technology.

Multiple figures of merit were provided because there is no single figure of merit suitable for decision makers. Here, two useful figures of merit are presented as an aid in the form of histograms. The first is a count of the number of scenarios served by a given technology. However, this figure of merit, while useful, can be quite biased. There could for example be two equally important physical measurements that need to be made. However there could be many scenarios for making the first measurement while only one scenario might exist to make the second equally important measurement. Additionally a given scenario may provide not just a single measurement but also a variety of other measurements. For this reason the number of measurements supported by a given technology was also tabulated in the form of a histogram. Finally, it should be mentioned that the science priority is an important figure of merit. However, the science priority was not given in the Earth Science Enterprise (ESE) roadmaps.

In each section two types of technology roadmaps are provided for retiring the technical challenges over a10-year period. The first type of roadmap addresses an individual technology challenge. The second type of roadmap is an integrated technology roadmap that provides an overall summary of development in a broad technical area. For each technology in a technology integrated roadmap a bar appears which is colored green for the duration of the current funding, colored blue for the duration thought to be required to develop the desired technology and sometimes hashed in blue or followed by an arrow indicating probable continued development beyond that addressed in this document. The integrated technology roadmaps are related to the integrated science roadmaps of the next chapter. The later have a science orientation as opposed to the technology orientation taken here. Finally, the complete Capability Breakdown Summary (CBS) tables are included.

The CBS tables include many details and are compiled in the form of Excel spreadsheets. In the CBS table technologies are arranged according to groups of rows. In successive columns the CBS tables provide the measurement scenarios that each technology addresses by means of their identification numbers as well as short verbal descriptions, the type of instrument supported by the technology, and the waveband of operation. Subsequent columns describe in both a qualitative and quantitative way what is required of the technology and a list of tasks and subtasks to achieve these requirements along with a justification of these tasks. The remaining columns provide the starting and ending technology readiness level (TRL), estimated development time, need date, estimated manpower level as well as estimated hardware/contract cost, the methodology for making the estimates and point of contact information for the technology. However in the public version of this document the columns related to cost estimates have been edited out.

4.1 Active Instrument Technology

4.1.1 Antennas

4.1.1.1 Overview

The radar technology requirements were derived based on the following process as shown in Figure 4.1.1.1. First, we identified the measurement parameters that require the technology development using the ESE (Earth Science Enterprise) focused area roadmaps. The science requirements document specifies the performance required to measure these parameters. Then, technical approaches to measure these parameters are selected from the ESTO measurement scenario document. The measurement parameters and the associated scenarios are summarized in Table 4.1.1.1. Using the technical information and any modifications by the Working Group (WG) members, we generated a list of enabling technologies. The WG members developed the technology requirements for these enabling technologies. Other technologies classified as enhancing technologies are often required to lower the mission life-cycle cost. Several requirements were developed for enhancing technologies. The enabling technology requirements were considered to be higher priority requirements than the enhancing technology requirements. We also considered the system-level development that can improve a space-borne mission significantly. Since many system-level innovations are not invented yet, we only listed the objectives of the potential system-level development.

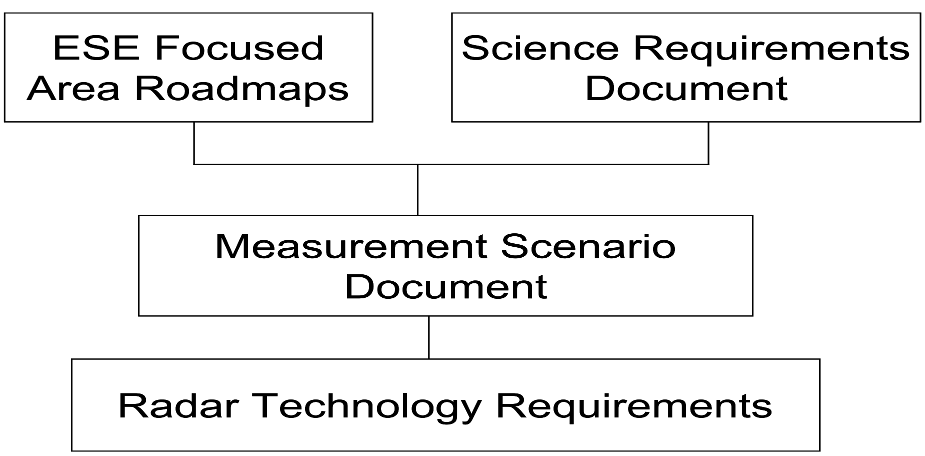


Figure 4.1.1.1 *Process to Derive Radar Technology Requirements*

Measurement Parameters	Focus Science Areas	Measurement Scenarios
Ice Mass Change	Climate Variability and Change	92, 93, 90, C1, 97, 161A, 161B,
Global Soil Moisture	Climate Variability and Change, Weather, Water and Energy Cycle	112
Global Cloud Characteristics	Climate Variability and Change	142, 156, 159
LEO Aerosol	Atmospheric Composition	68
Vegetation 3-D structure, Biomass, and Disturbance	Carbon Cycle and Ecosystems	19, 157, 158
Global River Discharge	Water and Energy Cycle	100
Snow Water Equivalent Observations	Water and Energy Cycle	102, 105, 161C,
Accurate space-borne radar geodetic imaging (InSAR)	Solid Earth and Natural Hazards	44a, 44b, 45, 47, 163, 51,
Other parameters that were not identified as “T” (Technology development required)	Climate Variability and Change, Weather, Water and Energy Cycle, Carbon Cycle and Ecosystems	22, 28, 61, 29, 75, 76, 160, 162, 154, 148, O2, 30, 151, 155

Table 4.1.1.1 Relationship between measurement scenarios and measurement parameters in the focus science areas.

4.1.1.2 Issues

The meaning of the “Technology Development Required” (in the ESE focused area roadmaps) must be clarified. In addition, it is difficult to prioritize the technology requirements due to unknown science priority and the future mission schedule.

4.1.1.3 Radar Antenna Technologies

The antenna technology is composed of three elements: structure, electromagnetic wave radiator, and electronics technologies. The antenna electronics technology will be described in the radar electronics section.

The antenna structure must be stiff enough to maintain the surface flatness. The required technology is to make the antenna structure as light as possible for the given stiffness. The stowed volume is also a significant factor since a large structure must be deployed in space. The need for a large antenna structure comes from two desired improvements. One is to develop a radar instrument at low frequencies (scenario 112) and the other is to operate an instrument at higher orbits (scenarios 160, 45, and 46). At low frequencies (UHF/VHF), a large antenna is required to satisfy the radar performance such as SNR (Signal to Noise Ratio) and the range ambiguity. At higher frequencies (L-band and Ka-band), a large antenna is required for the improved coverage and temporal sampling by increasing orbit altitudes. There are two types of antenna structures: a structure to form a large reflector antenna and a supporting deployment structure for a large phased array.

For a reflector, the only enabling technology identified was a 30m (diameter), deployable reflector antenna (scenarios 112 for VHF/UHF and 160 for 35GHz). Deployable and inflatable/rigidizable structures are two most promising candidates for a phased array antenna at MEO and GEO (scenarios 45 and 46). The minimum antenna area requirements are 400m2 for MEO and 700m2 for GEO. ESTO must take advantage of the investment made by DoD agencies and industry for deployable and inflatable/rigidizable structures. For a single pass interferometric SAR to measure the Earth topography, a 100m mast is required to form an interferometric baseline (scenario 163). The operating frequency for this application is X-band. For these large structures, a metrology system may be required to measure the antenna surface/structure deformation for the real-time compensation or the compensation during the data processing process.

For the radiator technology, the technology development is required to generate multiple beams. The multiple beams are required for various applications such as multiple frequency operation, wide area imaging, and advanced interferometric operation (scenarios 100, 112, 75,76, 159, 30, and 161A). A multiple feeds system and a shared aperture technology are two primary examples of this technology. For a phased array antenna, an innovative radiator technology is required to lower the mass and stowed volume of a large phase array (scenarios 45 and 46). The membrane technology is a promising candidate.

The system-level development is also an important component of the technology development. This system-level technology is often involved in innovative antenna designs. The objectives of the system-level development are wide-area imaging, resolution improvement, ionospheric/tropospheric compensation, enhanced measurements, and cost reduction. Even though specific technologies cannot be identified for the system-level innovation, ESTO should support the system-level development.

4.1.1.4 Scenario and Parameter Measurement Histograms

In table 4.1.1.4 we provide histograms of the two figures of merit, number of scenarios served and parameter measurements enabled.

Antenna Technology Challenges	**Number of Scenarios**	**Number of Parameters**
Light Weight Antenna Structure	30	14
High Efficiency T/R modules	28	12
Light Weight Phased Array	22	12
Multiple Frequency Antenna/Multiple Feeds	16	10
Phased Array Feed for Reflector-type Antenna	12	9
High Efficiency Reflectarray	5	3
Large Deployable Rotating Reflector	3	3
Adaptive waveform sensing and correction technology	3	3

Table 4.1.1.4 Antenna Technology Challenges and the Number of Measurement Scenarios and Measurement Parameters that Require each Technology.

4.1.1.5 Active Antenna Technology Roadmaps

The individual technology roadmaps appear in Appendix 4A. These technology roadmaps were used to populate the Capability Breakdown Structure (CBS) table for active antenna technology (Appendix 4B), which in addition to including the development plans found in the roadmaps, also includes estimates of cost to raise the TRL of each technology.

The technology integrated roadmap is given in Figure 4.1.2.5 within the active electronics section. The reason for this placement is that this integrated roadmap summarizes the entire area of active instruments including antennas and active electronics, and the later is covered in the following active electronics section.

4.1.2 Active Electronics

4.1.2.1 Overview

The development of technology requirements for the radar electronics followed the same process as for the radar antenna technologies. The first step in the process was to better define the technology requirements and challenges for each relevant scenario. A total of 42 Active Microwave measurement scenarios were reviewed. Appendix 4C summarizes the requirements for each scenario. For scenarios with incomplete requirements, the "scenario owner" was consulted if possible for clarification of the technology challenges. This table includes both

antenna and electronics requirements since these two elements are so closely coupled. For the active electronics, technology drivers considered include frequency and bandwidth of operation, peak transmit power and method (such as using T/R modules or single high power transmitter). Waveform characteristics, noise figure, dynamic range and special data handling requirements were also considered. Unique requirements such as calibration, phase stability or high-radiation were also assessed. The technology requirements were then used to identify scenarios that have enabling technology requirements, enhancing technology requirements and those scenarios where the measurement and technologies are mature or obsolete. We have defined these classifications as:

Enabling Technology: Technologies that need to be developed to enable a new measurement capability.

Enhancing Technology: New technology will be beneficial for incremental performance improvement; however, measurement can be made using existing technologies. OR Measurement is technically feasible now but expensive. Lower cost technologies are needed to fit within cost caps.

Technology Mature: Measurement technique is mature and no new technology is required.

Obsolete Scenario: Measurement scenarios that are now obsolete and are recommended to be deleted.

We then grouped the 42 Active Microwave (Radar) scenarios into different measurement types and technology classifications. The technology requirements and challenges are similar for scenarios for each measurement type. Table 4.1.2.1 summarizes these technology challenge classifications derived from Appendix 4C.

Measurement Type	Criticality	Utility (scenario ID)
Large aperture SAR	Enabling	MEO/GEO L-band InSAR (45, 46) UHF/VHF Deep Soil Moisture (112)
X-, Ku- & Ka-band Single-Pass Interferometers (using phased array antennas)	Enabling	100, 28?, 93, 161A, 163
Millimeter Wave Atmospheric Radars using phased array antennas (Ka-, W-band, G-band)	Enabling	75, 76, 159, 160
Moderate aperture SAR	Enhancing	22, 105, 92, 19, 44a, 44b, C1, 97, 158, 162
Millimeter Wave Atmospheric Radars (Ka-, W-band)	Enhancing	68, 142, 154
MEO Scatterometer	Enhancing	148
Misc (unclear where fits on science roadmap)	Enhancing	O2, 30, 51
Airborne/Suborbital Platforms	Enhancing	161B, 161C, 47, 157
Mature measurement scenarios	Mature technology	102, 151, 155, 29, 61, 90, 156
Obsolete measurement scenarios	Obsolete	103, 104

Table 4.1.2.1 Classification of Measurement Types for Each Relevant Active Microwave Scenario. Mature and obsolete scenarios are included.

4.1.2.2 Observations/Recommendations

1. Both enabling and enhancing technologies should be supported by ESTO. A technology program "portfolio" should attempt to balance investment in both of these types of technologies. Enabling technologies may have the highest potential performance payoff, but also are more risky. These are the lower TRL technologies needed for far-term missions. Enhancing technologies are important as they typically support more near-term requirements and are therefore less risky and may provide significant cost reduction. These technologies often can be adapted to multiple missions.
2. There are some scenarios where it is unclear where they fit within the overall ESE focused area roadmaps. Therefore, it is unclear how they should be prioritized. These have been grouped separately and given an "enhancing technology" classification, since they only

provide an enhanced capability. The unique technology requirements of these scenarios were not evaluated in detail.

3. Airborne and suborbital platforms typically do not require technology development to achieve their measurement goals. However, often these platforms are an important component of a larger technology development effort, for instance, to develop science algorithms for a given measurement scenario or validate a new measurement technique. They also serve as a good platform to test out new technologies. Therefore, we have classified these as "enhancing technologies".
4. Some of the measurement scenarios are considered "mature". We have not considered the technology requirements for these scenarios in detail and we recommend that they be deleted from the database (as the scenarios are currently defined).
5. Two Cold Land Process (snow radar) scenarios (103, 104) are obsolete. The CLP Working Group would like to delete these scenarios. Scenario ID #105 is the radar measurement scenario that the CLP Working Group endorses.

4.1.2.3 Radar Electronics Technology Challenges

The radar measurement scenarios were then mapped into the technology challenges table (Appendix 4D) where for each scenario the key technology challenges were identified. The active electronics element consists of both antenna electronics and radar sensor electronics. Antenna electronics includes T/R modules and devices, antenna signal distribution and interconnect technologies, thermal control hardware and components for wavefront sensing and control to compensate for deformation of large antenna apertures. The radar sensor electronics technologies include signal generation, amplification and reception (such as transmitters and chirp generators). A final category of technologies consists of basic MMIC device research and development, which is specified by frequency (L-, Ku-, Ka-, W-, G-band). In Table 4.1.2.3, technologies that are enabling to a measurement are listed E (for Enabling). Those that are required to reduce mission cost, are labeled CR (for Cost Reducing or enhancing). Table 4.1.2.3 summarizes the types of technology challenges and the utility to different measurement scenarios and measurement parameters.

Technology Description		Key Challenge	Utility # scenarios # parameters		
Antenna Electronics		E CR			
T/R Modules	UHF/P/L-band	High efficiency	2	11	8
	membrane T/R modules	Membrane compatible	2	9	7
	Ku-band	High efficiency	5		4
	Ka-band	High efficiency	5		3
	W-band	power combining and packaging	2		2
	G-band	power combining and packaging	1		1
MMIC Devices	L-band	Single chip T/R	2	9	7
	Ku-band	phase-stable receive components	2		2
	Ka-band	phase-stable receive components	6		4
	W-band	PA, LNA, phase shifter	3		2
	G-band	PA and LNA	1		1
RF, power, control signal distribution	Printed, wireless, optical	Lightweight alternatives to existing technologies	2	16	12
Large-scale Integration of electronics	Manufacturing, integration, interconnects	Lightweight, reliable, low cost	2	9	7
Thermal control	Membrane antennas	thermal management	2	9	7
	Interferometers	tight temperature control	3		3
Adaptive wavefront sensing and control	Large aperture antennas	maintain antenna shape/flatness to 1/20 lambda	3		2
Reconfigurable Radar Electronics (core components)		E CR			
High Power Transmitters	Ku-band TWTA	>500 W		4	4
	Ka-band EIKA	>1KW		4	4
	W-band EIKA	10 KW	1		1
Waveform Generator	DCG or AWG	flexible, high bandwidth, rad-hard, low power	5	26	17
ADC	For digital receivers or DBF	high-speed, high dynamic range, low power, rad-hard	3	17	12

Table 4.1.2.3 Radar Electronics Technology Challenges and the Number of Measurement Scenarios and Measurement Parameters that require each Technology.

4.1.2.4 Classification & Rationale for Radar Challenge Entries

T/R Modules: Classified by frequency, power, radiation hardness, phase stability, packaging, cost (or other unique requirements such as higher level of integration than exists).

High efficiency is key parameter for all T/R modules. Assumes device technologies (MMICs) are available.

MMIC devices: Classified by frequency. Investment in devices (CMOS, GaAs, SiC, GaN, InP, SiGe) is required to achieve higher levels of integration or improved performance than currently exists. Typical components: PAs, LNAs, Phase Shifters, and switches. Typically applies to millimeter wave devices (94 and 140GHz). Also applies to Ku-band and Ka-band phase stable components for interferometers and L-band SAR requiring single chip MMIC T/R modules to reduce cost.

Interconnects: Applies to phased array (ESA) antennas that have bulky signal distribution harnessing. Candidate technologies include printed, wireless or fiber-optic. Also includes integration and low-cost manufacturing to reduce cost and mass of fully integrated active phased arrays. "CR" or enhancing for all phased array antennas, "E" (enabling) for large-aperture arrays or multiple frequency phased arrays requiring lightweight antenna technology such as membrane antennas.

Thermal: Two types of thermal management technologies required. The first is for thermal management of lightweight membrane antennas. This includes methods for local thermal management (e.g., MEMS micro-heat pipes) that are compatible with membranes. The second is for precise thermal control of large phased array antennas for phase stability. These technologies apply to single-pass interferometers using electronically scanned array (ESA) antennas.

Adaptive Wavefront Sensing and Control: Applies to large aperture antennas that require technologies to sense and correct for deformations in reflector or phased-array antennas. Required for large aperture systems to achieve antenna flatness to 1/20 of a wavelength. For membrane antennas with multiple layers, an aperture separation accuracy to 1/10 of separation is also required.

High Power Transmitters: Applies to instruments requiring high power tube amplifiers at Ku, Ka and W-band. Includes TWTs and EIKs with associated high voltage power supplies (HVPS). Since all technologies are improvements to existing space-qualified tubes (Cloudsat and OVWM/WSOA), the technology developments are classified as enhancing. The primary challenges addressed are increasing transmit power of the tube amplifier and increasing the voltage of the HVPS accordingly.

Waveform Generators: Applies to the development of digital chirp generators (DCG) and arbitrary waveform generators (AWG), which are required for nearly all radar applications. Primary technology challenges include high bandwidth, low DC power consumption, low sidelobe (high spurious free dynamic range SFDR), and flexibility. Radiation hardness is particularly critical for MEO and GEO applications. A high level of integration (very low mass) is required for large aperture antennas. Notching and arbitrary waveform capability required for many applications.

ADC: Primary technology drivers include high speed, # bits, radiation hardness. "Enhancing" for most high bandwidth systems. "Enabling" for large aperture systems with distributed digital beamforming architectures. Radiation hardness is particularly critical for MEO and GEO applications. This is a core component of digital receivers and digital beamformers.

4.1.2.5 Active Electronics Technology Roadmaps

Twenty-one unique technologies have been identified as requiring further investment. Appendix 4E provides details in the form of technology roadmaps including the current status of each technology and a description of the specific tasks required to mature the technology. These technology roadmaps were then used to populate the Capability Breakdown Structure (CBS) table for active electronics (Appendix 4F), which in addition to including the development plans found in the roadmaps, also includes estimates of cost to raise the TRL of each technology. These 21 unique technologies were then mapped into five larger classes of instrument technology.

Moderate aperture SAR technologies for near-term L-band SAR missions: Focuses on technologies to reduce instrument mass, cost, power and risk. The goal is to reduce the antenna mass density to <8kg/m2 including aperture, integrated electronics and deployment structure.

Large aperture SAR technologies: Particularly for MEO and Geosynchonous SAR mission. Addresses enabling technologies required for ultra-lightweight, large aperture electronically scanning antennas and focusing particularly on electronics such as T/R modules and other distributed electronics compatible with large lightweight electronically scanning antennas. Also addresses signal distribution and interconnects and large-scale manufacturing for very large arrays. Includes wavefront sensing and control and advanced system architectures such as digital beamforming techniques. The goal is to reduce the antenna mass density to <2kg/m2 including aperture, integrated electronics and deployment structure. These technologies would also benefit SAR missions of moderate aperture size (although not required for feasibility).

Single-Pass Interferometers: Technology developments for X, Ku, Ka-band interferometers include large interferometric masts and metrology. Also required are phase-stable T/R modules (and associated devices) and precision thermal control to achieve phase-stable electronically scanning phase array antennas.

Atmospheric Radar: Focuses on the development of millimeter wave phased-array antennas, their associated electronics, integration with the aperture and addressing multi-frequency capability. Frequencies of highest priority are Ka and W-band. Includes device development particularly at W-band. G-band (140GHz) phased-array radar can be developed after Ka-band and W-band, but will require a very large technology investment since little radar technology exists at this frequency.

Core Radar Sensor Technologies: Addresses the need for low cost, reconfigurable, rad-hard radar core components that can be used for multiple radar missions. Key components include waveform generators, transmitters and receivers. Novel architectures and technologies that reduce mass and power, while increasing flexibility are particularly useful to reduce mission cost and risk.

An integrated radar technology roadmap, which summarizes all technology development plans for both antenna and electronics, is presented in Figure 4.1.2.5I below.

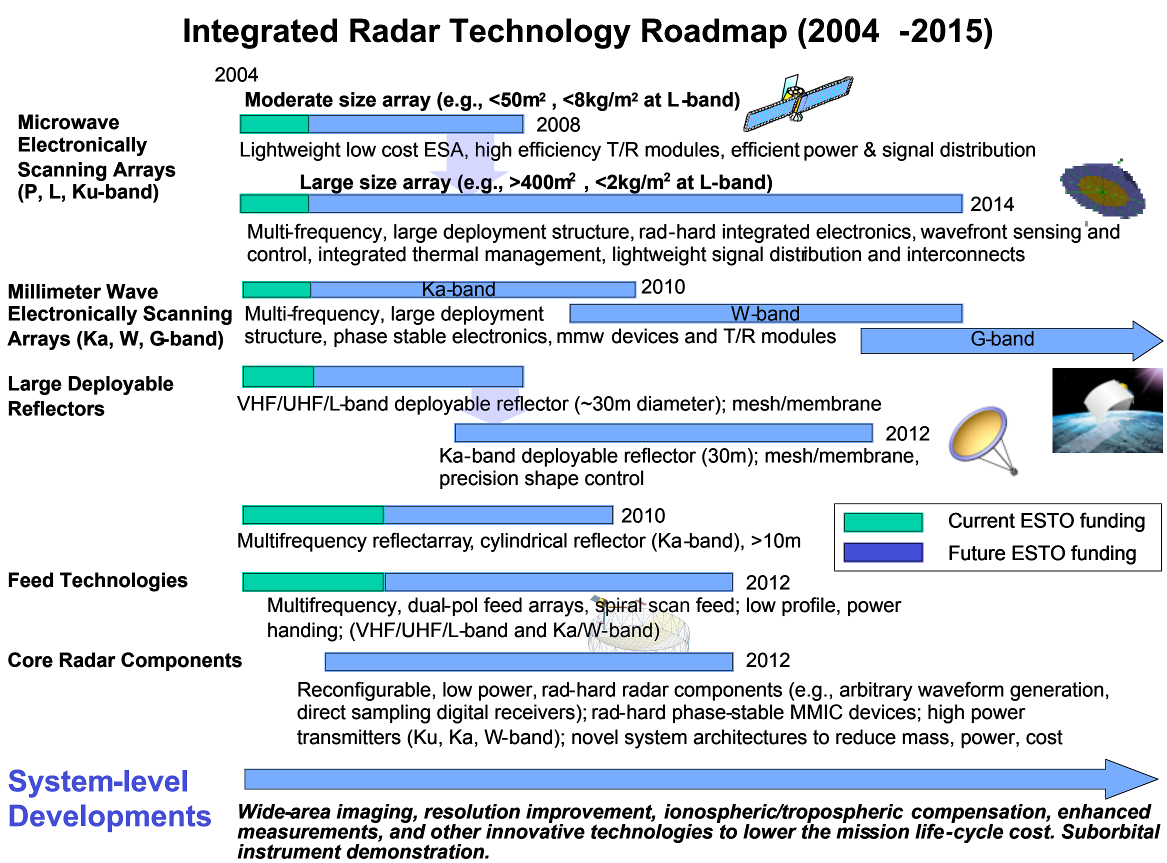


Figure 4.1.2.5I Integrated Radar Technology

4.2 Passive Instrument Technology

4.2.1.1 Process for Identifying Technology Requirements

The technology needs for radiometry followed the path described by Figure 4.1.1.1 under the active instrument technology section. The process followed by the working group considered passive (radiometers) and active (radars) microwave instruments each separately and in combination for determining the measurement scenarios. Accordingly, 19 measurement scenarios involving microwave radiometry as the primary or supporting measurement were defined from the ESE focused area roadmaps and the science requirements documents. From these measurement scenarios, technology development areas were identified in passive antennas, passive RF electronics and an area defined as 'system and precision control'.

Once the technology development areas were identified from the measurement scenarios, each technology development area was defined by more specific tasks designed to outline the development process from TRL 2 to TRL 5 or 6 in support of specific measurement scenarios. Therefore, each technology development area may have several associated tasks defined to mature the technology in support of a variety of measurement scenarios.

These tasks are summarized later in technology roadmaps for passive antennas and electronics as well as histograms relating each technology development to the measurement scenarios and to the science measurement parameters. The histograms can be used to help judge the relative importance of each technology development. An integrated technology roadmap for radiometer antennas and electronics was then completed as a summary of all related technology developments that were identified as supporting passive radiometry.

Measurement Parameters	Focus Science Areas	Measurement Scenarios
Snow Cover, Accumulation and Water	Water & Energy Cycle; Weather, and Climate Variability & Change	106, 107, 108, H2, C2
Freeze/Thaw Transition (Growing Season)	Water & Energy Cycle; Weather, and Climate Variability & Change	H1
Global Soil Moisture	Water & Energy Cycle, Weather, and Climate Variability & Change	34, 38, 111, 177, H2, H3
Global Precipitation	Water & Energy Cycle and Weather	67, 176, A1, A2
Sea Surface Salinity	Climate Variability & Change	34, 38, 111
Sea Surface Temperature	Climate Variability & Change	O1
Atmospheric Temperature	Water & Energy Cycle and Weather	67, 176
Atmospheric Water Vapor	Water & Energy Cycle and Weather	67, 176
Ocean Surface Winds	Weather	A2
Ozone Profile	Atmospheric Composition	140
Cloud System Structure	Atmospheric Composition	143
Wet Path Delay	Solid Earth (Geodesy)	53

Table 4.2.1.1 Relationship between measurement scenarios and measurement parameters in the focus science areas.

4.2.2 Overview of Passive Measurement Requirements

There are a total of 18 scenarios that included space-borne passive instruments (wet path delay is a ground-based VLBI-related scenario). A Synthetic Thinned Array Radiometer (STAR) instrument is required in 10 of the scenarios, a real aperture is required in 8 of these scenarios and 2 scenarios did not fully-specify. This suggests that investment in technologies that support STAR instruments should be a significant portion of the overall investment applied to support passive measurements. Real aperture systems also remain beneficial in support of NASA Earth science goals.

There are a total of 12 measurement parameters in the passive electronics area. Three parameters (soil moisture, sea surface salinity, and snow water equivalent/snow cover) are feasible using either the STAR or real aperture approaches. Three parameters (soil freeze/thaw state, precipitation, and ocean winds) appear to be better measured with the STAR approach, and six parameters (atmospheric temperature and water vapor sounding, atmospheric ozone-related parameters, cloud parameters, sea surface temperature, and VLBI wet path delay) appear to be better measured by the real aperture approach. In sum, 3-6 parameters are most compatible with STAR, and 6-9 parameters are most compatible with real apertures.

4.2.2.1 Instrument Characteristics

<u>4.2.2.1.1 Spatial Resolution</u>

For each measurement parameter within a focused science area, there can be many supporting measurement scenarios (particularly for soil moisture and for sea surface salinity). However, there are several key aspects of these measurements that can generally summarize the passive instrument needs. For passive antennas the following is suggested as a list of key desired capabilities, 1) 10 km spatial resolution at L-band from LEO in support of Soil Moisture (SM) and Sea Surface Salinity (SSS), 2) 5 km resolution at K- and Ka-band (18.6 and 37 GHz) in support of Snow Cover, Snow Water Equivalent and Cold Lands Hydrology, 3) 50 & 183 GHz measurements from GEO (3-4m class aperture), 4) 10 km spatial resolution at C-band for Sea Surface Temperature (SST), and 5) Submillimeter wave scanning and non-scanning antennas for atmospheric composition and cloud studies respectively.

<u>4.2.2.1.2 Polarization</u>

Eleven scenarios require one or two polarizations (V or H), eight scenarios also require them third and possibly the fourth Stokes' parameter and two scenarios require four all four Stokes' parameters.

One to two polarizations apply when no ionospheric propagation considerations or 2D-STAR polarization separation considerations apply. At least three Stokes' parameters are necessary when a scenario calls for either (a) real-aperture or 1D-STAR and ionospheric correction is required or (b) 2D-STAR and polarization separation might be needed. Four Stokes' parameters are required in the case of 2D-STAR when polarization separation is definitely needed. Some scenarios involve combinations of low frequencies (with ionospheric considerations) and higher frequencies (no ionospheric correction needed), resulting in certain measurement scenarios appearing in more than one category.

For the science measurement parameters, 11 measurement parameters require one to two polarizations, six require at least three Stokes' parameters, and two require all four Stokes' parameters.

These polarization requirements of the radiometry scenarios and measurement parameters show the increasing importance of three and four Stokes' parameter measurements, and an implied need to better-understand resource trades regarding the use of two, three, or four Stokes' parameters to best fulfill a selected measurement scenario or measurement parameter.

4.2.2.1.3 Frequency Bands

There are two important aspects of considering technology improvements for EOS as applicable to selected frequency bands, first there is a clear message from the measurement scenarios that larger antennas will enable several new measurements that require L-band brightness temperatures at the resolution currently available only at Ka-band and higher, however, a second important consideration is the performance enhancement that may be derived from technology investment (in both spatial resolution and sensitivity) within the bands currently used to provide critical scientific data. Both measurement enabling and enhancement should be considered.

Table 4.2.2-1 below is a tabulation of the frequencies and capabilities contained in the measurement scenarios considered for passive remote sensing. The measurement scenarios defined the complete set of enabling measurements considered by the study, however, the enhancing measurements obtained from the measurement scenarios, although included in the Table, are not complete when the broader picture of enhancements to all current capabilities is considered.

Frequency Band	L	C	X	Ku	K	Ka	50 GHz (V)	W	100-300 GHz	300-1000 GHz	>1 THz
Scenarios	10	5	5	6	1	7	2	3	4	2	2
Parameters	4	4	5	2	1	3	3	1	5	2	4

Table 4.2.2-1. Number of Scenarios vs. Frequency Band

Note that several scenarios depend on L- and C-band. These areas of the electromagnetic spectrum are heavily utilized by other radio services, although an exclusive allocation exists at L-band, out-of-band and spurious emissions are expected to impact measurements at L-band, thus RFI mitigation schemes appear to be highly beneficial for ensuring that high quality radiometric measurements can be obtained to support the related science objectives. For C-band there is no allocation supporting passive measurements in the vicinity of 6-GHz.

In-band emitters over land have been a serious problem with recently launched C-band radiometers. However, instances of contaminated brightness temperatures over the ocean are not expected to significantly diminish the scientific value of the radiometric measurements, although RFI mitigation schemes may also be valuable to ensure data quality.

Overall the 1 to100-GHz frequency range covers most of the interest and is the range over which the majority of microwave-water cycle interactions occur (soil moisture, salinity, snow, freeze/thaw, sea ice, precipitation). Frequencies above 100 GHz generally have specific applications, primarily atmospheric composition and clouds representing a more specialized subset of the measurement scenarios.

4.2.2.1.4 Instrument Platforms/Orbits

In Table 4.2.2-2, scenarios are broken down in terms of the required platform type.

Platform	**LEO**	**MEO**	**GEO**	**UAV**	**Ground**
Scenarios	**16**	**0**	**2**	**2**	**1**
Parameters	**9**	**0**	**3**	**2**	**1**

Table 4.2.2-2. Distribution of Scenarios with Respect to Platform

Note that two scenarios (A1 and A2) list both UAV and spaceborne LEO orbits as platform options. Furthermore, some precipitation scenarios call for LEO while others call for GEO. LEO applies to the greatest number of measurement scenarios combining improved resolution from larger apertures with the lower range of operating frequencies. This represents a desire for finer spatial resolutions attainable with larger apertures in lower orbits while subject to limitations on overall package size. The breakdown with respect to measurement parameters reflects identical priorities.

4.2.2.1.5 Combined Active and Passive Instruments

In Table 4.2.2-3, a breakdown is given relative to the potential for a combined active and passive instrument.

Potential	Yes	Possibly	No (Passive Only)
Scenarios	5	4	10
Parameters	3	2	7

Table 4.2.2-3. Potential for Combined Active and Passive Instrument

Combined active/passive retrievals appear to be gaining consideration. For example, several measurement scenarios supporting SSS and soil moisture specify active and passive coincident measurements as do the NASA Earth System Science Pathfinder (ESSP) missions Hydros and Aquarius. In the technology Challenge Breakdown Structures (CBSs in

Appendices G and H), the "technology development" for combined active passive apertures and electronics appear in the form of system-level trade studies and design. Due to the relatively preliminary nature of these trades (low TRL) coupled with a variety of instrument concepts, it would seem that a large return on investment might be achieved through such trade studies.

4.2.3 Radiometer Antenna Technologies

The antenna technology development areas identified were arranged in three general areas: 1) components, 2) subsystem (e.g. feed arrays and structural elements) and 3) systems. In order to define specific technology development tasks, several antenna concepts were considered: a two-dimensional Synthetic Thinned Array Radiometer (STAR) antenna based on lightweight membrane technology, a scaleable 2D STAR, a 1D STAR, a mechanically-scanned large real aperture, a torus with scanning sub-arrays and finally a millimeter wave scanning antenna.

4.2.3.1 Radiometer Antenna Technologies Histogram

Within the technology challenges identified for passive measurements were several challenges related to system or precision control capability. These were included in the passive antenna section.

Antenna Technology Challenge	Scenario Count	Parameter Count
Antenna Component Items		
Multi-frequency feeds with high beam efficiency	14	10
Combined active passive feeds	11	6
Low Cross polarization antenna elements	6	4
Antenna Arrays		
Waveguide arrays	6	4
Microstrip Patch arrays	11	
Multi frequency multi-polarization arrays	16	11
Feed clusters/focal plane arrays	13	9
Structural elements		
Lightweight structural elements	12	10

(continued)

Antenna Technology Challenge	Scenario Count	Parameter Count
System Level Designs		
Precision deployable/inflatable structures (other than reflectors)	8	6
Deployables large aperture	9	7
Millimeter wave/Submillimeter Wave antennas	4	5
Precision Control and System Challenges		
Precision Control		
Precision Antenna Pointing (momentum compensation)	3	4
Antenna Metrology	8	7
Precision Thermal Control	6	4
Control of Spinning aperture (balancing)	4	4
System		
Cryo-Cooler	1	1

Table 4.2.3-1. Technology Challenge Histogram for Radiometer Antennas

The technology challenge items for passive antennas have been grouped according to component vs. systems level challenges. Development of special antenna feedhorns or elements to support the desired large aperture of high frequency antennas are grouped first followed by antenna arrays. Structural elements are considered to be one of the building blocks for larger structures such as the support for a large real aperture or STAR elements. And finally, the system level challenges are split into three categories, 1) precision deployable/inflatable structures (other than reflectors) which generally support STAR concepts, deployables/large aperture (6 – 20 m) which generally refer to large filled apertures and 3) millimeter wave and sub-millimeter wave antennas.

Development of the technology challenge breakdown sheets (CBS, Appendices G and H) required at least one and sometimes several technology developments

4.2.3.2 Technology Challenge Breakdown

For passive antennas the full technology challenge breakdown sheet (CBS) table and technology challenge summary are given in Appendices 4G and 4G.1 respectively. Similarly for passive electronics the full CBS table and technology challenge summary are given in Appendices 4H and 4H.1 respectively. Development of the technology CBSs required at least one and sometimes several technology developments to be defined for each of the challenges listed in Table 4.2.3-1, in order to address the technology needs of all measurement scenarios (see Table 4.2.2-1) applicable to radiometry. In this process, technology challenges were considered to support the necessary "building blocks" for six antenna designs: 1) a large spinning aperture, 2) a 2-D STAR concept involving tensioned panels and membrane technology, 3) a 2-D STAR concept with scalable elements, 4) 1-D STAR concept, 5) torus antenna with mechanically scanned or electrically scanned feed array, and 6) millimeter/submillimeter wave scanning antennas.

System and precision control technology required for some of the measurement scenarios was also considered in the technology challenge CBS. In many cases precision pointing and antenna metrology needed consideration.

During development CBS for passive antennas, many of the technology developments identified for items within the antenna components and array developments (see Table 4.2.3-1) were included in technology developments directly within the specific antenna developments (system level). This is addressed within the integrated passive antenna technology summary sheet by rolling all of the antenna array developments into a single line describing the feed array that would generally be incorporated into a larger antenna system. For the technology roadmaps, general technology development that applies to many antenna concepts such as lightweight array feeds and lightweight structural elements are developed separately. However, these items may reappear within specific antenna developments with the understanding that some additional technology development is needed to incorporate this "building block" into the overall antenna concept/design. Typically these particular system issues begin to be addressed at the IIP level (TRL 4 - 6), which is the extent of consideration for technology developments in this exercise.

4.2.3.3 Passive Antenna Summary

In summary, antenna performance to support the passive measurement scenarios requires the following: 1) 10 km resolution at L-band from LEO, 2) ~5km spatial resolution at K- and Ka-band from LEO, 3) 3-4 meter class aperture at GEO at 50 and 183 GHz, 4) improved mmw/smmw antenna capability such as larger apertures and capability to accuracy scan and 5) 6 to 7 meter class scanning aperture at C- and X-band. These capabilities include various polarization characteristics and in many cases it is unclear if the best approach is by STAR or real aperture. System trades will be required to determine the optimal approach.

4.2.4 Passive Receiver Technology Challenge Histogram

A histogram of the 19 scenarios and 12 parameters is presented in Table 4.2.4-1 below.

Technology	Scenario Count	Parameter Count
High Frequency items		
High Frequency LNAs >160 GHz	**4**	**5**
High Frequency >= 50 GHz Sources (LO)	**7**	**6**
MMW/sMMW detectors	**7**	**6**
High Frequency Down-conversion Techniques >900 GH	**2**	**2**
Miniature radiometer items		
MMIC/ Miniature Radiometers& Low Mass/Power Receiver Elements	**16**	**7**
MEMS RF switches	**14**	**7**
MEMS filters	**14**	**7**
Systems-level design items		
Analog RFI Mitigation Technology	**15**	**8**
Calibration subsystem for correlation radiometers	**13**	**6**
On-board RF signal distribution	**13**	**9**
3 or 4 Stokes-polarimetric receiver design	**10**	**8**
Ultra-stable Low Loss Radiometers	**13**	**6**
Combined active/passive system design	**11**	**5**

Table 4.2.4-1. Technology Challenge Histogram

The entries in Table 4.2.4-1 may be grouped with regard to the following priorities according to decreasing numbers of science scenarios addressed:

Highest return:

Calibration Subsystem, MMIC/ Miniature+ Low Mass/Power Radiometers, analog RFI Mitigation Technology.

Next highest return:

MEMS filters and RF switches, Calibration subsystem for correlation radiometers, on-board RF signal distribution, combined active/passive system design, 3&4-Stokes polarimetric receiver design, ultrastable low loss radiometers.

Medium/Lower return:
High frequency LNAs > 160 GHz, LO sources >50 GHz, down-conversion techniques >900 GHz, and mmW/smmW detectors.

With respect to measurement parameters, the "Medium/Lower return" grouping does not change. The assignment of specific technology areas to "Highest return" or "Next highest return" changes slightly, but no items would move into the "Medium/Lower return" category.

4.2.5 Summary of Patterns & Linkages

The following is a description of selected special considerations for passive radiometer design arranged by 1) Antenna type, 2) Radiometer design, 3) Frequency range, and 4) geophysical measurements (e.g. Sea Surface Salinity, Atmospheric Sounding).

4.2.5.1 Antennas

STAR
Requires low mass/power receivers, MEMS, MMIC/mini receivers, correlation radiometer calibration subsystem, high rate downlink, ultra stable low loss radiometers (for good interchannel calibration), and precision thermal control. If a 2D-STAR is required by a measurement scenario and dual linear polarization is needed (e.g., "H and V"), then a quad-polarimetric (Four Stokes parameter) requirement is assumed in order to correctly determine polarizations within an imaging FOV.

Real Aperture
Requires control of large rotating structures; understanding and control of surface deformations.

4.2.5.2 Radiometer Design

Combined active/passive measurements
Requires active/passive antennas & feeds, active/passive system design

Three or four Stokes parameters
Requires low cross-polarization antennas, 3-4 Stokes parameter polarimetric receiver design, correlated radiometer calibration subsystem, precision attitude knowledge/cross-track (for ocean winds)

Analog RFI mitigation
Appears to be necessary or desirable for all scenarios except sounders.

4.2.5.3 Frequency Bands

L-band

Requires analog RFI mitigation, waveguide array antennas, microstrip patch array, lightweight structural elements, MEMS, MMIC/mini receivers, antenna aperture control, antenna metrology, control of large rotating structures, precision thermal control, 3-4 Stokes polarimetric receiver design (for correction of Faraday rotation)

C-band and lower frequencies

Requires deployable/large apertures (6-20m), analog RFI mitigation, MEMS.

>100 GHz

Requires mmW/smmW antennas, high-freq LNAs (>160 GHz), high-freq down-conversion techniques (>900 GHz), high-freq LO sources (>50 GHz), mmW/smmW detectors

4.2.5.4 Measurements

Sounders

Requires high-bandwidth digital spectrometry, MEMS, MMIC/mini receivers, ultra stable low loss radiometers (for good inter-channel calibration), precision thermal control, could be either real aperture or STAR.

Salinity

Requires ultra stable low loss radiometers (for retrieval algorithm), precision thermal control, co-observing with radar to provide roughness correction that appears to be necessary. It appears that tri-polarimetric (3-Stokes parameters) measurements are necessary in order to perform ionosphere correction. Full-polarimetric measurements (Four Stokes parameters) is assumed necessary for 2D-STAR implementation.

4.2..5.5 Summary

The measurement scenarios and parameters considered within the working group clearly indicate the value of technology development with the goal of obtaining L-band measurements at 10 km spatial resolution. This capability enables many measurements and parameters within the scenarios considered. Technology development for improving capability at X, K- and Ka-band through better resolution and sensitivity also enables new measurement parameters and may also provide benefits to current measurements that are not cataloged in the scenarios considered. The next area of technology development appears to be in enabling 50 & 183 GHz measurements from GEO (3-4m class aperture), obtaining 10 km spatial resolution at C-band for Sea Surface Temperature (SST), and finally, sub-millimeter wave scanning and non-scanning antennas and for atmospheric composition and cloud studies respectively coupled with advancements in receiver performance at frequencies above 100 GHz.

4.2.6 Radiometer Technology Roadmaps

The individual technology roadmaps for radiometer electronics appear in Appendix 4I and the individual technology roadmaps for passive antennas appear in Appendix 4J. The radiometer electronics and passive antenna integrated technology roadmaps are given in Figures 4.2.6.1 and 4.2.6.2 below.

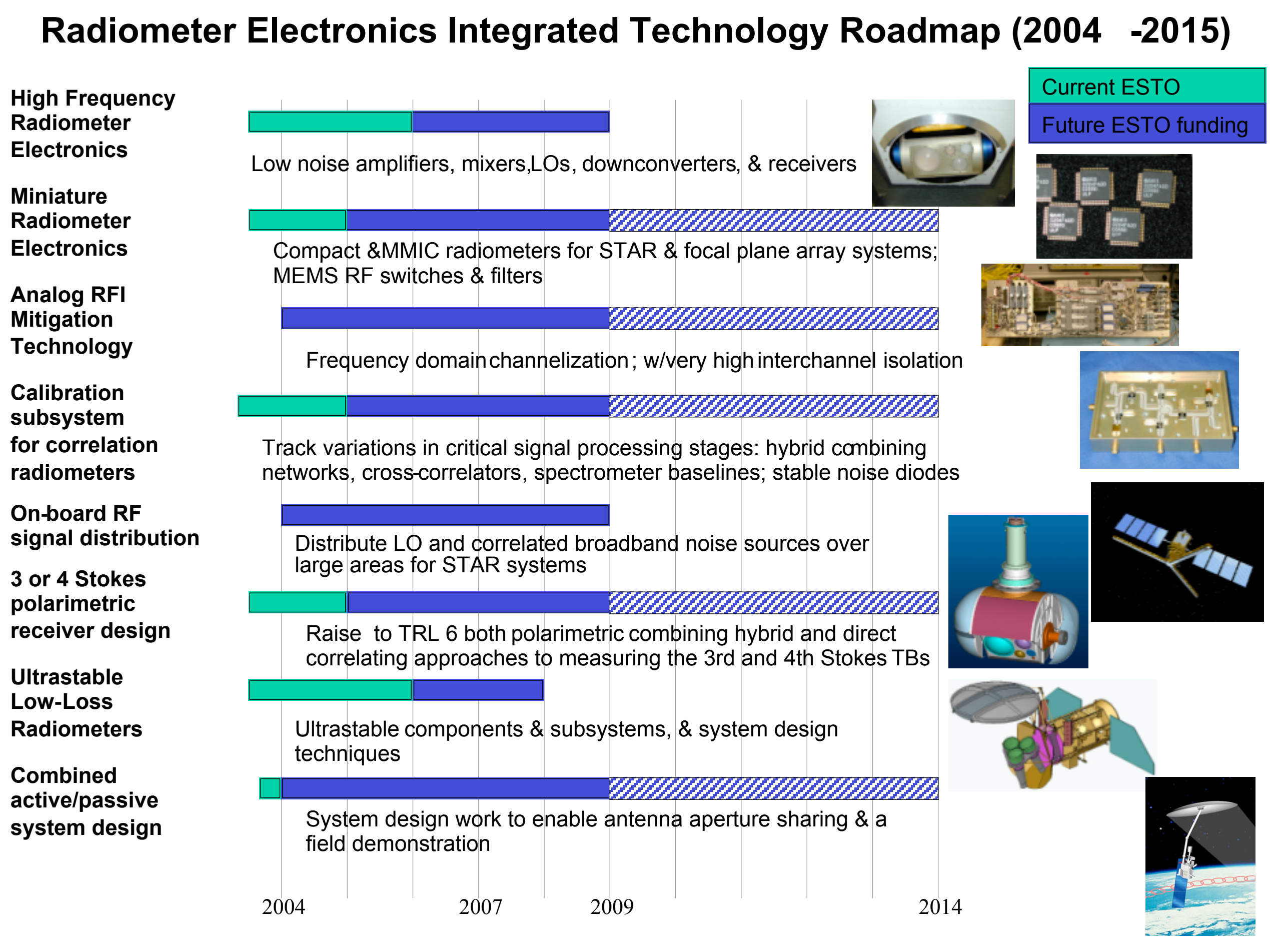


Figure 4.2.2.6.1

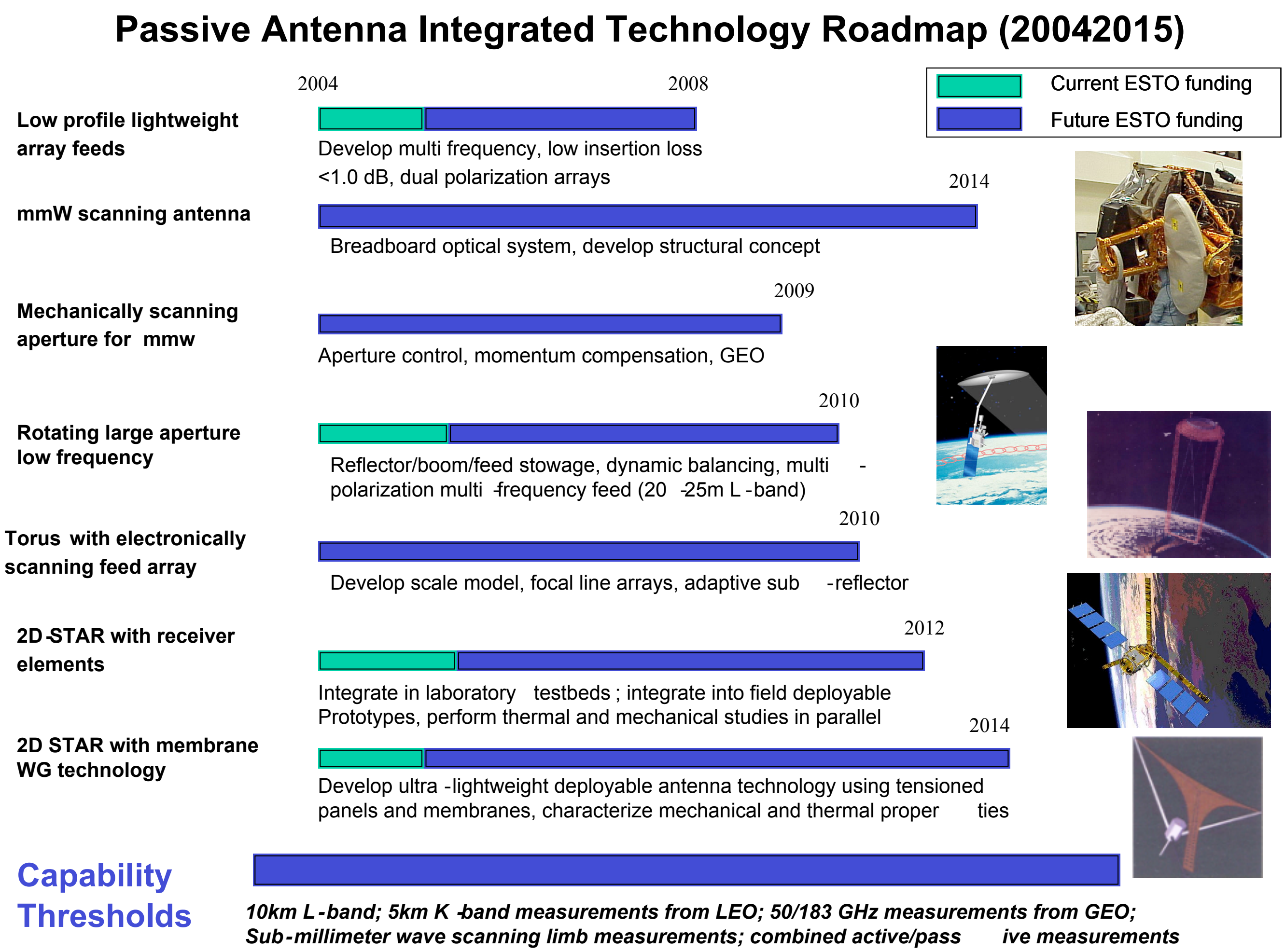

Passive Antenna Integrated Technology Roadmap (20042015)
2004
2008
Current ESTO funding
Future ESTO funding
Low profile lightweight array feeds
Develop multi frequency, low insertion loss <1.0 dB, dual polarization arrays
2014
mmW scanning antenna
Breadboard optical system, develop structural concept
2009
Mechanically scanning aperture for mmw
Aperture control, momentum compensation, GEO
2010
Rotating large aperture low frequency
Reflector/boom/feed stowage, dynamic balancing, multi-polarization multi-frequency feed (20-25m L-band)
2010
Torus with electronically scanning feed array
Develop scale model, focal line arrays, adaptive sub-reflector
2012
2D-STAR with receiver elements
Integrate in laboratory testbeds; integrate into field deployable Prototypes, perform thermal and mechanical studies in parallel
2014
2D STAR with membrane WG technology
Develop ultra-lightweight deployable antenna technology using tensioned panels and membranes, characterize mechanical and thermal properties
Capability Thresholds
10km L-band; 5km K-band measurements from LEO; 50/183 GHz measurements from GEO; Sub-millimeter wave scanning limb measurements; combined active/passive measurements

Figure 4.2.6.2

4.3 Processing Technology

4.3.1 Overview

Processing of various kinds is generally required to enable a given mission. A key issue however is where the processing will take place. In earlier times intensive processing (e.g. SAR processing) had to occur on the ground after transmission over a data link. If this approach were taken investment may be necessary in additional ground receiving and processing stations or in space borne data links, e.g. to a geostationary asset for reception, storage and subsequent transmission to a ground station(s). However as technology has progressed the option of onboard processing has become an increasingly feasible and favored approach. In some cases this approach necessitates large amounts of onboard storage.

On-board processing technologies identified here can be considered enabling technology. Presently, missions are designed to utilize affordable storage and downlink capabilities. Developing the on-board processing technologies identified here will enable a new class of measurements generated from orders of magnitude more data to be collected and reduced, increasing science measurement update rates.

4.3.2 The Technology Challenge

In the area of processing a number of technological challenges are enumerated. These challenges lie in the areas of: 1) Large, onboard, radiation hardened, storage with high clock-rate low power access for various missions, 2) Processing algorithms needed for a variety of missions, 3) A high performance radiation hardened processor, 4) A real time on board processor, 5) Digital radio frequency interference (RFI) mitigation, 6) High speed, high resolution digital spectrometers for sounding, and 7) Various technology development items needed to enable STAR instruments. The specific STAR technology development areas include 1) One-, two- and three- bit low power high bandwidth radiation tolerant A/D converters, 2) High-bandwidth data links (Interior to instrument and with possible application to other types of radiometers), 3) On-board high-rate digital signal distribution, 4) Massively parallel low power, high bandwidth, 1-bit cross correlates.

It should be noted that, while algorithms for science are funded through science programs, there is presently essentially no NASA investment in processing algorithms for radar and radiometry. Unlike other instruments that have fairly straightforward engineering processing but sophisticated science algorithms, radar and radiometry rely on both sophisticated data processing and calibration schemes to yield a fundamental measurement. Algorithms to enable specific measurements go hand in hand with the developing technologies, and investment in these algorithms is as essential as hardware technologies.

The summary processing technical challenge table (Table 4.3.1) below provides a summary of the technical challenges in the area of processing. It is comprised of five columns, the first of which is the processing challenge itself. The second column, labeled "Measurement Scenario", provides the ID number of the scenarios addressed by the technology. Subsequent columns describe the instrument type the technology supports, the waveband of operation, and the functional product needed. The processing summary technical table represents a subset of the material incorporated in the full CBS processing table. The full CBS table is comprised of 15 columns and includes both scenario ID numbers and short verbal scenario descriptions. Because of the unwieldy detailed nature of the full CBS table the technology challenge summary table provides a valuable segue to the full CBS table (Appendix 4K).

Technology	Measurement Scenario	Instrument Type	Waveband	Needed Functional Product
Large onboard data storage	F, A, 92, 93, 90, B, 97, 102, 44a, 44b, 45, 19, 158, 162, 22, 102, 103, 104, 105, 28 (also refered to as 26), 29, 27	SAR,interferometric radar, radar altimeter,scatterometer,etc.	Any Waveband	Numerous memory modules, each with several memory chips with necessary EDAC functions
Processing Algorithms	160	GEO Rain Radar	94 GHz band	Unambiguous rain radar data from GEO
	44b, 97	LEO Land and Ice Surface Topography	1.25-10 GHz	Real-time algorithms for accurate topography from two spacecraft or a dual aperture system
	45, 148	MEO Surface Deformation	1.25 GHz	Imagery from high MEO orbits
	51	Real-time GPS	1.25 GHz	Real-time algorithms for position and velocity
	112, 161A	UHF/VHF polarimetric SAR	100 MHz - 700 MHz	Polarimetric UHF/VHF imagery from space
High-Performance RHP	1) 68, 67 2) 142 3) 75, 76, 102, 154, 160, 67 4) A, B, 22, 26, 27, 44a, 44b, 45, 47, 90, 93, 148	Atmospheric sounder, atmospheric profiler, SAR, scatterometer, radar altimeter	Ku, X, S, C, L, P	**ATMOSPHERIC PARAMETERS:** water vapor, ozone, temperature, pressure profiles. **CLOUD PARAMETERS:** cloud structure, particle density and distribution. **PRECIPITATION PARAMETERS:** snow and water content, rain rate, snow and rain drop size distribution, rainfall velocity, vertical wind and horizontal shear. **LAND and OCEAN PARAMETERS:** ocean current, ice surface topography, sea ice thickness, extent, motion, deformation, snow cover over sea ice, ocean surface topography, ocean wind
High Performance A/D Digital Receivers	A, 92, 93, B, 97, 161, 160, 151, 44a, 44b, 45, 47, 163, 19, 157, 158, 162, 22, 104, 105, 112	SAR, repeat pass InSAR	L-, C-, X-, and P-band	All scenarios require digitized signal ADC output (offset/IF video signal or direct sub-harmonically sampled RF signal). In some scenarios, FFT spectral output is needed for channel equalization, sub-band channelization, digital beamforming, and/or digital RFI suppression.
Real-time On Board Processing	68, 142, 75, 76, 154, 160, 155, 156, 159, A, 93, 90, B, 97, 160, 102, 161, 44b, 45, 163, 19,162, 51, 22, 100, 102, 103, 104, 105, 112, 28, 29, 61, 148	SAR, InSAR	L, Ka	Single Look Complex Image, Multi-Look Image, Range Compressed Data
1-bit analog to digital conversion for radiometric measurements of the atmosphere, oceans, cryosphere and hydrology	C,D, F, G,H,I, 34, 32, 107, 108	STAR sounder/imager	400 MHz - 183 GHz	Radiation tolerant, high speed, low power, 1-bit, A/D converter

2-bit analog to digital conversion for radiometric measurements of the atmosphere, oceans, cryosphere and hydrology	C,D, F, G,H,I, 34, 32, 107, 108	STAR sounder/imager	400 MHz - 183 GHz	Radiation tolerant, high speed, low power, 2-bit, A/D converter
3-bit analog to digital conversion for radiometric measurements of the atmosphere, oceans, cryosphere and hydrology	C,D, F, G,H,I, 34, 32, 107, 108	STAR sounder/imager	400 MHz - 183 GHz	Radiation tolerant, high speed, low power, 3-bit, A/D converter
High-bandwidth Data Links (Interior to Instrument)	67, C, D, 38, 111, F, G, H, I, 34, 32, 107, 108, 177	Radiometers, generally STAR sounder/imagers		High-bandwidth data links
Digital RFI Mitigation	E, I, 32, 34, 111	Microwave radiometer	6 GHz and-L band	RFI mitigation algorithms
On-board high-rate digital signal distribution	34, 38, 67, 111	STAR sounder/imager	1.4, 50-60, 173-193 GHz,	Low power, ultra-wideband digital data interconnect bus
High speed, high resolution Digital Spectrometers for Sounding	140, 143, 67	Radiometer, Sounder, Microwave Sounder, Spectrometer, Microwave/RF Spectrometer, Microwave/ RF Radiometer, STAR Imager.	50 GHz to far IR {(140) 180 GHz and 2.5 THz, (67, 143) Bands near 50 GHz and 183 GHz}	Development of digital spectrometers (autocorrelators or polyphase with 4 - 8 GHz bandwidth, low power (a few Watts per spectrometer), and radiation hardening for long duration,LEO to MEO.
massively parallel 1-bit cross correlators for radiometric measurements of the atmosphere, oceans, cryosphere and hydrology	C, D, F, G, H, I, 34, 32, 107, 108	STAR sounder/imager	As low as 400 MHz and 1.4, 6.7, 10.7, 19.3, 36.5, 50-60, 173-193 GHz	Estimation of partial correlation between many pairs of broadband noise signals by digital cross-correlation (multiply & accumulate) of low bit resolution digitized samples of signals

Table 4.3.1 Summary of Processing Technical Challenges

4.3.3 Capability Requirements

In the area of processing a variety of capability requirements exist. These challenges come in the form of calls for: 1) Greater than one terabit onboard storage with high clock-rate and low power access capable of operation in harsh radiation environments, 2) Algorithms to a) compute real-time position and velocity with a 5 cm accuracy in all dimensions, with a goal of 1 cm, b) generate surface topography real time attaining DTED level 3 on a global scale, c) generate polarimetric UHF/VHF SAR imagery from space with 100 m resolution and 1 db radiometric accuracy, d) process SAR imagery taken at MEO attaining 20 m resolution and 1 m location accuracy, and e) generate unambiguous rain profiles from GEO with suppression of surface ambiguities to -60 dB, 3) Attainment of high performance processing in a harsh radiation environment to allow generation of atmospheric, cloud, precipitation, land, and ocean parameters, 4) Development of a prototype multi-channel digital receiver/beam-former system for use in large aperture SAR instruments, 5), The on-board generation of single look complex image, multi-look images, and range compressed data at a throughput of 20 - 30 GOPS with random access memory of 3 Gbytes and a memory bandwidth of 3 Gbps, 6) Enablement of scenarios involving measurement of precipitation, wind, snow, freeze/thaw, soil moisture, and sea surface salinity by means of a STAR instrument, 7) The digital mitigation of RFI, 8) The generation of digital spectrometers to measure atmospheric properties, ozone and precursors, cloud system structure and particles, atmospheric temperature and water vapor, as well as global precipitation.

The processing summary capability requirement table (Table 4.3.3) below provides a summary of the capability requirements in the area of processing. It is comprised of four columns, the first of which is the capability requirement itself. The second column labeled "Quantitative Requirement" describes the specific levels of performance required by the technology to achieve the required measurement. Subsequent columns describe the waveband of operation and the scenarios supported. The capability requirements technical table represents a subset of the material in the full CBS processing table. The full CBS table is comprised of 15 columns and includes both scenario ID numbers and short verbal scenario descriptions. Because of the unwieldy detailed nature of the full CBS table the summary capability requirement table provides a valuable segue to the full CBS table Appendix 4K).

Capability Requirement	Quantitative Requirement	Waveband	Measurement Scenario
Large data storage consisting of numerous memory modules. Each module consists of several memory chips with necessary EDAC functions.	Radiation tolerance > 300 kRad (LEO, 5 years), 1MRad MEO, Memory clock > 100 MHz, Data volumen > 1 Tbit, Power during access < 100 W	Any Waveband	F, A, 92, 93, 90, B, 97, 102, 44a, 44b, 45, 19, 158, 162, 22, 102, 103, 104, 105, 28 26, 29, 27
Algorithm for unambiguous rain radar data from GEO	Suppression of surface ambiguities to -60 dB	94 GHz band	160
Real-time algorithms for producing accurate topography from either two spacecraft flying tandem or a dual aperture system	DTED-3 global	1.25-10 GHz	44b, 97
Algorithms for imagery from data taken at high MEO orbits	20 m resolution, 1 m location accuracy	1.25 GHz	45, 148
Real-time algorithms for position and velocity determination	5 cm real-time in all dimensions, with a goal of 1 cm accuracy	1.25 GHz	51
Algorithms for radiometrically accurate polarimetric UHF/VHF imagery from space	100 m resolution, 1 db radiometric accuracy	100 MHz - 700 MHz	112, 161A
High-Performance RHP to produce: 1)ATMOSPHERIC PARAMETERS: water vapor, ozone, temperature, pressure profiles. 2)CLOUD PARAMETERS: cloud structure and particles' density and distribution. 3)PRECIPITATION PARAMETERS: snow and water content, rain rate, snow and rain drop size distribution, rainfall velocity, vertical wind and horizontal shear. 4)LAND and OCEAN PARAMETERS: ocean current, ice surface topography, sea ice's thickness, extent, motion, deformation, snow cover over sea ice, ocean surface topography, ocean wind	High-Performance RHP should constantly process data during the minimum mission lifetime, usually of three years, with graceful degradation thereafter. High-Performance RHP should 1) be flexible in terms of programmability and reconfigurability to allow for possible algorithm modifications to be uploaded after launch, and scalability (2X) to permit change in system parameters; 2) use the latest available advanced technology to ensure low mass, size, and power requirements; 3) have a bypass mode and large enough data storage to store raw data for at least one orbit and to download them when requested.	Ku, X, S, C, L, P	1) 68, 67 2) 142 3) 75, 76, 102, 154, 160, 67 4) A, B, 22, 26, 27, 44a, 44b, 45, 47, 90, 93, 148
All scenarios require digitized signal ADC output (offset/IF video signal or direct sub-harmonically sampled RF signal). In some scenarios, FFT spectral output is needed for channel equalization, sub-band channelization, digital beamforming, and/or digital RFI suppression.	Development of prototype multi-channel digital receiver/beamformer electronic system for use in large aperture SAR instruments.	L-, C-, X-, and P-band	A, 92, 93, B, 97, 161, 160, 151, 44a, 44b, 45, 47, 163, 19, 157, 158, 162, 22, 104, 105, 112
Single Look Complex Image, Multi-Look Image, Range Compressed Data	Throughput: 20 - 30 GOPS, Random Access Memory: 1-3 Gbytes, Memory Bandwidth: 3 Gbps	L, Ka	68, 142, 75, 76, 154, 160, 155, 156, 159, A, 93, 90, B, 97, 160, 102, 161, 44b, 45, 163, 19,162, 51, 22, 100, 102, 103, 104, 105, 112, 28, 29, 61, 148
STAR enabled by high speed, low power, 1-bit, A/D converters	2 GHz, 5mW, 20GHz bandwidth, 1 mV/quantum	400 MHz - 183 GHz	C, D, F, G, H, I, 34, 32, 107, 1

STAR enabled by high speed, low power, 2-bit, A/D converters	2 GHz, 5mW, 20GHz bandwidth, 1 mV/quantum	400 MHz - 183 GHz	C,D, F, G,H,I, 34, 32, 107, 108
STAR enabled by high speed, low power, 3-bit, A/D converters	1 GHz, 10mW, 20GHz bandwidth, 1 mV/quantum	400 MHz - 183 GHz	C,D, F, G,H,I, 34, 32, 107, 108
High-bandwidth data links (interior to instrument)	Over copper: >1 Gb/s data link, <20 mW DC power, >3-meter haul.		67, C, D, 38, 111, F, G, H, I, 34, 32, 34, 107, 108, 177
RFI mitigation algorithms	0.05 K for ocean temperature 0.3 K for land (soil moisture)	6 GHz and-L band	E, I, 32, 34, 111
On-board high-rate digital signal distribution	~30 Gbps channel capacity; ~20 W per channel by means of low power, ultra-wideband digital data interconnect bus	1.4, 50-60, 173-193 GHz,	34, 38, 67, 111
Development of digital spectrometers (autocorrelators or polyphase with 4 - 8 GHz bandwidth, low power (a few Watts per spectrometer), and radiation hardening for long duration low- to mid-Earth orbit missions.	Development of hi-speed, hi-res Aanalog to Digital converters (ADCs) and correlators or signal processing hardware. Develop systems design for use in spectrometer. Develop and test ADCs and digital signal processing hardware.	50 GHz to far IR {(140) 180 GHz and 2.5 THz, (67, 143) Bands near 50 GHz and 183 GHz}	140, 143, 67
Estimation of partial correlation between many pairs of broadband noise signals by digital cross-correlation (multiply & accumulate) of low bit resolution digitized samples of signals	10,000 (threshold) / 90,000(objective) (multiply-accumulate-MAC)1-bit cross-correlations per ASIC; 0.25 mW(threshold) / 0.1 mW(target) correlator cell at 220 MHz clock rate; Fully scalable interconnect architecture	As low as 400 MHz and 1.4, 6.7, 10.7, 19.3, 36.5, 50-60, 173-193 GHz	C, D, F, G, H, I, 34, 32, 107, 1

Table 4.3.3 Summary of Processing Capability Requirements

4.3.4 Scenario and Parameter Measurement Histograms

In order to prioritize technology developments a figure of merit is required. However there is no single figure of merit suitable for decision makers. Two useful figures of merit are presented here as an aid to the decision maker. The first is a count of the number of scenarios served a given technology. This figure of merit, while useful, can be quite biased. There could for example be two equally important physical measurements that need to be made, however there could be many more scenarios for achieving one measurement whereas only one scenario might exist to support another measurement. In addition a given scenario may provide not just a single measurement but also a variety of measurements. For this reason the number of measurements supported by a given technology is provided as an additional figure of merit. The histograms are given in Table 4.3.4

Processing Technology Challenges	Number of Scenarios	Number of Parameters
Large Data Storage	21	15
Processing Algorithms	8	11
High Performance RHP	21	21
High Performance A/D Digital Receivers	21	9
Real-time On-board Processing	34	37
1-bit A/D for Radiometry	9	11
2-bit A/D for Radiometry	9	11
3-bit A/D for Radiometry	9	11
High-bandwidth Data Links (Interior to Instrument)	13	13
Digital RFI Mitigation	5	2 (potentially 11)
On-board High-rate Digital Signal Distribution	4	8
High-speed, High-resolution, Digital Spectrometers for Sounding	3	7
Massively Parallel 1-Bit Cross-correlators for Radiometry	9	11

Table 4.3.4 Histogram of Processing Technology Challenges and the Number of Measurement Scenarios and Measurement Parameters.

4.3.5 Processing Roadmaps

The individual technology roadmaps appear in Appendix 4L. The integrated technology roadmap is given in Figure 4.3.5I below.

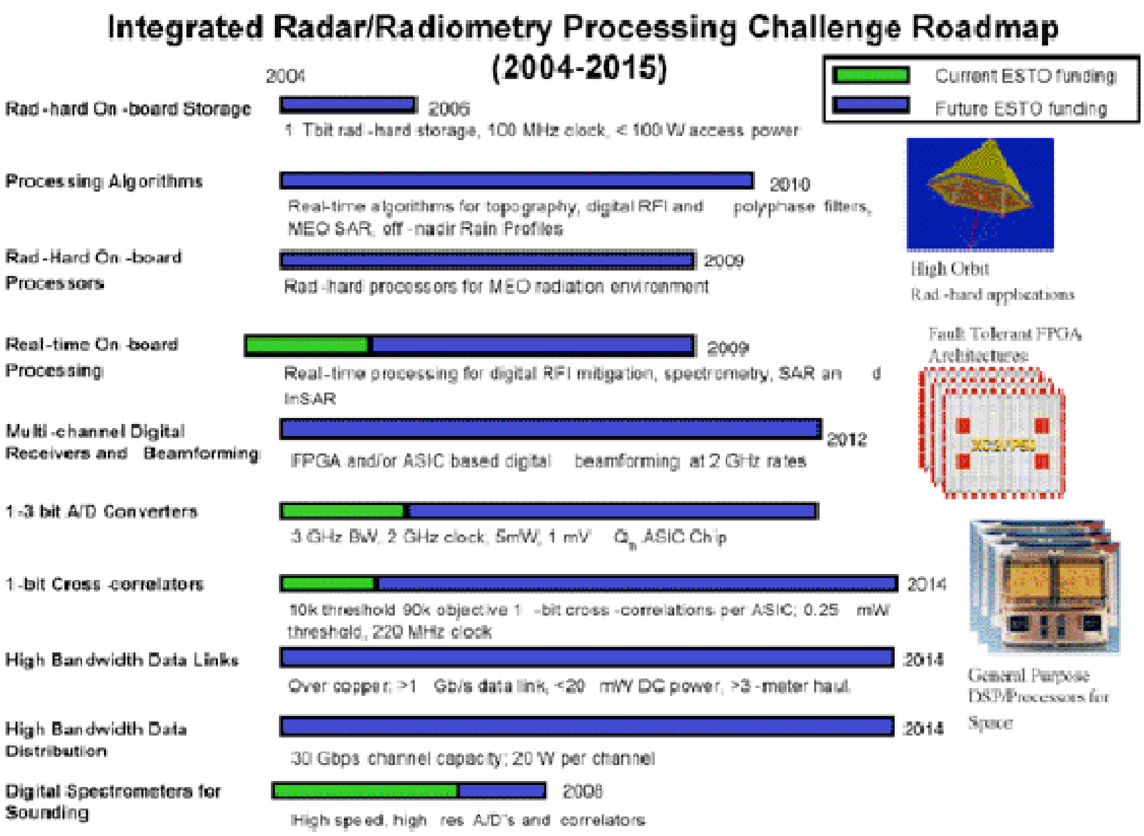


Figure 4.3.5I

5. MICROWAVE TECHNOLOGY ROADMAPS FOR ESE SCIENCE FOCUS AREAS

The details of the technology development program have been laid out in Chapter 4. Chapter 5 now summarizes the most important elements of that program, and it highlights their scientific significance. Associated with each ESE science focus area is an integrated science/technology roadmap that summarizes the recommended high-payoff microwave remote sensing technologies in active and passive remote sensing, as well as processing. The presence of a "T" in the text or the roadmaps indicates an item that is called out for technology development in the ESE science focus area roadmaps (in which a corresponding "T" will be found).

Atmospheric Composition

The Atmospheric Composition science focus area addresses the gaseous molecular species and aerosols that comprise the Earth's atmosphere. Important among these are ozone and the trace gases that are related to ozone depletion. An advanced passive microwave limb sounder with improved cooling allowing greatly reduced integration times, and with scanning in azimuth as well as elevation allowing improved coverage, could result in significant advances in our knowledge of ozone and certain trace gases [T = systematic stratospheric composition]. This could substantially advance our understanding of the processes related to ozone depletion. This instrument could also contribute to the measurement of total aerosol amount and stratospheric distribution [T = LEO aerosol/black carbon mapping ... but note the lack of any known microwave capability for measuring black carbon, or aerosol microphysical properties].

Such an instrument would operate from the high-frequency-microwave through the sub-mm-wave portions of the spectrum. Advanced cryocoolers yielding 30X improvement in sensitivity, thus 900X lower integration times, would be the cornerstone of this capability. Technological advances are required not only in cooling and 2-D scanning, but also in high-frequency local oscillators (LOs), mixers and detectors, up to a frequency of 2.5 THz. Related advances in processing, particularly in digital spectrometry, would be required.

The scientific advances that have been made by the Microwave Limb Sounder on UARS (Upper Atmosphere Research Satellite) indicate the progress in understanding that could be made with an advanced version of that instrument having the above capabilities. An advanced MLS incorporating the above technological advances is seen as the primary contribution to be made by microwave remote sensing to atmospheric composition.

The technology development item on geostationary tropospheric composition [T] needs to be addressed with an electro-optical, not a microwave, remote sensing technique. A limb sounder is the only known microwave technique for addressing any of the associated phenomena, and at GEO it would be restricted to limb measurements, which yields no coverage.

More details may be found in the roadmap in Appendix 5. (Note that “A” indicates an active microwave technology, while “P” indicates a passive microwave technology. Each bar ends when the technology has reached TRL 6, and is ready for flight.)

Carbon and Ecosystems

The Carbon and Ecosystems science focus area aims to characterize and model the cycling of carbon through the Earth system, and to determine the reliability and accuracy of models in predicting the future concentrations of atmospheric carbon dioxide and methane. Much of the Earth’s carbon is tied up in vegetative biomass, and there is great uncertainty in the amount of biomass present at any given time. A low-frequency polarimetric SAR operating at P-band (~0.5 GHz) would add to our knowledge of this difficult environmental parameter by penetrating the top layer of vegetation to yield an estimate of the underlying layer biomass [T = vegetation 3-D structure, biomass & disturbance].

Such an instrument would involve no inherently new technologies, except those needed to reduce the mass and cost of the instrument, to make it feasible to fly. Thus, this instrument potentially involves high short-term payoff for relatively little investment. A cost-effective technology to develop a phased array would be very beneficial for many missions using P-, L-, Ku- and Ka-band frequencies. A P-band polarimetric SAR is seen as the primary contribution to be made by microwave remote sensing to carbon and ecosystems. More details may be found in the below roadmap. [Note that most of the technology development items identified in the ESE science roadmap for this focus area cannot be addressed by microwave remote sensing.

More details may be found in the roadmap in Appendix 5.

Climate Variability and Change

The Climate Variability and Change science focus area addresses the understanding and prediction of time-varying interactions between the components of the global climate system and the effect of human activity on this system from seasonal and annual to decadal timescales. Unlike the preceding focus areas, more than one instrument stands out in the list of high-payoff candidates.

Clouds and aerosols represent the biggest unknowns in the global change equation. Improved knowledge of the three-dimensional structure of clouds is crucial to improving our understanding of global climate change, and ultimately to our ability to predict such change. NASA’s CloudSat will fly a single-frequency nadir-pointing proof-of-concept cloud radar. A vital next-generation instrument would employ more than one frequency (35 & 94 GHz), in order to separate out the effects of attenuation from those of backscatter, and it would not be restricted to nadir viewing. This would dramatically improve our knowledge of the 3-D properties of clouds [T = global cloud characteristics]. The proposed instrument would also employ 14 GHz to observe the precipitation associated with the clouds, since there are advantages to observing these phenomena simultaneously. This instrument represents a logical evolution of capability that should lead to a significantly improved understanding of the nature of clouds, which in turn is vital to improving our understanding of global change. Note that it is synergistic with the Weather focus area below. (Note that the 30 m antenna for the GEO precipitation radar was not included since it is already being funded.)

For cloud particle properties (specifically, ice water path), please see the sub-mm-wave radiometer discussion under the Weather focus area. For global soil moisture [T], please see the discussion under the Water and Energy focus area.

Changes that occur in the mass of the Earth's land ice cover [T = decadal measurements of ice mass change] can have a direct impact on global change, through changes in the Earth's albedo and thus its energy balance, and through changes in sea level, etc. There is presently no remote sensing capability for direct measurement of total ice sheet mass from top to bottom [although changes in glacier ice thickness can be measured using lidar altimetry (e.g., ICESat) or high-frequency single-pass InSAR]. A bistatic InSAR instrument operating at VHF frequencies would serve as a groundbreaking pathfinder to evaluate the ability of spaceborne instruments to directly measure ice sheet thickness, and thus mass. Such an instrument also has the potential to directly measure sea ice thickness, which presently is typically inferred by using techniques to measure the freeboard (the height of the ice above the ocean surface), plus certain assumptions. The development of this instrument would necessarily include algorithm work to overcome the limitations of the present VHF bandwidth allocation, since wide-band VHF would be required. The ability to monitor ice thickness would prove to be an invaluable tool in broadening our knowledge and understanding of climate change.

Sea surface salinity is an important indicator of the density of the ocean water, which drives ocean currents and circulation. Salinity is a thumbprint of the equator-to-pole deep-ocean "conveyor belt" that slowly transports heat from the equator to the poles, and that is an important regulator of climate. Sea surface salinity is a useful indicator of ocean circulation and its heat transport, and ultimately climate regulation. Aquarius will fly the first instrument to measure ocean salinity. It will use a low-resolution (~100 km) pushbroom microwave radiometer to cover the globe every 8 days. It is important to develop a next-generation instrument with greater capability. It is proposed that the technologies to support three alternative passive microwave radiometer concepts be investigated and pursued, with the goal of providing an order-of-magnitude improvement in spatial resolution (~10 km) and an improvement in revisit rate to 3 days. These concepts are: 1) a 25 m real-aperture conically scanning L-band radiometer; 2) a 25 m 2-D L-band STAR system; and 3) a 25 x 50 m torus with pushbroom scanning. (These would be augmented by a radar backscattering measurement, to measure and compensate for the ocean surface roughness effect.) One of these technologies would then serve as the future capability for sea surface salinity, whose measurement is the only known method for linking the global water cycle (e.g., ice melt and river runoff) with ocean circulation. Understanding this link is vital to the understanding of climate change. Note that there are synergies with the Water and Energy Cycle, as well as the Weather, focus areas, since these same instruments can be used to measure soil moisture in the top layer of the soil.

Sea surface temperature (SST) is a sensitive indicator of climate change. A microwave radiometer for nearly all-weather measurement of sea surface temperature, with capabilities beyond instruments that are now planned, would improve our knowledge of SST, and would provide important input for climate change models. A 7 m real-aperture conically scanning radiometer operating at 6 and 10 GHz (or an equivalent STAR system) is proposed for development.

The measurement of aerosols [T = global atmospheric aerosols] has been addressed above under Atmospheric Composition. Processing [T = advances in computational resources, high-end models and data distribution software] is discussed below, in the Processing section.

More details may be found in the roadmap in Appendix 5. Note that mitigation of RFI is important for all of the low-frequency instruments, as indicated.

Earth Surface and Interior Structure

The Earth Surface and Interior Structure science focus area addresses the Earth's solid surface and its evolution, as well as geologic processes within the Earth's interior, including earthquakes, volcanoes, and other phenomena. Two of the most basic measurements to be made are those of land surface topography, and surface deformation and stress. High-accuracy interferometric SAR (InSAR) could be used to make great strides in our knowledge of the Earth's surface and the changes that it is undergoing. This would increase our understanding not only of the Earth's surface, but also of the underlying phenomena that shape and change it, and thus our ability to predict those changes. [T = extremely accurate spaceborne radar geodetic imaging (InSAR)]

The proposed InSAR instruments progress stepwise, from low Earth orbit (LEO) to medium Earth orbit (MEO), and then to geosynchronous orbit (GEO), in a program of successively more capable instruments. The LEO instrument would involve no inherently new technologies, except those needed to reduce the cost of the instrument, to make it feasible to fly. Thus, there could be high short-term payoff for relatively little investment.

The most cost-effective starting point would be to fly a single LEO instrument to perform repeat-pass interferometry [T = airborne repeat pass InSAR would benefit from much of the same technology]. The next would be to formation-fly two LEO instruments to do cross-track interferometry. (A single pass interferometry option, with a 100 m mast, was not included, since tandem flights are a better solution once a LEO InSAR satellite is developed.) The benefit of stepping up from LEO to MEO is a higher revisit rate and improved geographical accessibility. Stepping up to GEO improves these attributes even more, offering essentially continuous refresh rate and accessibility. As the orbital altitude increases, the antenna size must increase to maintain measurement sensitivity, while the mass density must decrease to enable cost-effective development.

The scientific advances that would be afforded by a free-flying interferometric SAR are quite significant and widely recognized. Such an instrument has yet to be flown by the U.S. on a free-flying satellite. Its benefits would be many, in part because of the severe impact of phenomena such as earthquakes and volcanoes upon life on Earth. The proposed instrument development is phased such that instruments of increasing performance are flown, building upon the knowledge gained from the previous instruments. InSAR is seen as the primary contribution to be made by microwave remote sensing to Earth surface and interior structure, and its availability as a U.S. resource on a free-flying satellite is long overdue.

Improved knowledge of the terrestrial reference frame would also be very useful. This would require improvements in the ground-based VLBI (Very Long Baseline Interferometry) network that uses the Deep Space Network (DSN), which is beyond the scope of ESTO funding.

More details may be found in the roadmap in Appendix 5. [Note that the advanced gravity measurements from space technology development item cannot be addressed by microwave remote sensing.]

Water and Energy Cycle

The Water and Energy Cycle focus area addresses the exchange of water and energy between the oceans, atmosphere, terrestrial waters and terrestrial ice stores. Important aspects of this focus area include: 1) soil moisture; 2) snow properties; 3) precipitation; 4) surface water characteristics; and 5) the times of freeze/thaw transition of the land surface and the measurement of the length of the growing season.

Present spaceborne instruments only measure the moisture of the uppermost layer of soil, and there are significant limitations on the type of ground cover that can be present for measurements to be made. An instrument that could sense the soil moisture at root zone depth (1 to 5 m below the surface) would offer a tremendous advance in our ability to make meaningful measurements of global soil moisture [T], leading to a vastly improved ability to understand and model hydrological processes. A VHF/UHF SAR could yield high payoff here, since it is the only existing instrument concept for measuring soil moisture at root zone depth. (That is different from the concept of inferring the existence of water under the Earth's surface using gravity missions such as GRACE.) Soil moisture at the surface can be measured with the same type of instrument described above under the Climate Variability and Change focus area for measuring sea surface salinity. This encompasses the L-band radiometer, STAR, and torus technologies.

Snow is a very important aspect of the water and energy cycle. For measuring snow water equivalent and snow wetness, the development of three technologies is recommended (no ordering implied) [T = snow water equivalent]. The first is a C- and Ku-band polarimetric SAR. The second is a 6 m conically scanning K- and Ka-band passive radiometer. This would be similar to existing instruments, except for the factor of 3 larger antenna, which would require new technology. There is synergy with the 7 m aperture radiometer for sea surface temperature described under the Climate Variability and Change focus area. The third is a 6 m K- and Ka-band STAR. One of these technologies, or better yet, a passive/active combination, would then serve as the future observing capability for snow water equivalent and snow wetness.

The freeze/thaw transition of the land surface and the length of the growing season is an important aspect of the water and energy cycle. The development of 3 technologies is recommended; all have already been recommended for other applications. First, the Ku-band SAR described in the above paragraph can also be used for measuring the freeze/thaw transition. Second, the Ku- and C-band SAR described in the above paragraph can also measure freeze/thaw transition. The third is a 25 m L-band STAR described for sea surface salinity measurement under the Climate Variability and Change focus area.

Global precipitation is obviously a very important aspect of the water and energy cycle. Precipitation radar has already been described as part of the first instrument under the Climate Variability and Change focus area. The other recommended instrument is an X- and Ka-band STAR, in which recurring per unit costs have been reduced, in order to enable a constellation to be flown, in order to realize short revisit times. Temporal resolution is extremely important to the measurement of precipitation, since it is so variable in time. Note that this instrument is synergistic with the Weather focus area below.

It is not currently possible to measure river stage height and discharge rate [T] from space. This important aspect of the water and energy cycle is part of the link between the hydrological cycle and ocean circulation. The recommended instrument is a Ka-band InSAR operating in a cross-track mode. This initial proof-of-concept instrument could lead to an important ability to monitor the world's rivers on a routine basis, to improve the understanding, and ultimately the modeling, of the links between water on the land and in the oceans.

More details may be found in the roadmap in Appendix 5.

Weather

Weather refers to the state of the atmosphere and its variability on time scales of minutes to months. A complete characterization includes not only the state of the atmosphere, but also the temperature and moisture characteristics of the atmosphere-Earth surface interface, since these parameters are drivers of the weather. Important aspects of this focus area include: 1) cloud system structure; 2) cloud particle properties; 3) global precipitation; 4) atmospheric temperature and water vapor; 5) soil moisture; and 6) terrestrial snow/frozen soil.

Instruments for cloud system structure have been covered above under Climate Variability and Change. Instruments for global precipitation and soil moisture [T] have been covered under Climate Variability and Change, as well as Water and Energy Cycle. Instruments for snow and freeze/thaw have been covered under Water and Energy Cycle.

The ice water content of cirrus clouds is an environmental measurement parameter of great importance to the Earth's energy balance. High clouds may have a net warming or a net cooling effect on the Earth, depending on their exact makeup. The only known prospective method for measuring this quantity is a sub-mm-wave microwave radiometer (also referred to as sub-mm-wave/far IR, since the two portions of the spectrum overlap). The advantages that would accrue from the availability of data from such an instrument are widely recognized. This is perhaps the highest-payoff instrument related to this focus area that has not already been discussed. It is synergistic with Climate Variability and Change.

It is advantageous to perform temperature and moisture sounding from geosynchronous orbit (GEO), owing to the potential for synoptic coverage with high refresh rate. Presently, this is done with IR instruments that suffer from outages due to weather. Because microwave sounders can operate under nearly all weather, a temperature and moisture microwave sounder at GEO could add significantly to our knowledge, and thus our understanding, of the weather. A 4 m aperture scanning radiometer is recommended for GEO, operating in the 50 and 183 GHz bands. As an alternative to a mechanically scanned dish antenna, a STAR operating at 50 and 183 GHz should be considered as an alternative.

More details may be found in the roadmap in Appendix 5. [T: Note that the global tropospheric winds technology development item cannot be addressed by microwave remote sensing.]

Processing

Processing technology development needs cut across the focus areas, as shown in the roadmaps in this chapter. The following is a summary of those needs.

Large Radiation Hard Onboard Storage Capability

There is a clear need for onboard storage capability for Earth Science measurements in general, and particularly for radar imaging measurements, where data volumes are large but downlink opportunities tend to be limited. Typical Earth science radar measurements require hundreds of Gbits of storage capacity, and this is well within the limits of current technology. However, there is a need for storage that is faster to access (> 100 MHz), more compact and lighter weight (< 0.1 m3, 10 kg for 1 Tbit), and radiation tolerant for measurements made from orbits above 2000 km altitude (> 1 Mrad total dose). Power usage of less than 100 W for this storage capacity is also needed.

Real-time Onboard Processing

For Earth science applications where data compression and processing onboard are essential to rapidly disseminate information to field scientists and agency users, real-time processing onboard the spacecraft is essential. Also, when data must be reduced in volume to accommodate limited mission downlink channel bandwidths, the processing must often be done in real-time to prevent overflow of memory. Missions to date have been limited in their science potential by not having real-time processing capability onboard the spacecraft. There is a need for real-time space-qualified processors. For polarimetric and topography measurements for the Earth Surface and Interior Structure and the Carbon Cycle and Ecosystems focus areas, a real-time processing capability will enable rapid dissemination of wide-area data. For GEO atmospheric radars (Weather), real-time processing is essential. Requirements for real-time on board processing are: 20-30 Billion operations per second (Gops) with 1-3 Gbytes of available random access memory and 3 Gbps internal memory bandwidth.

Radiation Hard Processors

For measurements requiring processing at orbital altitudes exceeding 2000 km, radiation effects can limit processor performance. Research is needed in the area of processing devices and fault tolerant processing architectures to build robust processing capability. Measurements in essentially all the science focus areas will head to higher orbits in the future, and nearly all will require onboard processing (though not all in real-time). This technology need area spans all science focus areas. Radiation hardness to 1 Mrad total dose at MEO is needed.

Processing Algorithms

Algorithms are needed for onboard interferometric topography generation because they cannot presently be specified, since a number of issues regarding near-real-time knowledge of the spacecraft state vector and attitude, as well as the interferometer configuration, have not been investigated. Active radars in high Earth orbit will require new algorithms, because the current models have been developed for orbits with minimal Earth curvature effects. Mapping these algorithms to special purpose onboard processors also requires research. Digital RFI mitigation also fits into this category. Specific performance metrics are difficult to produce as they are highly application dependent. For SAR algorithms, the goal is to produce imaging data that is as well resolved and as radiometrically accurate as possible given the measurement. This translates into as fine as 1 m resolution and 1 dB radiometric accuracy for some applications. For RFI mitigation, the goal is to preserve the design accuracy of the instrument that would be achievable without RFI present. Examples are ocean temperature accuracy of 0.05 K or land temperature accuracy of 0.3K for radiometers.

High Performance ADC and Digital Receivers

As active radar apertures become larger and orbits become higher, it is clear that the apertures will need to be segmented into small units. Future radars will likely be highly digital, with some number of receiving elements being grouped together, then digitized close to the aperture. This approach, with digital data being transported through fiber optic connections (30 Gbps channel capacity), should greatly reduce mass and power requirements. To realize this capability, high performance, low power ADCs and modular digital receivers must be developed. In addition, digital beam-forming processors that operate in real time must be developed. In this area, 8-12 bit A/D converters operating at 200-400 MHz sampling rates are anticipated. Power levels below 0.1 W per ADC is needed for systems with thousands of T/R modules. This technology benefits the Earth Surface and Interior Structure and the Water and Energy Cycle science focus areas, as measurements in these areas require large apertures and high orbits. For STAR radiometers, there is a need for 1-bit, 2-bit and 3-bit A/D converters with 2 GHz sampling rate over a 20 GHz acceptance range, with 5 mW power consumption, and 1 mV/level sensitivity.

6. Technology Priority Analysis and Summary

The technology requirements were discussed in Chapter 5. In this chapter, we prioritize the requirements according to the following criteria.

ESE Science Value

Measurement Importance – The importance is rated only within a science focus area by NASA HQ program mangers and as it appears on the ESE science roadmaps (Appendix 1A).

Measurement Timeline – The timeline is determined by ESE science roadmaps or other relevant documents (e.g. SESWG report).

The science value has the highest ranking of all prioritization criteria.

* High priority measurements noted on the science roadmaps requiring investment in technology

Figure 6.1 Environmental parameters measured primarily with the microwave technique

Candidate Scenario Value

Scenario Uniqueness – Unique capabilities that a particular scenario offers to meet the science requirements.

Scenario Relevance – Whether the scenario meets or exceeds the threshold and goal science requirements as discussed in Chapter 2.

Technology Value

Criticality – Whether the technology is enabling (i.e. needed to enable a new measurement capability) or enhancing (i.e. provides incremental performance improvement or is cost enabling).

Utility – The number of measurement parameters that are served by a given technology.

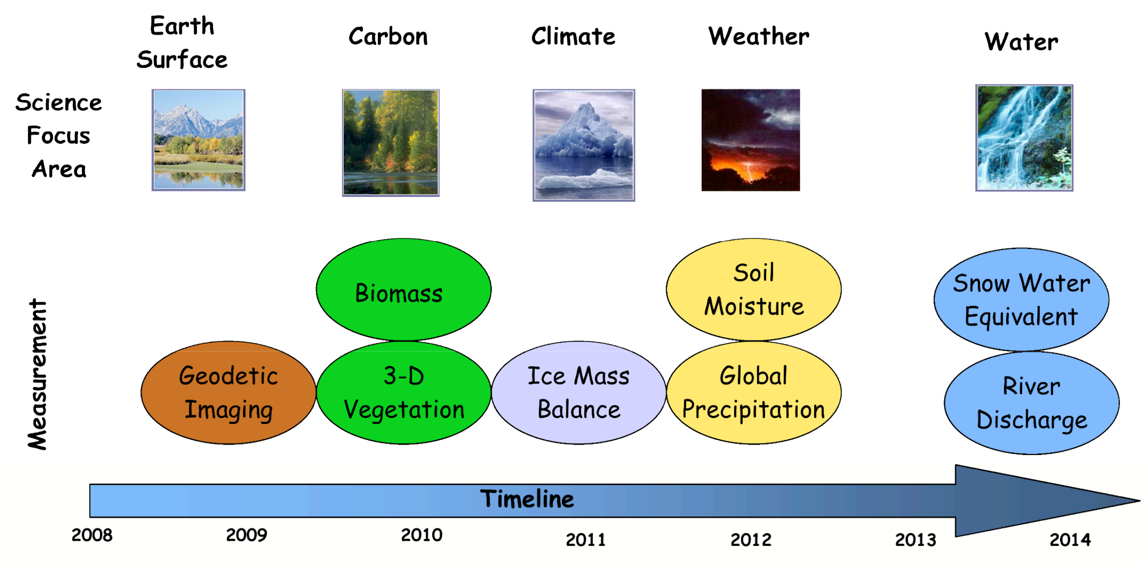


Figure 6.2 Science Importance and Timeline (Extracted from ESE Science Roadmaps assuming all measurements across 6 science focus areas are equally important)

Let us address the science value criteria first. Figure 6.1 shows the environmental parameters that are primarily measured via microwave techniques under each of the ESE science focus areas. High priority measurements noted on the science roadmaps (Appendix 1A) requiring investment in technology are indicated in red on this figure.

The science importance and timeline of each of the above measurements is indicated on the science roadmaps. Assuming all measurements across the 6 science focus areas are equally important, the timeline for accomplishing each measurement drives the priority for technology investment. Figure 6.2 summarizes the ESE science priorities and timeline according to the science roadmaps.

Next, we combine the scenario value and corresponding technology value with the science value to determine technologies that provide the highest return on investment.

In chapter 3, each scenario was characterized according to its performance. A scenario was assigned the letter "T" if it met all threshold science requirements. A scenario was assigned the letter "E" if it met all thresholds and exceeded one or more of the threshold science requirements. Finally, a scenario was assigned the letter "G" if it met all thresholds and met one or more science requirement goals. Additionally, the technology utility is measured by the number of environmental parameters that are measured utilizing the same technology. Figure 6.3 shows the measurement parameter and timeline against the scenario value and technology utility.

Technology Utility

Technology/ Measurement	Geodetic Imaging	Biomass	Ice	Precipitation	Soil Moisture	Snow Water Equivalent	River Discharge
InSAR	E	E	E		E	E	E
SAR	E	T	E/T		E/G	E/T	
STAR				G	G	G	
Real Aperture Radiometer					T	T	
Atmospheric Radar				T			
Scatterometer			T				

Timeline: 2008, 2009, 2010, 2011, 2012, 2013, 2014

Figure 6.3 Measurement scenario and technology value combined with science value

Combining all three priority criteria, it is concluded that for the science priorities of ESE, InSAR, SAR, and STAR technologies provide the highest return on investment.

Based on the analysis above, the following priorities were established in each of the technology areas:

Active Antenna Technologies

Both enabling and enhancing (mostly for reducing the mission cost) technologies were considered. For each measurement selected, the feasibility of satisfying the threshold requirements using the current technology was evaluated. If new technologies were required to meet the threshold requirements, the technologies were classified as enabling technologies.

If the mission cost could be reduced by new technologies, they were identified as enhancing technologies. Enabling technologies to satisfy objective (or goal) science requirements defined in Chapter 2 were studied. Since no science priority is provided by the science roadmaps, the importance of each measurement across the six science focus areas was assumed to be equal. A higher priority was given to the technology that can support more measurements.

The following list summarizes the high priority technologies:

1. Light weight, large antenna structure technology - Deployable and inflatable technologies, reflector and phased array structure technologies, and adaptive waveform sensing and correction technologies.

2. Low cost phased array technology - Enhancing L-band phased array technologies (system level development), Enabling Ku- and higher frequency phased array technologies

3. Multiple beam technology- Multiple frequency and multiple beam technologies.

Passive Antenna Technologies

For the radiometer antennas, technology development was considered at the component level and subsystem level, and then at the antenna system level. Accordingly, the individual technology development items were defined independent of the aperture type (STAR or real). Then, in order to provide a more complete perspective, the technology developments were related to specific antenna designs or concepts. The technology development items are therefore generally applicable to a large number of scenarios and measurement parameters. The guiding theme for antenna feeds and arrays is lightweight, and low insertion loss along with multi-polarization and multi-frequency feed capability to enable many designs of large STAR and real aperture antennas. The key aspect is to achieve current performance with new, significantly lighter-weight materials.

Trade studies and optimum system design were recurring themes during the discussion of specific antenna concepts such as 2D STAR or stationary torus. A future trade study may need to weigh the relative merits of a spinning primary aperture vs. a stationary aperture with a scanning feed system (e.g. torus antenna). Industry input suggests 15 – 20 meter aperture may be the maximum size to consider for a rotating antenna before other designs would be preferred. Another area in need of study appears to be requirements on position control vs. knowledge for STAR elements. There was general consensus on position control to ~l/20 as a goal, however, it was suggested this value may not be necessary to achieve desired overall performance.

Based on the histogram of technology development items against measurement scenarios and measurement parameters, and discussion within the working group, three relative levels of payoff are suggested for radiometer antennas.

High payoff:

1. Lightweight, low insertion loss array feeds
2. Lightweight structures and structural elements
3. Active/passive feeds/systems

Medium payoff:

1. Antenna metrology
2. Trade studies: spinning vs. non spinning real aperture
3. Thermal control/measurement of structures

Specific developments:

1. Millimeter and sub-millimeter wave antennas
2. Control of spinning apertures / momentum compensation for precision pointing

It should be noted that these technology developments do not represent a “complete set” for passive radiometry. Finally, industry participation in trade studies, particularly in cases involving large real aperture concepts and their relative merit, should not be overlooked.

Active Electronics Technologies

The priority of the active electronics technologies was decided by first classifying the scenarios into general instrument types and whether the scenarios requires "enabling" technology or "enhancing" technology. If new technologies were required to meet requirements, then these were considered enabling technologies. Technologies resulting in significant cost reduction were considered to be "cost enabling". Enhancing technologies means that measurement can be made with existing technologies, but new technologies would provide improved performance or some reduced cost. Technology requirements for mature scenarios and obsolete scenarios were not considered in any detail. The priority was set as follows: Enabling, Cost Enabling, Enhancing. A higher priority was also given to technologies supporting multiple measurements.

In order of importance:

Large Aperture SAR technologies -- criteria: enabling technology for ultra-lightweight SAR antennas (<5kg/m2)

Focuses on electronics required for lightweight ESA (particularly L-band and Ku-band). This will also benefit near-term SAR missions (of moderate aperture size). Highest priority technologies are (1) T/R modules, (2) rad-hard, low power chirp generators and digital receivers, (3) components required for wavefront sensing and control, (4) lightweight, reliable signal distribution

Millimeter (Ku, Ka & W-band) Wave Phased Array Antenna Components -- criteria: enabling technology for multiple measurements parameters

Benefits single-pass interferometer missions and atmospheric radar missions. Priority is on Ku, Ka and W-band. G-band is lower priority. Technology priorities are phase stable T/R modules and MMIC devices.

Passive Electronic Technologies

The following list ranks the required technologies according to priority.

Highest return:
1. MMIC/ miniature plus low mass/power radiometers
2. MEMS filters
3. RF switches
4. Analog RFI Mitigation Technology

Next highest return:
1. Calibration subsystem for correlation radiometers
2. On-board RF signal distribution
3. Combined active/passive system design
4. 3&4-Stokes polarimetric receiver design
5. Ultrastable low loss radiometers

Medium/lower return:
1. High frequency LNAs > 160 GHz
2. LO sources >50 GHz
3. Down-conversion techniques >900 GHz
4. mmW/smmW detectors

Processing Technologies

Each processing technology was rated as to its importance. Among those judged of highest importance were those required to enable STAR instruments (low precision A/D converters, massively parallel 1-bit cross correlators, high bandwidth data links (interior to instrument), and on-board high-rate digital distribution), the development of a high performance radiation hard processor (RHP) was also deemed of high importance.

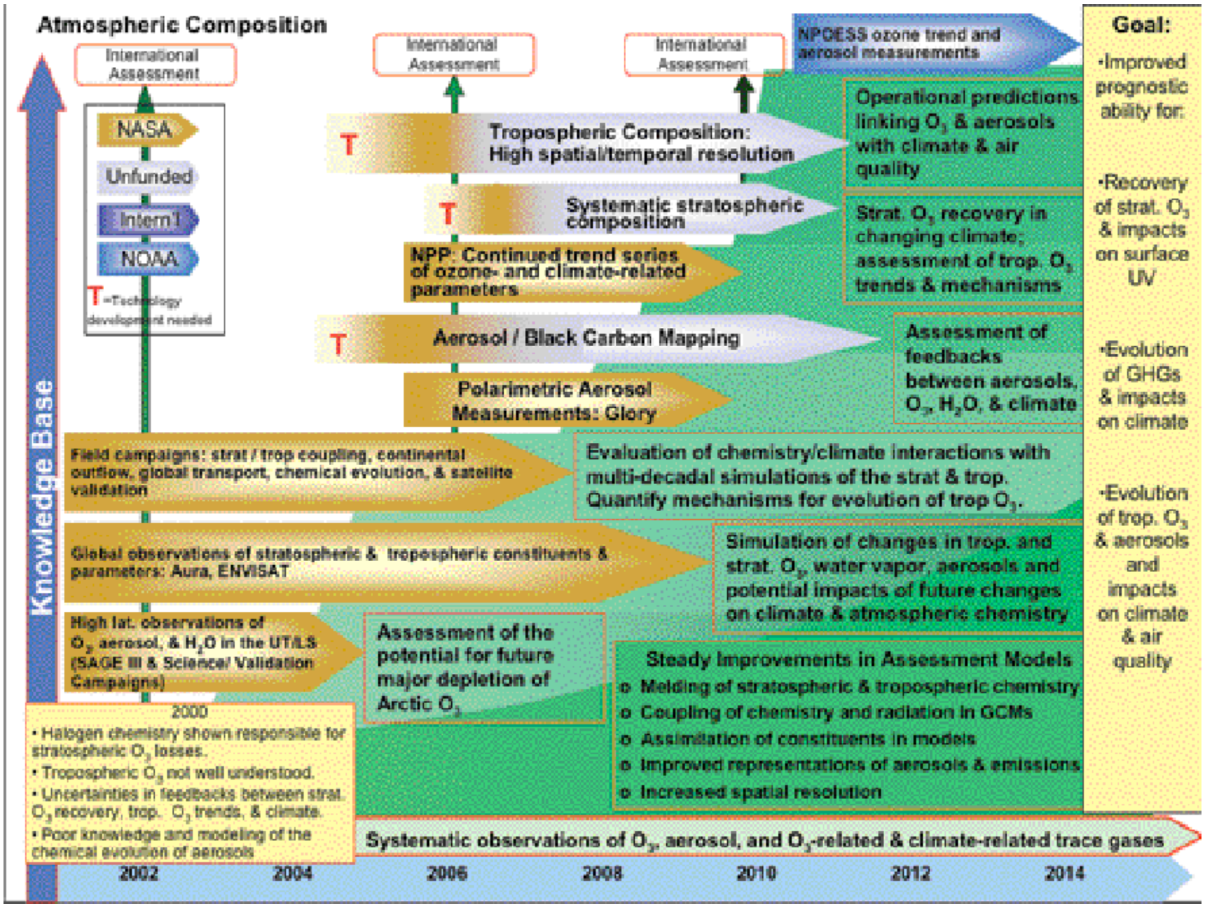
Those judged of next highest importance include large on board data storage, high performance on-board A/D digital receivers, real time on-board processing, digital RFI mitigation, and high-speed, high-resolution digital spectrometers for sounding.

Finally, processing algorithms were deemed to be of medium or lower importance.

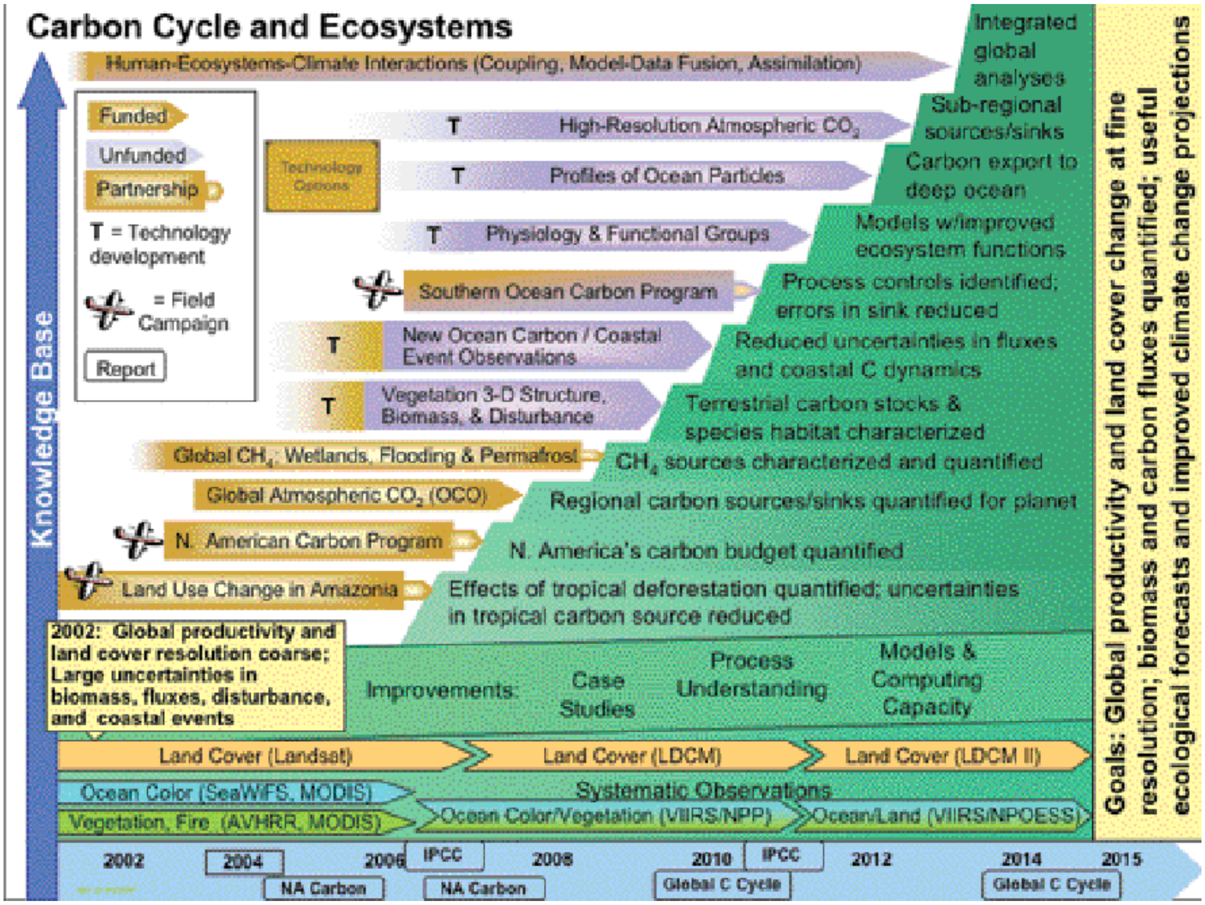
Technologies enabling STAR instruments were deemed to be among those of highest importance for several reasons. For instance, STAR instruments have much promise in providing unique capabilities but this is a relatively new approach that requires the greatest development of new technology. The development of a RHP was also rated of high importance. It is a long-term trend that instruments operate at higher altitudes for greater coverage. This places instruments in a harsher radiation environment where radiation hardened hardware is required.

Several technologies were rated to be of next highest importance. In the case of large on board data storage there is the alternative approach of additional communication links to either additional ground stations or to a high altitude asset for transmission to existing ground stations. In particular Spaced Based Radar program and perhaps other programs will have to deal with similar issues and may develop relevant technology. Similarly, there may be DOD radar programs that may on their own develop related digital receiver technology. Although real-time on board processing is a concept gaining greater interest, processing can always be performed on the ground and real-time on-board processing may be developed for other programs (e.g. the Space Based Radar program). Also, although digital RFI mitigation for radiometers will be of increasing importance in the future, its importance is secondary to the development of new radiometer instruments. Finally, high-speed, high-resolution digital spectrometers for sounding are not of the highest applicability.

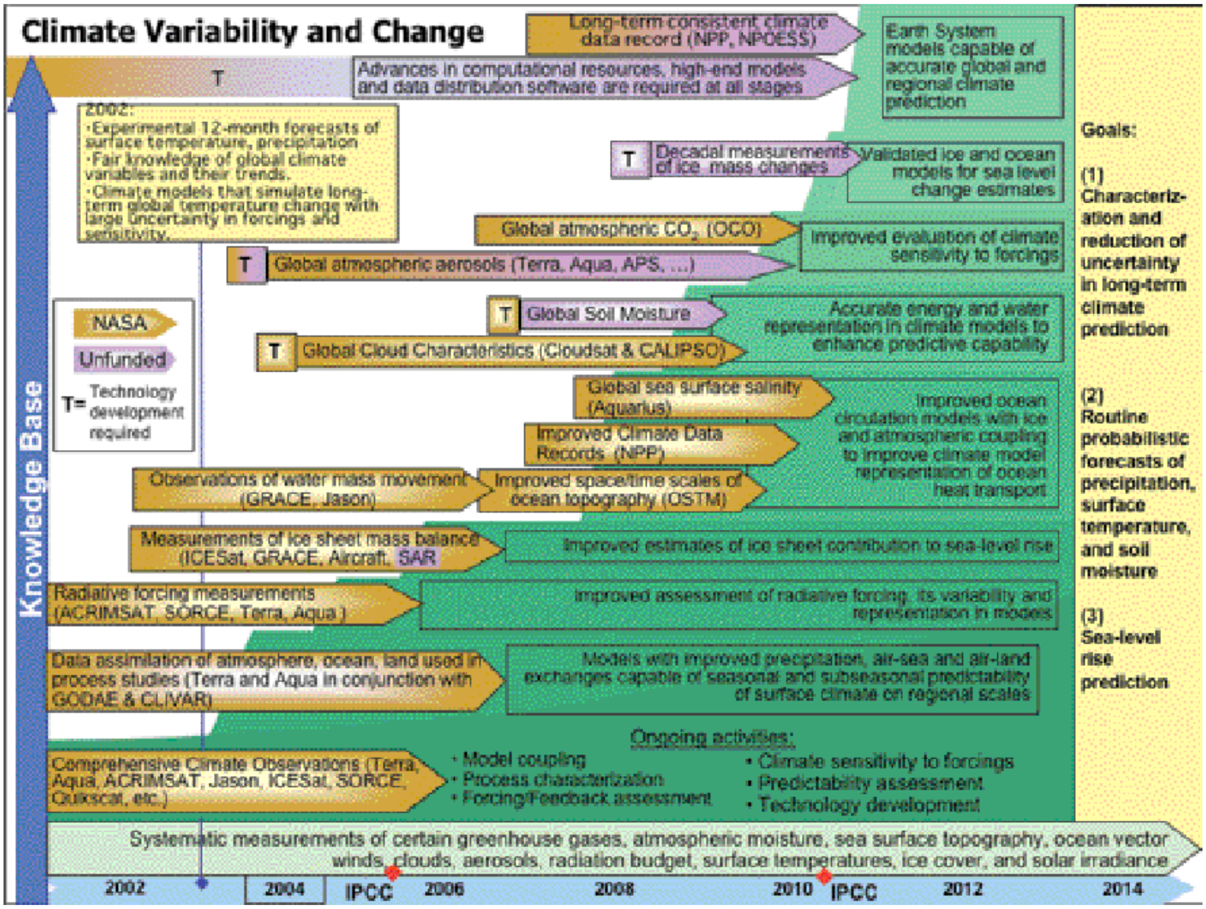
It might be reasonable to collectively rate the algorithm development technology category higher, however this area actually represents the development of a set of unrelated specialized algorithms. Due to their specialized nature, each individual algorithm is generally of quite limited applicability. Additionally, it is not clear how different some or these algorithms will have to be from algorithms developed for related purposes.



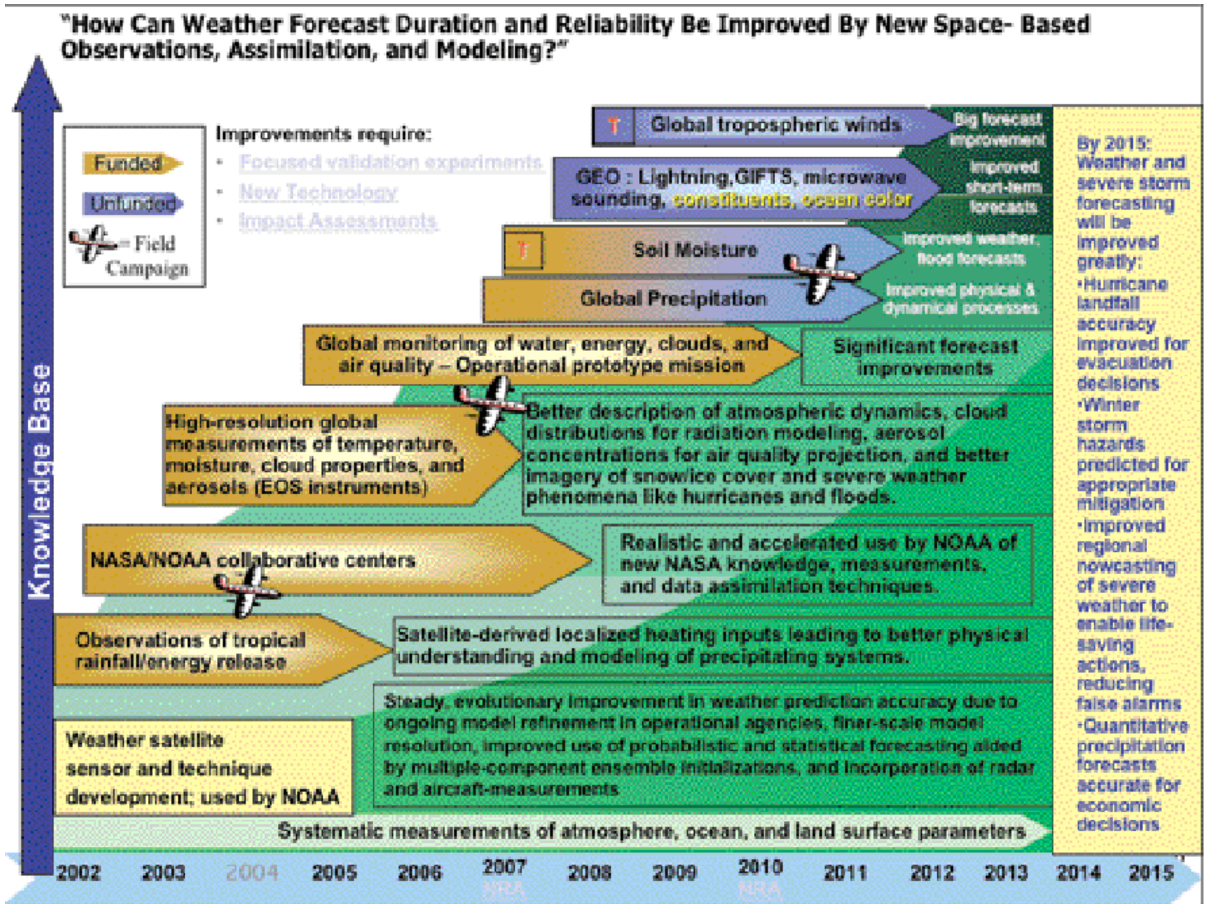
Atmospheric Composition
International Assessment
International Assessment
International Assessment
NPOESS ozone trend and aerosol measurements
Goal:
•Improved prognostic ability for:
•Recovery of strat. O_3 & impacts on surface UV
•Evolution of GHGs & impacts on climate
•Evolution of trop. O_3 & aerosols and impacts on climate & air quality
NASA
Unfunded
Intern'l
NOAA
T=Technology development needed
Knowledge Base
T
Tropospheric Composition: High spatial/temporal resolution
Operational predictions linking O_3 & aerosols with climate & air quality
T
Systematic stratospheric composition
Strat. O_3 recovery in changing climate; assessment of trop. O_3 trends & mechanisms
NPP: Continued trend series of ozone- and climate-related parameters
T
Aerosol / Black Carbon Mapping
Assessment of feedbacks between aerosols, O_3, H_2O, & climate
Polarimetric Aerosol Measurements: Glory
Field campaigns: strat / trop coupling, continental outflow, global transport, chemical evolution, & satellite validation
Evaluation of chemistry/climate interactions with multi-decadal simulations of the strat & trop. Quantify mechanisms for evolution of trop O_3.
Global observations of stratospheric & tropospheric constituents & parameters: Aura, ENVISAT
Simulation of changes in trop. and strat. O_3, water vapor, aerosols and potential impacts of future changes on climate & atmospheric chemistry
High lat. observations of O_3, aerosol, & H_2O in the UT/LS (SAGE III & Science/ Validation Campaigns)
Assessment of the potential for future major depletion of Arctic O_3
Steady Improvements in Assessment Models
o Melding of stratospheric & tropospheric chemistry
o Coupling of chemistry and radiation in GCMs
o Assimilation of constituents in models
o Improved representations of aerosols & emissions
o Increased spatial resolution
2000
• Halogen chemistry shown responsible for stratospheric O_3 losses.
• Tropospheric O_3 not well understood.
• Uncertainties in feedbacks between strat. O_3 recovery, trop. O_3 trends, & climate.
• Poor knowledge and modeling of the chemical evolution of aerosols
Systematic observations of O_3, aerosol, and O_3-related & climate-related trace gases
2002
2004
2006
2008
2010
2012
2014



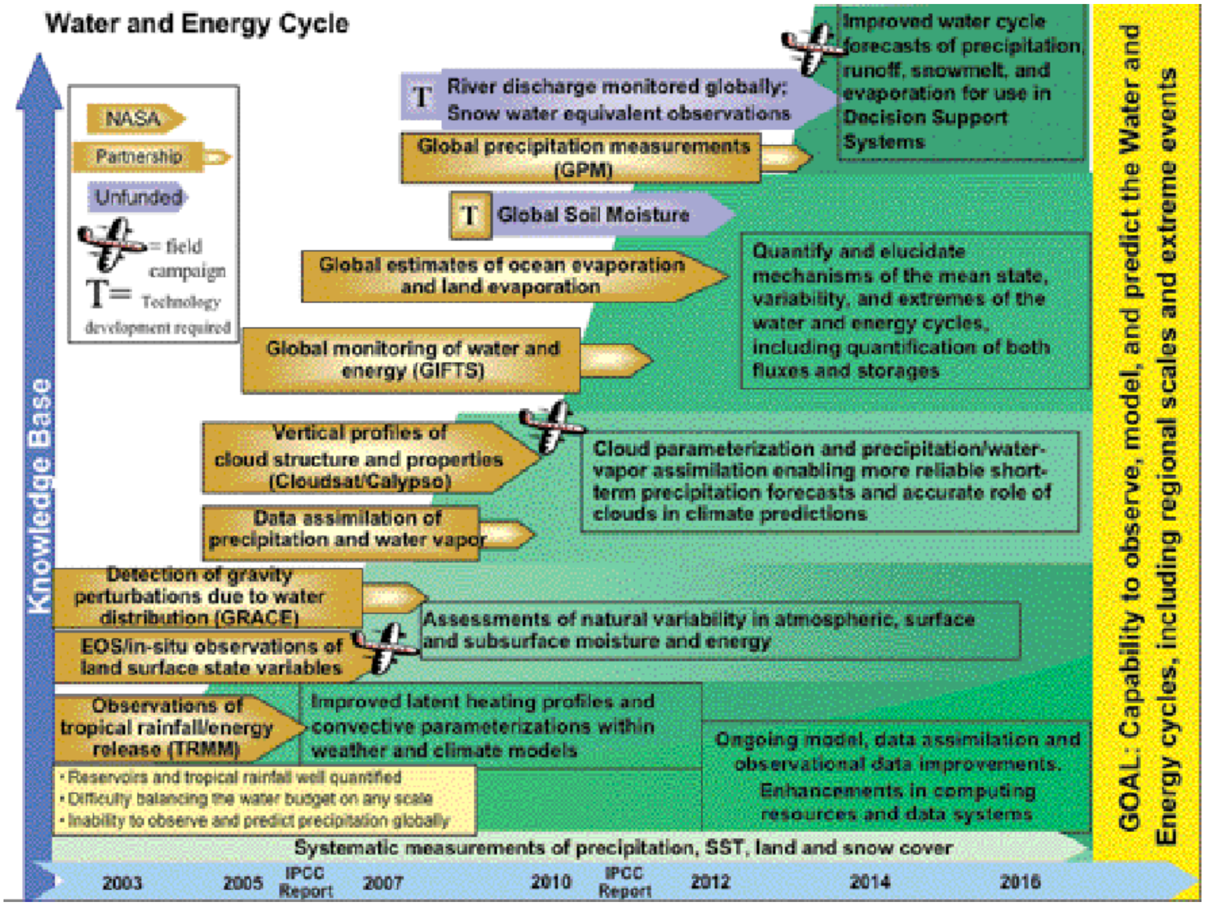
Carbon Cycle and Ecosystems
Human-Ecosystems-Climate Interactions (Coupling, Model-Data Fusion, Assimilation)
Integrated global analyses
Funded
Unfunded
Partnership
T = Technology development
= Field Campaign
Report
Technology Options
T High-Resolution Atmospheric CO_2
Sub-regional sources/sinks
T Profiles of Ocean Particles
Carbon export to deep ocean
T Physiology & Functional Groups
Models w/improved ecosystem functions
Southern Ocean Carbon Program
Process controls identified; errors in sink reduced
T New Ocean Carbon / Coastal Event Observations
Reduced uncertainties in fluxes and coastal C dynamics
T Vegetation 3-D Structure, Biomass, & Disturbance
Terrestrial carbon stocks & species habitat characterized
Global CH_4: Wetlands, Flooding & Permafrost
CH_4 sources characterized and quantified
Global Atmospheric CO_2 (OCO)
Regional carbon sources/sinks quantified for planet
N. American Carbon Program
N. America's carbon budget quantified
Land Use Change in Amazonia
Effects of tropical deforestation quantified; uncertainties in tropical carbon source reduced
2002: Global productivity and land cover resolution coarse; Large uncertainties in biomass, fluxes, disturbance, and coastal events
Improvements: Case Studies
Process Understanding
Models & Computing Capacity
Knowledge Base
Goals: Global productivity and land cover change at fine resolution; biomass and carbon fluxes quantified; useful ecological forecasts and improved climate change projections
Land Cover (Landsat)
Land Cover (LDCM)
Land Cover (LDCM II)
Ocean Color (SeaWiFS, MODIS)
Systematic Observations
Vegetation, Fire (AVHRR, MODIS)
Ocean Color/Vegetation (VIIRS/NPP)
Ocean/Land (VIIRS/NPOESS)
2002
2004
2006
IPCC
2008
2010
IPCC
2012
2014
2015
NA Carbon
NA Carbon
Global C Cycle
Global C Cycle

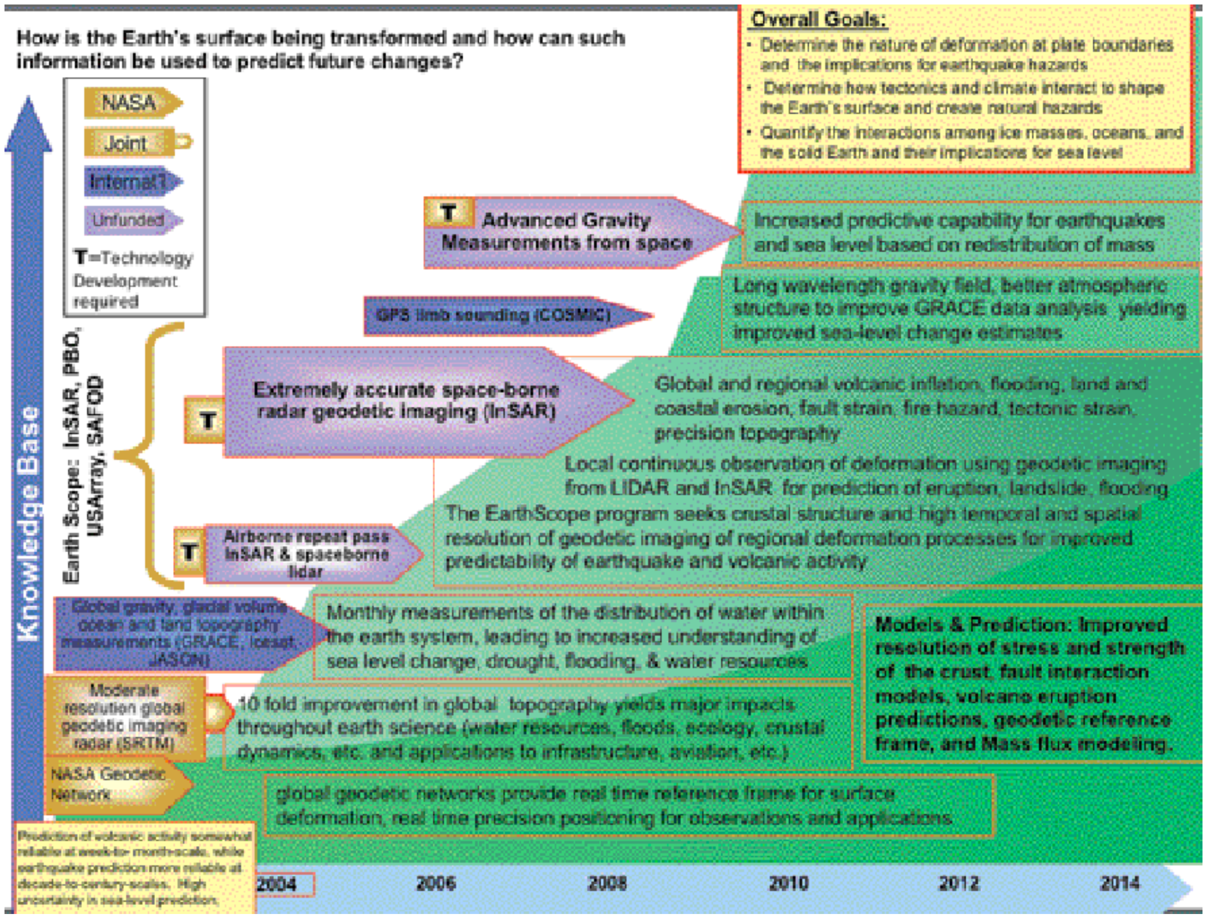


Climate Variability and Change
Long-term consistent climate data record (NPP, NPOESS)
T
Advances in computational resources, high-end models and data distribution software are required at all stages
Earth System models capable of accurate global and regional climate prediction
2002:
·Experimental 12-month forecasts of surface temperature, precipitation
·Fair knowledge of global climate variables and their trends.
·Climate models that simulate long-term global temperature change with large uncertainty in forcings and sensitivity.
T
Decadal measurements of ice mass changes
Validated ice and ocean models for sea level change estimates
Global atmospheric CO_2 (OCO)
Improved evaluation of climate sensitivity to forcings
T
Global atmospheric aerosols (Terra, Aqua, APS, ...)
NASA
Unfunded
T= Technology development required
T
Global Soil Moisture
Accurate energy and water representation in climate models to enhance predictive capability
T
Global Cloud Characteristics (Cloudsat & CALIPSO)
Global sea surface salinity (Aquarius)
Improved Climate Data Records (NPP)
Improved ocean circulation models with ice and atmospheric coupling to improve climate model representation of ocean heat transport
Observations of water mass movement (GRACE, Jason)
Improved space/time scales of ocean topography (OSTM)
Measurements of ice sheet mass balance (ICESat, GRACE, Aircraft, SAR)
Improved estimates of ice sheet contribution to sea-level rise
Radiative forcing measurements (ACRIMSAT, SORCE, Terra, Aqua)
Improved assessment of radiative forcing, its variability and representation in models
Data assimilation of atmosphere, ocean, land used in process studies (Terra and Aqua in conjunction with GODAE & CLIVAR)
Models with improved precipitation, air-sea and air-land exchanges capable of seasonal and subseasonal predictability of surface climate on regional scales
Ongoing activities:
Comprehensive Climate Observations (Terra, Aqua, ACRIMSAT, Jason, ICESat, SORCE, Quikscat, etc.)
· Model coupling
· Process characterization
· Forcing/Feedback assessment
· Climate sensitivity to forcings
· Predictability assessment
· Technology development
Systematic measurements of certain greenhouse gases, atmospheric moisture, sea surface topography, ocean vector winds, clouds, aerosols, radiation budget, surface temperatures, ice cover, and solar irradiance
Knowledge Base
2002
2004
IPCC
2006
2008
2010
IPCC
2012
2014
Goals:
(1) Characterization and reduction of uncertainty in long-term climate prediction
(2) Routine probabilistic forecasts of precipitation, surface temperature, and soil moisture
(3) Sea-level rise prediction



"How Can Weather Forecast Duration and Reliability Be Improved By New Space- Based Observations, Assimilation, and Modeling?"
Knowledge Base
Funded
Unfunded
= Field Campaign
Improvements require:
• Focused validation experiments
• New Technology
• Impact Assessments
Global tropospheric winds
Big forecast improvement
GEO : Lightning, GIFTS, microwave sounding, constituents, ocean color
Improved short-term forecasts
Soil Moisture
Improved weather, flood forecasts
Global Precipitation
Improved physical & dynamical processes
Global monitoring of water, energy, clouds, and air quality – Operational prototype mission
Significant forecast improvements
High-resolution global measurements of temperature, moisture, cloud properties, and aerosols (EOS instruments)
Better description of atmospheric dynamics, cloud distributions for radiation modeling, aerosol concentrations for air quality projection, and better imagery of snow/ice cover and severe weather phenomena like hurricanes and floods.
NASA/NOAA collaborative centers
Realistic and accelerated use by NOAA of new NASA knowledge, measurements, and data assimilation techniques.
Observations of tropical rainfall/energy release
Satellite-derived localized heating inputs leading to better physical understanding and modeling of precipitating systems.
Weather satellite sensor and technique development; used by NOAA
Steady, evolutionary improvement in weather prediction accuracy due to ongoing model refinement in operational agencies, finer-scale model resolution, improved use of probabilistic and statistical forecasting aided by multiple-component ensemble initializations, and incorporation of radar and aircraft-measurements
Systematic measurements of atmosphere, ocean, and land surface parameters
By 2015: Weather and severe storm forecasting will be improved greatly:
•Hurricane landfall accuracy improved for evacuation decisions
•Winter storm hazards predicted for appropriate mitigation
•Improved regional nowcasting of severe weather to enable life-saving actions, reducing false alarms
•Quantitative precipitation forecasts accurate for economic decisions
2002 2003 2004 2005 2006 2007 NRA 2008 2009 2010 NRA 2011 2012 2013 2014 2015


Water and Energy Cycle
NASA
Partnership
Unfunded
= field campaign
T= Technology development required
Knowledge Base
River discharge monitored globally; Snow water equivalent observations
Improved water cycle forecasts of precipitation, runoff, snowmelt, and evaporation for use in Decision Support Systems
Global precipitation measurements (GPM)
Global Soil Moisture
Global estimates of ocean evaporation and land evaporation
Quantify and elucidate mechanisms of the mean state, variability, and extremes of the water and energy cycles, including quantification of both fluxes and storages
Global monitoring of water and energy (GIFTS)
Vertical profiles of cloud structure and properties (Cloudsat/Calypso)
Cloud parameterization and precipitation/water-vapor assimilation enabling more reliable short-term precipitation forecasts and accurate role of clouds in climate predictions
Data assimilation of precipitation and water vapor
Detection of gravity perturbations due to water distribution (GRACE)
Assessments of natural variability in atmospheric, surface and subsurface moisture and energy
EOS/in-situ observations of land surface state variables
Observations of tropical rainfall/energy release (TRMM)
Improved latent heating profiles and convective parameterizations within weather and climate models
Ongoing model, data assimilation and observational data improvements. Enhancements in computing resources and data systems
• Reservoirs and tropical rainfall well quantified
• Difficulty balancing the water budget on any scale
• Inability to observe and predict precipitation globally
Systematic measurements of precipitation, SST, land and snow cover
2003
2005
IPCC Report
2007
2010
IPCC Report
2012
2014
2016
GOAL: Capability to observe, model, and predict the Water and Energy cycles, including regional scales and extreme events



How is the Earth's surface being transformed and how can such information be used to predict future changes?
Overall Goals:
• Determine the nature of deformation at plate boundaries and the implications for earthquake hazards
• Determine how tectonics and climate interact to shape the Earth's surface and create natural hazards
• Quantify the interactions among ice masses, oceans, and the solid Earth and their implications for sea level
NASA
Joint
Internat'l
Unfunded
T=Technology Development required
Knowledge Base
Earth Scope: InSAR, PBO, USArray, SAFOD
T
Advanced Gravity Measurements from space
Increased predictive capability for earthquakes and sea level based on redistribution of mass
GPS limb sounding (COSMIC)
Long wavelength gravity field, better atmospheric structure to improve GRACE data analysis yielding improved sea-level change estimates
T
Extremely accurate space-borne radar geodetic imaging (InSAR)
Global and regional volcanic inflation, flooding, land and coastal erosion, fault strain, fire hazard, tectonic strain, precision topography
Local continuous observation of deformation using geodetic imaging from LIDAR and InSAR for prediction of eruption, landslide, flooding
T
Airborne repeat pass InSAR & spaceborne lidar
The EarthScope program seeks crustal structure and high temporal and spatial resolution of geodetic imaging of regional deformation processes for improved predictability of earthquake and volcanic activity
Global gravity, glacial volume ocean and land topography measurements (GRACE, Icesat, JASON)
Monthly measurements of the distribution of water within the earth system, leading to increased understanding of sea level change, drought, flooding, & water resources
Models & Prediction: Improved resolution of stress and strength of the crust, fault interaction models, volcano eruption predictions, geodetic reference frame, and Mass flux modeling.
Moderate resolution global geodetic imaging radar (SRTM)
10 fold improvement in global topography yields major impacts throughout earth science (water resources, floods, ecology, crustal dynamics, etc. and applications to infrastructure, aviation, etc.)
NASA Geodetic Network
global geodetic networks provide real time reference frame for surface deformation, real time precision positioning for observations and applications
Prediction of volcanic activity somewhat reliable at week-to- month-scale, while earthquake prediction more reliable at decade-to-century-scales. High uncertainty in sea-level prediction.
2004
2006
2008
2010
2012
2014

APPENDIX 1B: NASA ESTO MICROWAVE TECHNOLOGY WORKING GROUP MEMBERS

NASA ESTO Microwave Technology Working Group Members

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Study Lead	**Valinia, Azita**	NASA/ESTO	Azita.Valinia@nasa.gov

APPENDIX 1C: NASA ESTO RADAR/RADIOMETRY COMMUNITY FORUM PARTICIPANTS

NASA ESTO Radar/Radiometry Community Forum Participants

Name	Organization
Abdalati, Waleed	NASA Headquarters
Albjerg, Mariann	NASA ESTO
Anderson, Ken	NASA ESTO
Avery, Don	NASA Langley Research Center
Bajpai, Shyam	NOAA / NESDIS
Bauer, Robert	NASA ESTO
Britt, Jamie	NASA Goddard Space Flight Center
Chang, Al	NASA Goddard Space Flight Center
Dixon, Tim	University of Miami
Dobson, Craig	NASA Headquarters
Doiron, Terence	NASA Goddard Space Flight Center
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Elsherbeni, Atef	The University of Mississippi
Evans, Daniel	The Aerospace Corp.
Gervin, Janette	NASA Goddard Space Flight Center
Goodman, Steve	NASA Headquarters
Herrell, Linda	NASA Jet Propulsion Laboratory
Hildebrand, Peter	NASA Goddard Space Flight Center
Hilliard, Lawrence	NASA Goddard Space Flight Center
Hook, Simon	NASA Jet Propulsion Laboratory
Kaye, Jack	NASA Office of Earth Science
Kim, Ed	NASA Goddard Space Flight Center
Kim, Yunjin	NASA Jet Propulsion Laboratory
Komar, George	NASA ESTO
Kunkee, David	The Aerospace Corp.
Kwok, Ronald	NASA Jet Propulsion Laboratory
Long, Catherine	NASA Goddard Space Flight Center
Madsen, Soren	NASA Jet Propulsion Laboratory
Moussessian, Alina	NASA Jet Propulsion Laboratory
Newsome, Penny	GST / ESTO
Pett, Todd	Ball Aerospace & Technologies Corp.

Piepmeier, Jeff	NASA Goddard Space Flight Center
Rahmat-Samii, Yahya	UCLA
Rincon, Rafael	NASA Goddard Space Flight Center
Roberts, Erik	Analex Corporation
Rosen, Paul	NASA Jet Propulsion Laboratory
Ruf, Chris	University of Michigan
Salisbury, Gary	Ball Aerospace & Technologies Corp.
Sarabandi, Kamal	University of Michigan
Shiue, James	NASA Goddard Space Flight Center
Stevens, Christopher	Jet Propulsion Laboratory / NMP
Stocky, John	NASA Jet Propulsion Laboratory
Stoermer, Pierre	Ball Aerospace & Technologies Corp.
Sun, Guoqing	University of Maryland
Swift, Cal	University of Massachusetts
Tratt, David	NASA ESTO
Valinia, Azita	NASA ESTO
Walton, Amy	NASA ESTO
Watson, Bill	NASA Headquarters
Yuhas, Cheryl	NASA Headquarters
Zewari, Wahid	NASA Goddard Space Flight Center

Appendix 1D: Working Group Technology Subgroups

Working Group Technology Subgroups

Active Antennas
Yunjin Kim (co-lead)
Yahya Rahmat-Samii (co-lead)
Tim Dixon
Wendy Edelstein
Daniel Evans
Ed Kim
Soren Madsen
Mahta Moghaddam
Rafael Rincon
Paul Rosen
Gary Salisbury
Kamal Sarabandi
Cal Swift

Passive Antennas
David Kunkee (co-lead)
Yahya Rahmat-Samii (co-lead)
Wendy Edelstein
Tony England
Daniel Evans
David Glackin
Prasad Gogineni
Ed Kim
Rafael Rincon
Chris Ruf
Gary Salisbury
Kamal Sarabandi
Cal Swift

Active Electronics
Wendy Edelstein (lead)
Ken Anderson
Daniel Evans
Prasad Gogineni
David Kunkee
Soren Madsen
Rafael Rincon
Gary Salisbury
Cal Swift

Passive Electronics
Ed Kim (lead)
Ken Anderson
Wendy Edelstein
Tony England
Daniel Evans
Prasad Gogineni
David Kunkee
Chris Ruf
Cal Swift

Processing
Daniel Evans (co-lead)
Paul Rosen (co-lead)
Tim Dixon
Tony England
Prasad Gogineni
Ed Kim
David Kunkee
Soren Madsen
Rafael Rincon
Chris Ruf

APPENDIX 1E: WORKING GROUP SCIENCE SUBGROUPS

Working Group Science Subgroups

Atmosphere, Water Vapor and Precipitation
Ken Anderson
Al Chang
Wendy Edelstein
David Glackin
Ed Kim
David Kunkee
Rafael Rincon
Chris Ruf
Yahya Rahmat-Samii

Oceans
Daniel Evans
David Glackin
Yunjin Kim
David Kunkee
Ron Kwok
Yahya Rahmat-Samii
Rafael Rincon
Chris Ruf
Cal Swift

Hydrology
Al Chang
Wendy Edelstein
Tony England
David Glackin
Prasad Gogineni
Ed Kim (T)
Yunjin Kim
David Kunkee
Yahya Rahmat-Samii
Gary Salisbury
Cal Swift

Carbon and Solid Earth
Tim Dixon
Wendy Edelstein
Daniel Evans
Yunjin Kim
Soren Madsen
Mahta Moghaddam
Paul Rosen
Gary Salisbury
Kamal Sarabandi
Woody Turner

Cryosphere
Ken Anderson
Daniel Evans
Prasad Gogenini
Ed Kim
Ron Kwok
Paul Rosen
Chris Ruf
Gary Salisbury
Cal Swift

APPENDIX 2A: ATMOSPHERIC CHEMISTRY SCIENCE REQUIREMENTS

Science Requirement	Description	Measurement Requirements	horizontal resolution	vertical resolution	revisit rate	coverage	accuracy
Volcanic gas and ash emissions	Measure volcanic gas and ash emissions to determine their effects on global climate.	need to characterize tropospheric constituents, column ozone, column SO2, ash, dust, smoke, cloud top height, thermal anomalies	5 km	N/A	5 minutes	global	cloud top height 30mb; thermal anomalies 5 K
Solar UV irradiance	Conduct long-term monitoring of spectrally resolved solar ultraviolet irradiance, which affects stratospheric ozone and temperature.	spectrally resolved monitoring of solar UV radiation	N/A	N/A	1 day; 1 hour	N/A	3% radiometric; 1% consistency over solar cycle
Total aerosol amount	Conduct global observations of total aerosol amount, which has a significant effect on atmospheric temperature.	Total aerosol optical depth and single scattering albedo	5 km	N/A	1 day	global	10% of optical depth, 5% of scattering albedo
Stratospheric aerosol distribution	Conduct global observations of aerosol distribution with good vertical resolution.	stratospheric aersol loading/extinction, profile and optical parameter chemical composition, density, particle size	50 km; 10 km	500 m	1 day	global	10% of optical depth
Aerosol properties	Conduct in-situ and ground-based measurements of aerosol properties.	Total aerosol optical depth, single scattering albedo, chemical composition	N/A	N/A	1 hour	global	10% of optical depth, 5% of scattering albedo
Surface trace gas concentration	Conduct in-situ measurements of total atmospheric concentrations of long-lived trace gases such as carbon dioxide, methane, nitrous oxide, and CFCs, which trap IR radiation and contribute to global warming.	Determine concentrations of long-lived surface trace gas as noted via in-situ measurements	N/A	N/A	1 day	global	1%
Atmospheric properties in the tropopause	Conduct a detailed investigation of the relationship between ozone distribution, water vapor, aerosols, temperature, and trace constituents (chlorine, bromine, nitrogen oxide) in the tropopause. The highly complex, interactive relationships between these factors could reinforce and accelerate ozone layer destruction.	measure several parameters as noted in the tropopause region	15 km; 1 km	1 km	1 day	global	temp profile 1 K, water vapor 10%, others 1%
Total column ozone	Conduct long-term total column measurements of stratospheric ozone and key factors governing its abundance, such as chlorine, bromine, CFCs, halogens, aerosols, methane, nitrous oxide, and water vapor.	measure stratospheric ozone cloumn over long-term for trend studies	5 km		1 day	global	1%
Ozone vertical profile	Conduct long-term vertical profile measurements of stratospheric ozone and key factors governing its abundance, such as chlorine, bromine, CFCs, halogens, aerosols, methane, nitrous oxide, and water vapor.	measure vertical profile of ozone and atmospheric minor constituents	50 km	500 m	1 day	global	Water vapor 10%, others 1%
Tropospheric ozone and precursors	Conduct global observations of tropospheric ozone, nitrogen oxides, carbon monoxide, hydrocarbons, and aerosols to understand the large-scale transport, removal, and chemical transformation of air pollution.	distribution of tropospheric ozone and other trace gases	50 km; 5 km	5 km; 1 km	1 day	global	ozone 1%, other 5%
Total solar irradiance	Measure variations in total solar irradiance, which could have important consequences for the Earth's climate.	measure variations in total solar irradiance over long periods	N/A		1 day		1%
Earth radiation budget	Measure radiation flows at the top of the atmosphere to relate cloud dynamics and properties to climate change. Cloud processes affect climate by controlling planetary radiation balance and, indirectly, through vertical transport and condensation of water vapor and the greenhouse effect.	measure broadband radiation; need to resolve diurnal cycle over a period of 2 months	30 km		12 hours	global	1%
Cloud system structure	Conduct observations which resolve the 3-dimensional structure of cloud systems, cloud types, cloud particle density and size, ice and water content	Global cloud parameters	10 km	30 m	2.5 hours	global	0.01 g/m**3
Cloud particle properties and distribution	Conduct observations which cover a representative sample of all different cloud types and distributions of condensation nuclei and aerosol particles that affect cloud particle distributions. Cloud processes affect climate by controlling planetary radiation balance and, indirectly, through vertical transport and condensation of water vapor and the greenhouse effect.	measure particle density & size; ice & water content, albedo, optical depth	10 km; 1 km	30 m	1 day	global	10% of optical depth

APPENDIX 2B: CARBON CYCLE AND ECOSYSTEMS SCIENCE REQUIREMENTS

Science Requirement	Description	Measurement Requirements	horizontal resolution	vertical resolution	revisit rate	coverage	accuracy
Trace gas sources	Measure trace gases (including natually occurring and industrially produced), especially CO2 column mapping, to determine the potential for climate change.	Total column CO2 including tropospheric CO2	20 km	1km for profiles, to discriminate boundary layer	2 days; 0.5 days (to remove bias)	global	0.30%
Terrestrial primary productivity	Measure variations in productivity, composition, and health of global ecosystems, which produce food and fiber for human use, govern changes in the Earth's carbon cycle, and modulate the water cycle over land. The desired parameters can be derived from measurements of chlorophyll concentration and vegetation index.	crop/forest yields, photosynthesis, respiration, carbon sequestration	20 m; 5 m	N/A	seasonal	global	sufficient to discriminate year to year changes
Land cover and land use	Conduct systematic global multispectral mapping of land cover once or a few times per year to generate periodic global inventories of land cover and land use for land usage/management practices.	land cover types, land cover change	30m; 10 m (both with 1m sampling)	N/A	2 months	global	N/A
Land cover and land use	Conduct systematic global multispectral mapping of land cover once or a few times per year to generate periodic global inventories of land cover and land use for lan usage/management practices.	land cover types, land cover change	1 km; 250 m	N/A	2 months	global	N/A
Biomass	Quantify the responses of terrestrial ecosystems to disturbance in terms of (above-ground) biomass changes and consequent carbon sequestration or emission. Responses may include changes in physiology, biogeochemical cycling, species composition, biomass density, canopy architecture, and distribution patterns.	vegation/forest rate of recovery; forest structure & density	100 m; 10 m	None; 0.5m	1 year; 3 months	global	0.5 dB relative radiometric, 1 dB absolute
Marine productivity in coastal regions	Observe ocean color to determine the productivity of marine ecosystems in coastal regions. This will resolve weather-induced changes and tidal fluxes, which quantify variability in the primary biological productivity of coastal regions. Coastal regions are highly productive and extremely variable. They affect the biological pump which is a critical component of the ocean carbon cycle and affects the balance of carbon dioxide (a greenhouse gas) between the atmosphere and the ocean. Because of the smaller scale and rapid changes, this need is distinct from marine primary productivity.	primary productivity, biomass, chlorophyll, absorbance of chromophoric dissolved organic matter and detritus, dissolved organic carbon (DOC), dissolved inorganic carbon, particulate organic carbon, particulate inorganic carbon, terrestrial DOC flux, algal DOC production, phytoplankton pigments, taxonomy, physiology and photosynthetic activity, phenology, algal blooms, start/end growing season, mixed layer depth, photosynthetically available radiation	100m; 30 m	N/A	1 day; 8 hours	regional	N/A
Marine primary productivity	Conduct global observations of the spatial distribution, extent, and temporal dynamics of marine productivity with moderate-resolution multispectral images at near-daily frequency. Ocean color is the primary means of measuring marine productivity. Peaks in marine primary productivity (blooms) usually occur when oceanic motions bring nutrient-rich waters into the well-lit upper oceans. Such events often dominate the downward flux of organic carbon.	primary productivity, biomass, chlorophyll, absorbance of chromophoric dissolved organic matter, dissolved organic carbon (DOC), dissolved inorganic carbon, particulate organic carbon, particulate inorganic carbon, algal DOC production, phytoplankton pigments, taxonomy, physiology and photosynthetic activity, mixed layer depth, photosynthetically available radiation	500 m	N/A	1 day	global	N/A

APPENDIX 2B: CARBON CYCLE AND ECOSYSTEMS SCIENCE REQUIREMENTS (CONTINUED)

Science Requirement	Description	Measurement Requirements	horizontal resolution	vertical resolution	revisit rate	coverage	accuracy
Fuel quantity and quality	Conduct global observations in IR, Vis/NIR, and hyperspectral to determine fuel load	fuel moisture/canopy openness, fuel mass, quantity, quality, location	100 m; 10 m	None; 0.5 m	weekly during fire season, but only needed seasonally otherwise	regional to global	0.5 dB relative, 1.0 dB absolute (and better than MODIS)
Fire occurances and extent	Conduct global observations in IR, Vis/NIR, and hyperspectral to determine fire occurance	Fire intensity, extent, and location; Smoke column quantity and quality	TBD km; 100 m	N/A	weekly during fire season, but only needed seasonally otherwise	regional to global	better than MODIS
C02 and methane	Conduct precise measurements of spatial, temporal, and (perhaps) vertical variations in total column amount of carbon dioxide and methane in the atmosphere in order to quantify regional carbon sources and sinks. These measurements are important for understanding the global carbon cycle and predicting future climate changes.	Total column CO2 including tropospheric CO2	10km	1km for profiles, to discriminate boundary layer	2 days; 0.5 days to remove bias	global	0.30%
Coastal region properties and productivity	Conduct repeated multispectral observations of coastal regions (beaches, low lying land areas near oceans, estuaries and river deltas) at the highest practicable spatial and temporal resolution to provide information on the distribution and properties of biological material. These regions are important because their human population is fast increasing and the regions are particular susceptible to climate and sea level changes.	primary productivity, chlorophyll, absorbance of chromophoric dissolved organic matter and detritus, dissolved organic carbon (DOC), dissolved inorganic carbon, particulate organic carbon (POC), particulate inorganic carbon, terrestrial DOC and POC flux, black carbon, phytoplankton taxonomy	100 m; 30 m	N/A	1 day; 5 hours	regional	N/A
growing season length in high latitutes	Conduct daily measurement of freeze/thaw conditions in high latitudes to estimate growing season length	freeze/thaw	1 km; 100 m	N/A	daily	regional	0.2 dB relative, 1.0 dB absolute
Land cover and land use	Conduct systematic global polarimetric radar (SAR) mapping of land cover once or a few times per year to generate periodic global inventories of land cover and land use for land usage/management practices.	coarse resolution land cover types, land cover change	250 m; 20 m	N/A	60 days; 20 day	global	0.5 dB relative radiometric; 1 dB absolute.

APPENDIX 2C: CLIMATE VARIABILITY SCIENCE REQUIREMENTS

Science Requirement	Description	Measurement Requirements	horizontal resolution	vertical resolution	revisit rate	coverage	accuracy
Sea ice extent	Measure the extent of sea ice over polar oceans, which is a sensitive indicator of climate change. Recent observations indicate a decrease in sea ice extent and thickness in the Arctic, which could have a major amplifying effect on global warming in northern latitudes.	extent; concentration; age; salt content; albedo	25 km; 5 km	n/a	1 day; 12 hours	polar oceans	edge detection 5 km, ice concentration 2 %
Ice surface topography	Measure topography of polar ice sheets, smaller ice caps and glaciers to determine changes in the Earth's ice cover, which is an important indicator of climate and exerts controls on climate which are not well understood.	Precise elevation, and changes in elevation with time	1 km; 100 m	1cm precise elevation, 1m changes in elevation with time	achieved frequently through crossover analysis	polar regions	1 cm precise elevation, 1 m changes in elevation with time
Sea ice thickness	Measure sea ice thickness to investigate the potential for changes in ocean circulation, and changes in energy fluxes. Recent observations indicate a decrease in sea ice extent and thickness in the Arctic, which could have a major amplifying effect on global warming in northern latitudes.	sea ice thickness	For mass balance: 50km; 10 km For energy flux: 50 m; 10 m	30 cm; 10 cm	1 month; 1 week	polar oceans	10 cm
Polar ice sheet velocity	Map the velocity fields of the great ice sheets of Greenland and Antarctica to estimate the rate at which the polar ice caps are changing. Melting of the polar ice sheets could lead to a significant rise in sea level around the world in a few years or decades.	Surface velocities and velocity gradients, particularly in fast-moving outlet glaciers, and changes in these velocities	Ice sheets: 10 km; 1 km Mountain and outlet glaciers: 1 km; 100 m	n/a	1 month; 1 week	polar regions	1 m/yr
Ice sheet Bed Topography	Map the topography of the beds of the ice sheets and outlet glaciers. Also, the topography on ice caps and ice fields in Alaska, Patagonia and other mountain glaciers.Topography is important for predictive modeling.	Basal topography of the beds.	5 km; 100 m	10 m; 1 m	once	polar regions	5 m
Accumulation on ice sheet	Measure the time-varying accumulation of snow over the ice sheets. This is used to help resolve seasonal variability in elevation changes measured by altimeters.	accumulation thickness.	100 km; 10 km	1cm	1 week; 1 day	polar regions	1 cm
Ice Sheet Melt Extent and Seasons	Measure/quantify surface melt process on icesheet, which is important to mass balance/sea level. Recent observations on Greenland icesheet show record melt extent, long and intense melting seasons.	melt season duration, melt/refreeze days, melt/refreeze area and location	25 km; 1 km	n/a	1 day; 12 hours	Ice Sheets	1 day
Snow depth on sea ice	Measure the snow depth over sea ice. This is an important parameter than controls energy exchanges between the ocean and the atmosphere.	snow thickness relative to ice surface.	12.5km; 5km	5 cm	1 month; 1 week	polar oceans	5 cm
Sea Ice Motion (small scale)	Sea ice velocity at a length scale that resolves discontinuities on the ice cover. Small scale motion allows to measure openings and closings - open water production and ridging statistics. Changes in these statistics will change the energy balance over t	sea ice velocity.	5 km; 2.5km	n/a	3 days 1 day	polar oceans	0.1 cm/s
Sea Ice Motion (large-scale)	Controls ice transport, redistribution and ice export. Large scale ice advection for understanding changes in export and circulation. Recent changes in circulation patterns are significant as they are associated with large scale atmospheric modes and thes	sea ice velocity	25 km; 10 km	n/a	1 day; 12 hours	polar oceans	2 cm/s
Sea Ice surface temperature	Fundamental parameter regulating the rate of growth and melt of ice. Important parameter in energy balance over sea ice.	skin temperature, snow/ice interface temperature	5 km; 1km	n/a	1 day; 12 hours	polar oceans	0.5 K
Meltpond fraction	Fraction and characteristics of ponding on sea ice regulates albedo, freshwater storage and surface topography	meltpond fraction, characteristics	5 km; 1km	n/a	1 day; 12 hours	polar oceans	5%

APPENDIX 2C: CLIMATE VARIABILITY SCIENCE REQUIREMENTS (CONTINUED)

Science Requirement	Description	Measurement Requirements	horizontal resolution	vertical resolution	revisit rate	coverage	accuracy
Shore-fast ice extent	Important parameter for coastal processes, human and biological activity, sediment entrainment	extent	200 m; 50 m	n/a	1 week; 1 day	Arctic near-shore areas	200 m
Surface boundary layer fluxes	Determines ice growth and melt and influence of surface layer on the atmospheric column.	W/m2	5km; 1 km	lowest 100m	1 day; 12 hours	polar oceans	2 W/m**2
Sea Ice melt Extent and Seasons	Sea Ice melt Recent observation shows long melting seasons and short freezing seasons that impact the total Arctic sea ice thickness and extent.	melt season duration, melt/refreeze days, melt/ refreeze area and location	10 km; 5 km		1 day; 12 hours	polar oceans	edge detection 5 km
Sea Ice Albedo	Measure/quantify surface albedo over sea ice cover throughout melt season, which is important for assimilation in regional/global model to study feedback processes and forecast changes and trends in sea ice cover.. Recent observation shows long melting s	Integreated surface albedo	25 km; 5 km	n/a	1 day; 12 hours	polar oceans	0.05
Ocean surface topography	Measure global ocean surface height (altimetry) to determine changes in ocean circulation, which could have a significant effect on climate due to the enormous amount of heat stored in the ocean. Use global oceansurface height measurements to detect global sea level variations to test long-term prediction of sea level rise. Altimetry and gravity measurements also reveal changes in subsurface ocean temperature and heat storage.	measure ocean surface topgraphy	Along-track: 10 km; 5 km Cross-track: 100 km;15 km	N/A	15 days; 5 days	global	1 cm
Ocean Surface Currents	Study air/sea interactions coupled to coincident surface winds measurements. Detect El Nino and La Nina onsets with ocean current.	measure mixed scattering layer depth	100 km; 10 km	N/A	10 days; 1 day	global	5 cm/s
Sea surface salinity	Measure sea surface salinity to investigate the interaction between the water cycle, ocean circulation and climate. These processes influence El Niño and La Niña in the tropics, mid latitude subduction, and the large scale overturning circulation driven by changes in high latitudes, and profoundly affect climate variability on all time scales. The sea surface salinity is also a useful constraint for estimating the air-sea freshwater flux, an important component of the hydrological cycle.	measure sea surface salinity	100 km; 10 km	N/A	1 month; 5 days	global	0.2 psu
Deep ocean circulation	Use an ocean general circulation models to combine satellite observations of oceanographic variables at sea surface and of ocean gravity changes with in situ oceanographic observations of deep ocean circulation globally to improve the ability to assess and predict long-term climate trends.	combine satellite and in situ observations of oceanographic variables in general circulation models	100 km; 5 km	Upper 200 m: 10 m; 5 m 200-1000 m depth: 100 m; 25 m 1000 m - bottom: 300m ; 100 m	1 month; 1 week	global and high resolution regional	1 cm/s
Sea surface temperature	Measure global ocean surface temperature in order to model and predict natural climate variations such as El Nino and associated weather disturbances.	measure sea surface temperature	25 km; 1 km		1 day; 3 hours	global	0.3K
Ocean surface winds	Measure ocean surface wind speed and direction in order to: a) determine changes in upper ocean circulation (which has significant effects on climate due to the enormous amount of heat stored in the ocean); b) calculate air-sea fluxes of all quantities (energy, water, gases) which depend on wind-modulated ocean surface roughness and which couple the ocean and atmosphere; c) determine locations, intensities and extent, and the evolution of storms and meteorological phenomena; and d) support improvements to operational marine hazard forecasting and numerical weather and wave prediction.	Measure near-surface wind speed and direction over the entire ice-free oceans under nearly all-weather conditions.	25 km; 1 km	N/A	12 hours; 1 hour	global	Speed 2 m/s, Direction 20 deg

APPENDIX 2D: EARTH SURFACE AND INTERIOR SCIENCE REQUIREMENTS

Science Requirement	Description	Measurement Requirements	horizontal resolution	vertical resolution	revisit rate	coverage	accuracy
Land Surface Topography	Accurate land surface topography is fundamental for achieving a thorough understanding of the solid Earth, how it is changing and the consequences for life on Earth (e.g. earthquakes, volcanic eruptions, sea-level change, floods, etc.)	Measure land surface topography.	10 m;1 m	3 m; 0.5 m	5 years; 3 years	global	3 m; 0.5 m
Land Surface Topography	Accurate land surface topography is fundamental for achieving a thorough understanding of the solid Earth, how it is changing and the consequences for life on Earth (e.g. earthquakes, volcanic eruptions, sea-level change, floods, etc.)	Measure surface topography below vegetation	10 m; 1 m	3 m; 0.5 m	repetitive mapping as needed	global	3 m; 0.5 m
Surface deformation and stress	Measure the deformation and stress accumulation in the Earth's crust before, during, and after seismic events to understand landscape-forming processes. These measurements will also lay the basis for assessment and prediction of geological hazards such as earthquakes and volcanic eruptions.	Measure land surface deformation (strain)	50 m; 1 m	N/A	30 days; continuous	global	Displacement per unit distance: 1E-6; 1E-9 (Also note desire for vector displacement)
Earth Surface Compositions & Chemistry	Resolve the surface attributes and expression of many of the process related to natural and human-induced landscape change, volcanism, tectonics, and ice dynamics. The near-surface materials and their properties often determine a region's susceptibility to natural hazards such as earthquakes, wild fires and volcanic activity.	Measure surface reflectance and emittance for geomorphic feature mapping; stratigraphy, structure and surface dynamics	10 m; 1 m	N/A	One-time baseline mapping and repeated as necessary	global	0.1 dB radiometric
Terrestrial reference frame	Measure the Earth's center of mass to translate raw altimetry measurements (such as ocean surface height) into useful data and, eventually, enable mapping global water mass distribution, ocean bottom pressure, and total ocean transport.	Determine displacement of reference frame with respect to Earth's center of mass.	5000 km; 200 km	N/A	1 week; continuous	global	5 mm; 1 mm
Terrestrial reference frame	Measure the Earth's center of mass to translate raw altimetry measurements (such as ocean surface height) into useful data and, eventually, enable mapping global water mass distribution, ocean bottom pressure, and total ocean transport.	Determine Earth rotation relative to inertial space for Geodetic reference frame components of polar motion and length of day.	5000 km; TBD	N/A	1 week; continuous	global	1 cm; 1 mm
Terrestrial reference frame	Measure the Earth's center of mass to translate raw altimetry measurements (such as ocean surface height) into useful data and, eventually, enable mapping global water mass distribution, ocean bottom pressure, and total ocean transport.	Determine geodetic reference frame components of site positioning and velocity and polar motion.	2000 km; 100 km	N/A	1 week; continuous	global	1 cm; 1 mm
Earth gravity field	Measure the Earth's gravity field to translate raw altimetry measurements (such as ocean surface height) into useful data and, eventually, enable mapping global water mass distribution, ocean bottom pressure, and total ocean transport.	Map the Earth gravitational field (and its variation with time) with high precision. For the static gravity, optimal measurement is that of gravity gradient tensor.	100 km; 50 km	N/A	1 month; continuous	global	2 cm geoid error
Motions of the Earth's interior	Changes in the Earth interior induce significant changes in the shape, rotation and wobbling motion of the Earth. Knowledge of these changes is essential for a variety of applications such as establishing the reference frame for precision geodesy, GPS satellite navigation, and ocean altimetry as well as for understanding the dynamics of the Earth's interior.	Knowledge of the Earth's gravity field, magnetic field, and rotation is needed to probe the Earth's interior. See the measurement requirements for these parameters.	N/A	N/A	N/A	global	N/A
Earth's Magnetic Field	Knowledge of the Earth's magnetic filed provides one of three space-based techniques to probe the Earth's interior (the other two are Earth gravity and rotation).	Map Earth's magnetic field with high accuracy which is important for interannual secular variation measurements.	N/A	N/A	Monthly solution; Solution from several spacecraft with mixed inclinations and altitudes	global	vector field: 1 nanoTesla; magnetic gradient tensor: 0.1 picoTesla/m @ 10Hz

APPENDIX 2E: WATER AND ENERGY CYCLE SCIENCE REQUIREMENTS

Science Requirement	Description	Measurement Requirements	horizontal resolution	vertical resolution	revisit rate	coverage	accuracy
River stage height	Measure river stage height to study regional hydrological impacts of climate change, such as floods, droughts, and water availability.	meaure stage height for major world rivers & inland water bodies	10m	2cm	1 day	global	1cm
River discharge rate	Measure river discharge rate to study regional hydrological impacts of climate change, such as floods, droughts, and water availability.	measure discharge rate for major world rivers & inland water bodies	10m	2cm	1 day	global	15%; 10% of the flow volume
Freeze-thaw transition	Conduct large-scale observations of the transition between frozen and thawed soil conditions to develop a quantitative understanding of hydrologic processes. These processes control river flow, available water resources, surface temperature, and the growth of terrestrial ecosystems.	Measure freeze-thaw transition in all cloud and vegetation conditions.	250 m; 10 m	2cm	12 hours	global	15%; 10%
Snow cover and accumulation	Conduct large-scale observations of snow accumulation and snowpack to develop a quantitative understanding of hydrologic processes. These processes control river flow, available water resources, surface temperature, and the growth of terrestrial ecosystems.	measure snow extent, snow melt onset, snow wetness and duration, snow water equivalent and surface-freeze thaw with and without snow cover. Need ultra-wide 2000km swath	1 km; 500 m	N/A	12 hours	global	10%
Soil moisture	Measure soil moisture, which is a key factor in the global water and energy cycles, climate variations, the ability of ecosystems to support life, large-scale hydrology, and weather prediction.	measure top soil moisture	25 km; 1km	5 cm top soil	2 days; 1 day	global	4 volume percent moisture
Soil moisture	Measure soil moisture, which is a key factor in the global water and energy cycles, climate variations, the ability of ecosystems to support life, large-scale hydrology, and weather prediction.	Model-based inference of soil moisture through root zone of vegetation	25 km; 1 km	50cm; 1 cm top soil	1 month; 1 week	global	TBD; 4 volume percent moisture
Soil moisture	Measure soil moisture, which is a key factor in the global water and energy cycles, climate variations, the ability of ecosystems to support life, large-scale hydrology, and weather prediction.	Measure Deep Soil Moisture	100 m; 30 m	1 m top soil	1 year	global	
Freeze-thaw transition	Large-scale observations of the transition between frozen and thawed soil conditions in prairie and agricultural terrains to improve quantitative monitoring of hydrologic processes. These processes control river flow, available water resources, surface temperature, growth of terrestrial ecosystems, and land-atmosphere moisture fluxes.	measure freeze-thaw transition in all cloud and vegetation conditions.	50 km; 1 km	2 cm	1 week; 12 hours	global	15%; 10%
Snow cover and accumulation	Large-scale observations of snow accumulation and snowpack in prairie and agricultural terrains to improve quantitative monitoring of hydrologic processes. These processes control river flow, available water resources, surface temperature, and the growth of terrestrial ecosystems.	measure snow extent, snow wetness, snow water equivalent, and surface-freeze thaw with and without snow cover in prairie and agricultural terrains.	50 km; 1 km	N/A	1 week; 12 hours	global	10%; 5%
Snow Cover	Measure snowpack properties to develop a quantitative understanding of cold-season hydrologic processes and land-atmosphere energy exchanges at scales ranging from local to global. These processes control river flow, available water resources, atmospheric boundary layer, and affect terrestrial ecosystems.	Measure 1) a real extent of binary snow cover (snow or no snow); 2) percentage of snow cover per unit area (fractional snow cover).	500 m; 100 m	N/A	1 week; 12 hours	Global above 30 degrees latitude and selected mid-latitude areas	1) 5%; 2% 2) 10%; 5%
Snow Water Content	Measure snowpack properties to develop a quantitative understanding of cold-season hydrologic processes and land-atmosphere energy exchanges at scales ranging from local to global. These processes control river flow, available water resources, atmospheric boundary layer, and affect terrestrial ecosystems.	Measure depth of water contained in snowpack (snow water equivalent).	500 m; 100 m	N/A	1 week; 12 hours	Global above 30 degrees latitude and selected lower-latitude areas	5 cm; 2 cm
Snow Wetness	Measure snowpack properties to develop a quantitative understanding of cold-season hydrologic processes and land-atmosphere energy exchanges at scales ranging from local to global. These processes control river flow, available water resources, atmospheric boundary layer, and affect terrestrial ecosystems.	Measure 1) a real extent of binary snow wetness (snow is wet or dry); 2) percentage of liquid water contained in the snowpack.	500 m; 100 m	N/A	1 week; 12 hours	Global above 30 degrees latitude and selected mid-latitude areas	1) 5%; 2% 2) 10%; 5%

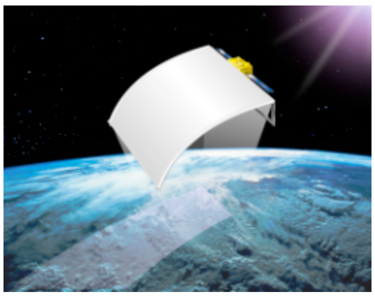
APPENDIX 2F: WEATHER SCIENCE REQUIREMENTS

Science Requirement	Description	Measurement Requirements	horizontal resolution	vertical resolution	revisit rate	coverage	accuracy
Storm cells properties	Measure the three-dimensional structure of atmospheric temperature, moisture, and wind around storm cells to determine the life cycle of mesoscale storms over land and relate that life cycle to atmospheric circulation and climate change.	measure meteorological properties around storms	1 km	250m	10 min	local	Temp: 0.5 deg K Precip: 2 mm/hr
Atmospheric temperature	Measure atmospheric temperature, which determines large-scale atmospheric flow, including weather.	measure atmospheric temperature under all weather conditions & presence of clouds	10 km	0.5 km	12 hours	global	1 K
Atmospheric water vapor	Measure atmospheric water vapor, which is the principal vehicle of atmospheric energy driving weather and precipitation. Water vapor is also a factor in the global water cycle and amplifies the greenhouse effect.	measure atmospheric water vapor (total columnar and profile)	15 km; 1 km	2 km; 0.5 km	6 hours; 30 minutes	global	10%
Global precipitation	Measure global precipitation, which is a principal indicator of the global water cycle rate and is an input for numerical weather forecasting. It is also important to relate global precipitation to climate change.	Global precipitation rate	25km; 1 km	250m	8 hours; 3 Hours	global coverage up to +/-75 latitude band	2 mm/hr
Lightning rate	Measure the rate of lightning strokes to get information about thunderstorms, severe weather, and rainfall; relate climate change to weather systems.	measure lightning rate	10 km	N/A	Continuous staring	Hemisphere	90%
Tropospheric winds	Measure tropospheric winds as a prototype operational application to improve weather forecasting.	measure trop winds with 2-D vector component	100 km	1km mid/upper troposphere, 250m in PBL	6 hours	global	3 m/s; 1 m/s
Ocean surface winds	Measure ocean surface winds to determine changes in ocean circulation, which could have a significant effect on climate due to the enormous amount of heat stored in the ocean. Ocean surface winds also provide a direct measure of storm tracks, strength, and life cycle. This measurement will help relate large-scale atmospheric circulation and climate change to severe weather systems.	measure wind vector field over both ocean and coastal areas; need 200 km single-pass swath	20 km; 1 km	N/A	12 hours	global	speed 2m/s, direction 20deg

APPENDIX 4A ACTIVE ANTENNA TECHNOLOGY ROADMAP

Below are the individual antenna technology roadmaps.

14/35/94-GHz Doppler Precipitation/Cloud Radar



Tasks Needed for 6mx6m cross-track scanning (±35°) reflector

1. Space rigidization reflector structure
2. Longevity of membrane material for space
3. Ka/W-band T/R modules each at 0.75-W power level
4. Ka/W-band phase shifters with low insertion loss
5. Ka/W-band linear feed technologies (dual-polarization with 30-dB cross-pol isolation)
6. Verification method to compensate for gravitational loading (artificial) effect during ground testing
7. Metrology to detect the reflector surface distortion
8. Compensation of distorted reflector surface

Current Status

IIP PR-2 and APRA Tasks:

- 2.7mx2.7m, 0/30° pointing Ku- and Ka-band
- Prototype model complete in 9/04

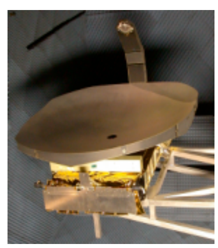
ESSP CloudSat radar:

- 2mx2m, nadir pointing W-band
- Flight model completed in 3/03

Current TRL: 1
IIP Exit TRL: 3

APRA reflector

APRA Ku-band feed

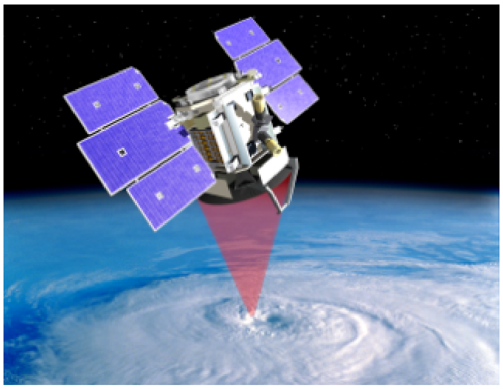


CloudSat antenna

Future Effort for reaching TRL=7

Figure 4A4

94/140 -GHz Doppler Cloud Profiling Radar



Tasks Needed for 2m (dia.) cross-track scanning (±5°) reflector Antenna

1. 94 -GHz T/R modules each at 0.75 -W power level
2. 140 -GHz T/R modules each at 0.5 -W power level
3. 94/140 -GHz phase shifters with low insertion loss
4. 94/140 -GHz linear feed technologies

Current TRL: 1

Current Status

ESSP CloudSat radar:

- 2mx2m, nadir pointing W -band
- Flight model completed in 3/03

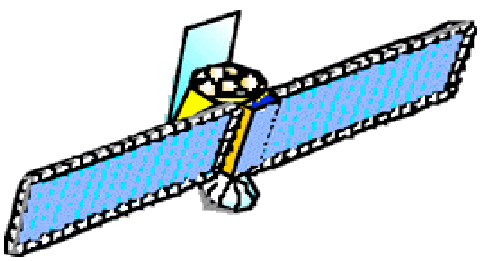
Future Effort for reaching TRL=7

Figure 4A 6

MEO (Medium Earth Orbit) SAR

Current Status

1. Preliminary understanding of inflatable/ rigidizable and deployable structure
2. Preliminary understanding of membrane electronics and radiators



MEO SAR antenna
- 2-D electronic steering
- Minimum area: $400m^2$
- Peak power: >20kW
- Mass density: <$2kg/m^2$
- Rad hard to MEO orbit.

Tasks Needed for MEO SAR

1. Light weight, high efficiency T/R module development
2. Radar architecture [membrane, panel etc.]
3. Light weight, low stowed volume mechanical structure
4. Innovative power and signal distribution
5. Radiation hardening at the MEO radiation environment
6. Subpanel beamforming technology

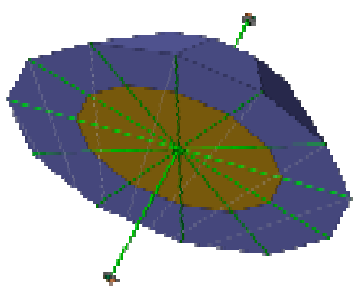
Current TRL: 2
Exit TRL: 4

Figure 4A7

GEO (Geosynchronous Earth Orbit) SAR

Current Status

1. Preliminary understanding of inflatable/ rigidizable and deployable structure
2. Preliminary understanding of membrane electronics and radiators



GEO SAR antenna
- 2-D electronic steering
- Minimum area: 700m ^{2}
- Peak power: >50kW
- Mass density: <1kg/m ^{2}
- Rad hard to GEO orbit.

Tasks Needed for GEO SAR

1. Light weight, high efficiency T/R module development
2. Radar architecture [membrane, panel etc.]
3. Light weight, low stowed volume mechanical structure
4. Innovative power and signal distribution
5. Radiation hardening at the GEO radiation environment
6. Subpanel beamforming technology

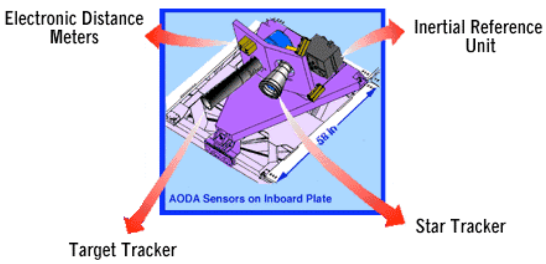
Current TRL: 2
Exit TRL: 4

Figure 4A8

X-band Single Pass Interferometric SAR

Current Status

1. SRTM mast and metrology system



SRTM Mast and metrology system to measure Earth topography
- 7m vertical accuracy
- 10m horizontal accuracy
- 60m mast
- 200 km altitude (Space Shuttle)
- C-band

Tasks Needed for X-band Single Pass InSAR

1. Develop a 100m mast system that is capable of maintaining two X -band antenna for interferometric baseline (azimuth beam overlap)
2. Develop a metrology system to measure the interferometric baseline (knowledge, not real time)
   - Approximately 10 times better than the SRTM system

Current TRL: 4
Exit TRL: 6

Figure 4A9

APPENDIX 4B: ACTIVE ANTENNA TECHNOLOGY CAPABILITY BREAKDOWN STRUCTURE (CBS)

Discussion of Each Level from "The NASA Technology Plan, Appendix B: Technology Readiness Levels", as updated 24 July 2001 The following paragraphs provide a descriptive discussion of each technology readiness level, including an example of the type of activities that would characterize each TRL.

TRL 1: Basic principles observed and reported

This is the lowest "level" of technology maturation. At this level, scientific research begins to be translated into applied research and development. Examples might include studies of basic properties of materials (e.g., tensile strength as a function of temperature for a new fiber).

TRL 2: Technology concept and/or application formulated

Once basic physical principles are observed, then at the next level of maturation, practical applications of those characteristics can be 'invented' or identified. For example, following the observation of high critical temperature (Htc) superconductivity, potential applications of the new material for thin film devices (e.g., SIS mixers) and in instrument systems (e.g., telescope sensors) can be defined. At this level, the application is still speculative: there is not experimental proof or detailed analysis to support the conjecture.

TRL 3: Analytical and experimental critical function and/or characteristic proof-of-concept

At this step in the maturation process, active research and development (R&D) is initiated. This must include both analytical studies to set the technology into an appropriate context and laboratory-based studies to physically validate that the analytical predictions are correct. These studies and experiments should constitute "proof-of-concept" validation of the applications/concepts formulated at TRL 2. For example, a concept for High Energy Density Matter (HEDM) propulsion might depend on slush or super-cooled hydrogen as a propellant: TRL 3 might be attained when the concept-enabling phase/temperature/pressure for the fluid was achieved in a laboratory.

TRL 4: Component and/or breadboard validation in laboratory environment

Following successful "proof-of-concept" work, basic technological elements must be integrated to establish that the "pieces" will work together to achieve concept-enabling levels of performance for a component and/or breadboard. This validation must devised to support the concept that was formulated earlier, and should also be consistent with the requirements of potential system applications. The validation is relatively "low-fidelity" compared to the eventual system: it could be composed of ad hoc discrete components in a laboratory. For example, a TRL 4 demonstration of a new 'fuzzy logic' approach to avionics might consist of testing the algorithms in a partially computer-based, partially bench-top component (e.g., fiber optic gyros) demonstration in a controls lab using simulated vehicle inputs.

TRL 5: Component and/or breadboard validation in relevant environment

At this, the fidelity of the component and/or breadboard being tested has to increase significantly. The basic technological elements must be integrated with reasonably realistic supporting elements so that the total applications (component-level, sub-system level, or system-level) can be tested in a 'simulated' or somewhat realistic environment. From one-to-several new technologies might be involved in the demonstration. For example, a new type of solar photovoltaic material promising higher efficiencies would at this level be used in an actual fabricated solar array 'blanket' that would be integrated with power supplies, supporting structure, etc., and tested in a thermal vacuum chamber with solar simulation capability.

TRL 6 : System/subsystem model or prototype demonstration in a relevant environment (ground or space)

A major step in the level of fidelity of the technology demonstration follows the completion of TRL 5. At TRL 6, a representative model or prototype system or system - which would go well beyond ad hoc, 'patch-cord' or discrete component level breadboarding - would be tested in a relevant environment. At this level, if the only 'relevant environment' is the environment of space, then the model/prototype must be demonstrated in space. Of course, the demonstration should be successful to represent a true TRL 6. The demonstration might represent an actual system application, or it might only be similar to the planned application, but using the same technologies. At this level, several-to-many new technologies might be integrated into the demonstration. For example, a innovative approach to high temperature/low mass radiators, involving liquid droplets and composite materials, would be demonstrated to TRL 6 by actually flying a working, sub-scale (but scaleable) model of the system on a Space Shuttle or International Space Station 'pallet'. In this example, the reason space is the 'relevant' environment is that microgravity plus vacuum plus thermal environment effects will dictate the success/failure of the system - and the only way to validate the technology is in space.

TRL 7: System prototype demonstration in a space environment

TRL 7 is a significant step beyond TRL 6, requiring an actual system prototype demonstration in a space environment. It has not always been implemented in the past. In this case, the prototype should be near or at the scale of the planned operational system and the demonstration must take place in space. The driving purposes for achieving this level of maturity are to assure system engineering and development management confidence (more than for purposes of technology R&D). Therefore, the demonstration must be of a prototype of that application. Not all technologies in all systems will go to this level. TRL 7 would normally only be performed in cases where the technology and/or subsystem application is mission critical and relatively high risk. Example: the Mars Pathfinder Rover is a TRL 7 technology demonstration for future Mars micro-rovers based on that system design. Example: X-vehicles are TRL 7, as are the demonstration projects planned in the New Millennium spacecraft program.

TRL 8: Actual system completed and "flight qualified" through test and demonstration (ground or space)

By definition, all technologies being applied in actual systems go through TRL 8. In almost all cases, this level is the end of true 'system development' for most technology elements. Example: this would include DDT&E through Theoretical First Unit (TFU) for a new reusable launch vehicle. This might include integration of new technology into an existing system. Example: loading and testing successfully a new control algorithm into the onboard computer on Hubble Space Telescope while in orbit.

TRL 9: Actual system "flight proven" through successful mission operations

By definition, all technologies being applied in actual systems go through TRL 9. In almost all cases, the end of last 'bug fixing' aspects of true 'system development'. For example, small fixes/changes to address problems found following launch (through '30 days' or some related date). This might include integration of new technology into an existing system (such operating a new artificial intelligence tool into operational mission control at JSC). This TRL does not include planned product improvement of ongoing or reusable systems. For example, a new engine for an existing RLV would not start at TRL 9: such 'technology' upgrades would start over at the appropriate level in the TRL system

Tech-nology	Measurement Scenario	Instrument Type	Wave-band	Needed Functional Product	Quantitative Requirement	Task	Subtask	Explanation	TRL @ Start	TRL @ End	Development Period (years)	Year Needed (at least 3 years before launch)	POC Name	POC Phone	POC e-mail
Light weight antenna structure (Reflector)/ Multiple frequency/ Adaptive waveform sensing and correction	112, (22), (103), (104), (160), (O2), (161A), (19)	UHF/VHF Polarimetric SAR	UHF/ VHF	Deep soil moisture	Antenna length: 30m; antenna width: 11m at VHF, 3m at UHF	(1) demonstration indicating achievement of 30m circular mesh reflector technology, (2) demonstration of dual long aperture formation on reflector with dual-frequency feed	(1) detailed mechanical design of 30m reflector (currently being done under MOSS IIP), (2) scaled engineering model (12m) of AM-2 reflector technology, which is planned for use in this missions, (3) Component level ground verification of all "new" full-scale components and subsystems in their relevant environment(s), (4) Testing a scaled AM2 antenna system (such as existing 12-meter engineering model) in the relevant launch environment, (5) Establish the remainder of TRL 6 justification by similarity to heritage, (6) 1:10 scaled frequency full antenna system demo and prototype of VHF/UHF feed (currently underway under MOSS IIP), (7) consideration for adding more frequencies to the feed	The path to TRL 6 in the box to the left titled "subtask" could be accomplished at a relatively small cost (not including item (7)) for both reflector and feed. Alternatively, we could build and test a scale reflector model of 12 - 15 meters with full similarity to the mission configuration and predominantly flight representative materials and components for a much greater cost, but it may not make sense since all new engineering and fabrication will have to be redone for the full-size article later. On the high end we would build a dedicated, full-scale protoflight system for qualification testing. This is approximately how Astro has done commercial programs such as Thuraya, where they flew the qualification unit so as not to waste it. This is the most convincing approach, and the engineering and manufacture of the flight unit would be done. This would be at an even greater cost. The TRLs and costs shown for this scenario do not include any activity related to the multiple-frequency (>2) system of item (7) under "subtask."	5	6	2	2006	Moghaddam	734-647-0244	mmoghadd@umich.edu

Tech-nology	Measure-ment Scenario	Instrument Type	Wave-band	Needed Functional Product	Quantitative Requirement	Task	Subtask	Explanation	TRL @ Start	TRL @ End	Development Period (years)	Year Needed (at least 3 years before launch)	POC Name	POC Phone	POC e-mail
Light weight phased array/ Multiple frequency	75, (100), (103), (76), (154), (93), (97)	Dual-frequency (14/35 GHz) Precipitation Radar	14/35 GHz	Precipitation (Rain rate, Doppler velocity and other characteristics)	Size: 5.5m x 5.5m, Antenna type: Phased array or reflector with phased array feeds (14/35 GHz), dual-frequency, dual polarized shared aperture, cross-track scanning (±30°), light weight, and deployable	(1) Space rigidization reflector structure (2) Longevity of membrane material for space (3) Ka-band T/R modules each at 0.75-W power level (4) Ka-band phase shifters with low insertion loss (5) Ka-band linear feed technologies (dual-polarization with 30-dB cross-pol isolation) (6) Verification method to compensate for gravitational loading (artificial) effect during ground testing (7) Metrology to detect the reflector surface distortion (8)Compensation of distorted reflector surface		The current IIP (PR-2) will improve the technology from TRL 3 to TRL 5	5	6	2	2007	Eastwood Im	818-354-0492	eastwood.im@jpl.nasa.gov
Light weight phased array/ Multiple frequency	76, (100), (103), (75), (154), (93), (97), (142), (159)	Tri-frequency (14/35/94 GHz) Precipitation Radar	14/35/94 GHz	Precipitation (Rain rate, Doppler velocity and other characteristics) and Cloud	Size: 5.5m x 5.5m, Antenna type: Phased array or reflector with phased array feeds (14/35/94 GHz), tri-frequency, dual polarized shared aperture, cross-track scanning (±30°), light weight, and deployable	(1) Space rigidization reflector structure (2) Longevity of membrane material for space (3) Ka/W-band T/R modules each at 0.75-W power level (4) Ka/W-band phase shifters with low insertion loss (5) Ka/W-band linear feed technologies (dual-polarization with 30-dB cross-pol isolation) (6) Verification method to compensate for gravitational loading (artificial) effect during ground testing (7) Metrology to detect the reflector surface distortion (8) Compensation of distorted reflector surface		The current IIP (PR-2) will improve the technology from TRL 1 to TRL 3	4	6	4	2009	Eastwood Im	818-354-0493	eastwood.im@jpl.nasa.gov
Light weight structure/ Phased array feed	160, (112)	Doppler rain profiling radar (35 GHz, Geostationary)	35 GHz	Precipitation (Rain rate, Doppler velocity and other characteristics)	Size: 30m , Antenna type: Spherical reflector antenna and a pair of spiral-scan feeds (4 degrees scan angle)	(1) Light weight, rigid, deployable spherical reflector (2) Longevity of membrane/mesh material for space (3) Innovative low-loss power dividing network Ka-band low-loss planar array feed technologies (4) Innovative electro-mechanism for spiral scanning for twin array feeds (5) Ground testing and verification method (hybrid of measurements and simulation) (6) Verification method to compensate for gravitational loading (artificial) effect during ground testing (7) Metrology to detect the reflector surface distortion (8) Adaptive compensation of distorted reflector surface		The current IIP (INexrad-In-Space (NIS)) will improve the technology from TRL 2 to TRL 4	5	6	4	2012	Eastwood Im	818-354-0494	eastwood.im@jpl.nasa.gov

Tech-nology	Measurement Scenario	Instrument Type	Wave-band	Needed Functional Product	Quantitative Requirement	Task	Subtask	Explanation	TRL @ Start	TRL @ End	Development Period (years)	Year Needed (at least 3 years before launch)	POC Name	POC Phone	POC e-mail
Phased array feed/ Efficient T/R modules	159, (76)	Dual frequency scanning cloud profiling radar (94/140 GHz)	94/140 GHz	Cloud Profile	Size: 2m, Antenna type: phased array (+/- 5 deg. Cross track scanning), Efficient T/R modules and low loss phase-shifters at both frequencies	(1) 94-GHz T/R modules each at 0.75-W power level (2) 140-GHz T/R modules each at 0.5-W power level (3) 94/140-GHz phase shifters with low insertion loss (4) 94/140-GHz linear feed technologies			1	6	6	2010	Eastwood Im	818-354-0495	eastwood.im@jpl.nasa.gov
Light weight structure/ Light weight phased array	45	SAR (L-band, MEO)	L-band	Surface deformation and land topography	Electronically 2-D Scanned Phase Array Antenna 400 sq.m., >20kW peak power; <2kg/m2; Rad hard to MEO orbit.	Develop lightweight ESA antenna concept, including power & signal distribution	1) T/R modules; 2) architecture [membrane, panel etc.]; 3) mechanical structure; 4) power, signal distribution; 5) Radiation hardening; 6) and subpanel beamforming.	This activity requires that many interrelated technology elements are addressed [see previous box.] Best approach is technically not well defined at this point.	2	4	3	2008	Soren Madsen	818-393-2913	soren.n.madsen@jpl.nasa.gov
Light weight structure/ Light weight phased array	46	SAR (L-band, GEO)	L-band	Surface deformation and land topography	Electronically 2-D Scanned Phase Array Antenna >700 sq.m., >50kW peak power; <1kg/m2; Rad hard to GEOsync orbit.	Develop lightweight ESA antenna concept, including power & signal distribution	1) T/R modules; 2) architecture [membrane, panel etc.]; 3) mechanical structure; 4) power, signal distribution; 5) Radiation hardening; 6) and subpanel beamforming.	This activity requires that many interrelated technology elements are addressed [see previous box.] Best approach is technically not well defined at this point.	2	4	5	2012	Soren Madsen	818-393-2914	soren.n.madsen@jpl.nasa.gov
Lighweight structure/ Metrology	163	X-band Single Pass Interferometric SAR	X-band	High resolution topography (DTED 3-4)	Two X-band antennas (size: 15m x 1m) connected by a dual deployed 100m mast to form an interferometric baseline; Metrology system to measure the interferometric baseline (10-20 times better than the SRTM metrology)	Develop a 100m mast system that is capable of maintaining two X-band antenna for interferometric baseline (azimuth beam overlap). Develop a metrology system to measure the interferometric baseline (knowledge, not real time)			4	6	3	2010	Yunjin Kim	818-354-9500	yunjin.kim@jpl.nasa.gov

Appendix 4C: Active Electronics Requirements For Each Scenario

Below a tabular summary is provided of the requirements for each scenario in the active electronics section 4.1.2.1.

4C - Radar Technology Requirements Derived from ESTIPS database

Measurement Parameter	Scenario ID	Sensor type	Antenna Technology Requirements	Radar Electronics Requirements	Comments
			Hydrology		
Freeze-thaw	22	L-band dual polarization SAR	Size: 10-15m x 2-3 m Antenna type: Reflector (larger swath) or phased array High efficiency T/R modules	80 MHz DCG 3-5KW (150 x 30W T/R mod) 3dB system NF 8-bit, 250 MHz ADC Data: digital filters, BFPQ Radiation & Life: <20kRad, 3 yrs feasible now but expensive	Enhancing Technology (S. Madsen, 01-21-04)
River stage height, River discharge rate	100	Ka-band along/across track interferometric SAR (50-100km swath)	Size: 5-10 m along-track dimension Antenna type: Phased array 3-beam antenna (multiple low-loss feed network) Ka-band high efficiency T/R modules or low-loss feed network	80MHz bandwidth chirp 1kW Klystron or distr Ka-band phase stable T/R modules 4dB System NF 300kbits/sec ADC Phase stable receivers LNA, switches & phase shifters (SiGe, GaN, InP devices) Radiation & Life: <20Krad, 3yrs	Enabling Technology (E. Rodriguez 1/29/04)
Snow cover, accumulation, and water equivalent	102	Ku-band polarimetric real aperture radar - (scatterometer 2000km swath)	Size: > 3m diameter Antenna type: Spinning reflector antenna (high aperture efficiency (>80%) at Ku-band)	<5MHz BW DCG <500W Ku-band TWTA Reduced mass, power and cost compared to SeaWinds	Technology Mature (S. Yueh, 2/9/04)
Snow cover, accumulation, and water equivalent	103	Ku-band polarimetric interferometric SAR (500km swath, 10-50m baseline)	Size: 5m Antenna type: Steering reflector (phased array feed) or phased array (if radiometer is not needed) Ku-band High efficiency T/R modules	80MHz DCG Peak Tx Pwr: >2KW (250 x 10W Ku-band phase stable T/R mods) Sys NF: 3dB Phase stable receivers, baseline knowledge Radiation & Life: <20Krad, 5yrs	Enabling Technology (S. Yueh, 2/9/04, recommends deleting this scenario)

Snow cover, accumulation, and water equivalent	104	Ku-band polarimetric interferometric SAR+L-band polarimetric SAR (80MHz bandwidth)	Size: 10m for L-band, 5m for Ku-band Antenna type: Steering reflector (phased array feed) or phased array (if radiometer is not needed) L- and Ku-band High efficiency T/R modules	80MHz DCG Peak Tx Pwr: >2KW (250 x 10W phase stable Ku & L-band T/R mods) Sys NF: 3dB Phase stable receivers, baseline knowledge Radiation & Life: <20Krad, 5yrs	Enabling Technology (S. Yueh, 2/9/04, recommends deleting this scenario)
Snow cover, accumulation, and water equivalent	105	Wide Swath Ku/L-band Polarimetric SAR	Size: 10m for L-band, 5m for Ku-band Antenna type: Steering reflector (phased array feed) or phased array (if radiometer is not needed) L- and Ku-band High efficiency T/R modules & low cost antenna technology	80MHz DCG Peak Tx Pwr: >2KW (250 x 10W Ku & L-band T/R mods) Sys NF: 3dB Radiation & Life: <20Krad, 5yrs Cost cutting technologies, low power electronics	Enhancing Technology (S. Yueh, 2/9/04)
Soil moisture (deep)	112	UHF/VHF polarimetric SAR (1km resolution)	Size: 30m x 11m aperture at VHF and 30m x 3m aperture at UHF Antenna type: Reflector antenna with array feeds (dual frequency) or phased array (1MHz bandwidth at UHF)	1MHz BW AWG to enable frequency notching or alternative waveforms. 5KW peak Tx power 4dB System NF 0.1dB relative 0.5 dB absolute calibration Radiation & Life: 20krad 3 years primary challenge is in antenna	Enabling Technology - Antenna (E. Rodriguez, 01-29-04)
Snow cover, accumulation, and water equivalent, Sea ice thickness	151	Radar for rover (in-situ sensing)	Ultra-wideband antenna	Low mass and low power electronics	Technology Mature
			Atmosphere		
Atmospheric water vapor, Ozone vertical profile	68	Atmospheric occultation (1 km vertical resolution, horizontal resolution of 200 km) 10-22 GHz, 183 GHz, 195 GHz, and above plus GPS L1 and L2	Size: 30 cm diameter antenna	183 GHz power generation (10mW) (ESSP concept)	Enhancing Technology (C. Zuffada, 1/23/04)

Cloud system structure, Cloud particle properties and distribution	142	Cloud Profiling Radar (94 GHz nadir-looking radar which measures the power backscattered by cloud liquid and ice particles as a function of distance. Instrument may include Doppler measurement)	Size: 3m Antenna type: Deployable 94 GHz antenna	3.3-μs pulsed CW, Peak Tx Pwr: 10KW EIKA Sys NF: 5 dB ADC: >12-bit Calib: 2 dB Data Handling: 300 Kbps Radiation & Life: 10KRad Mass: 300 Kg DC Power: 300 W	Enhancing Technology (E. Im, 2/12/04)
Global precipitation	75	Dual-Frequency Precipitation Radar (14/35-GHz), co- and x-pol reflectivity and Doppler velocity cross-track scanning: > +/-25 degrees (both frequencies) Preferred light-weight, deployable antenna radar design to support long-term observations.	Size: 5.5m x 5.5m Antenna type: Phased array or reflector with phased array feeds (14/35 GHz), dual-frequency, dual polarized shared aperture, cross-track scanning (±30°), light weight, and deployable	4 MHz chirp, -60 dB sidelobe Peak Tx Pwr: <200W (1W Ka-band T/R modules), Sys NF: 5 dB, ADC: >12-bit Calib: 2 dB, Data Handling: on-board proc Radiation & Life: 10KRad Mass: 280 Kg DC Power: 300 W Integrated dual-freq electronics	Enabling Technology (E. Im, 2/12/04)
Global precipitation	76	Tri-Frequency Precipitation Radar (14/35/94 GHz) HH and HV-polarization, 94 GHz for cloud patterns, Doppler	Size: 5.5m x 5.5m Antenna type: Phased array or reflector with phased array feeds (14/35/94 GHz), tril-frequency, dual polarized shared aperture, cross-track scanning (±30°), light weight, and deployable	4 MHz chirp, -60 dB sidelobe Peak Tx Pwr: <200W (1W Ka-band T/R modules) Peak Tx Pwr: <100W (0.5W 95GHz T/R modules) Sys NF: 6 dB, ADC: >12-bit Calib: 2 dB Data Handling: on-board proc Radiation & Life: 10Krad Mass: 300 Kg DC Power: 350 W Integrated tri-freq electronics 2dB W-band phase shifters digital beamforming	Enabling Technology (E. Im, 2/12/04)

Global precipitation	154	Differential Frequency Precipitation Radar (35 GHz with 10% separation) 4.3 km horizontal, 250 m vertical resolution, cross-track scan +/-5 degrees of nadir	Size: 1m – 2m (100 –200 wavelengths) Antenna type: Dual frequency scanning reflector or phased array (+/- 5 degrees) Better than 0.1 degree match in pointing and beamwidth	BW & waveform: 10% BW Peak Tx Pwr: 1KW EIKA	Enhancing Technology
Global precipitation, Storm cells properties	160	Doppler rain profiling radar (35 GHz, Geostationary orbit)	Size: 35m Antenna type: Spherical reflector antenna and a pair of spiral-scan feeds (4 degrees scan angle)	2 MHz chirp, -60 dB sidelobe >300W EIKA or TWTA Sys NF: 5 dB system NF >12-bit ADC Calib: 2 dB Data Handling: on-board proc Radiation requirement same as GOES, 10 year lifetime DC Power: < 280 W	Enabling Technology (E. Im, 2/12/04)
Global precipitation, Storm cells properties	155	Precipitation and cloud profiling UAV radar (10, 13.8, and 94 GHz)	Size: ~50 cm	Small, low power electronics	Technology Mature
Cloud system structure, Cloud particle properties and distribution, Aerosol properties	156	Cloud Profiling Radar (94 GHz, constellation of stratospheric long- duration balloons)	Size: unspecified (less than CloudSat)	Mmw radar (similar to Cloudsat) < 70kg	Technology Mature
Cloud system structure, Cloud particle properties and distribution	159	Dual-frequency scanning cloud profiling radar (94/140 GHz)	Size: 2m Antenna type: phased array (+/- 5 deg. Cross track scanning) Efficient T/R modules and low loss phase-shifters at both frequencies	94 GHz Peak transmit power <100W (0.5W 95GHz T/R modules) & 140GHz peak transmit power <100W (0.8W 140GHz T/R modules) 94 & 140GHz devices: PA, LNA, phase shifters Sys NF: 6 dB (94GHz); 7 dB (140 GHz) >12-bit ADC, low sidelobe 2 MHz chirp,-60dB sidelobe Calib: 2 dB Data Handling: on-board proc Radiation & Life: 10Krad DC Power: 350 W	Enabling Technology (E. Im, 2/12/04)

Oceans					
Ocean surface current	O2	Delta-k radar at geostationary orbit (X or Ku)	Size: 10m Antenna type: reflector	1KW X-band TWTA Small, low power, rad-hard electronics	Enhancing Technology
Ocean surface topography	28	Ka-band synthetic aperture altimeter	Size: 1.5m Antenna type: reflector Phased array? T/R Modules?	320 MHz chirp 1W Peak Tx Pwr (?) 4dB Sys NF 800kbit/sec ADC (Deramp) 1mm/year timing stability Data Handling: onboard processing Radiation & Life: 5 year <80Krad	Enhancing Technology (E. Rodriguez, 01-29-04)
Ocean surface topography	29	Ku-band interferometric radar (10m baseline)	Size: 0.5m x 5.0m Antenna type: Slotted waveguide array/Reflectarray (no scanning is required)	20MHz chirp 200 W Peak Tx Pwr TWTA 4dB Sys NF ADC: 32 MBytes/sec, 8-bit 0.1 deg deviation over 80 seconds calibration Data Handling: Onboard range compression Radiation & Life: <80Krad 5 years	Technology Mature (E. Rodriguez, 01-29-04)
Ocean surface winds	61	Ku-band polarimetric scatterometer	Size: 1m Antenna type: spinning reflector antenna (multiple beams)	SeaWinds follow-on. No new technology required.	Technology Mature
Ocean surface winds	148	Ku-band polarimetric scatterometer at MEO	Size: 3-10m Antenna type: spinning reflector antenna (multiple beams)	Rad-hard electronics to 35Krad (behind 300 mil aluminum)	Enhancing Technology (less than 6m) Enabling Technology (larger than 6m)
Ocean surface topography	30	GPS reflection (L1 and L2)	Size: 4-5m Antenna type: Steerable phased array (up to 10-beams)	Advanced receiver architecture to add many (perhaps thousands) of correlators.	Enhancing Technology (J. Zumberge, 01-23-04)
Cryosphere					
Polar ice sheet/glacier velocity	92	L-band Interferometric SAR	Size: 14-m x 3-m Antenna type: Phased array antenna 4KW peak transmit power Efficient T/R modules Low loss phase-shifters	BW & waveform: 80MHz DCG Peak Tx Pwr: 3-5 KW Sys NF: 3dB ADC: >10-bit, 250MHz Data: digital filters, BFPQ Radiation & Life: <20kRad, 5 yrs feasible now but expensive	Enhancing Technology (S. Madsen, 1/29/04)

Ice surface topography	93	Single pass interferometric SAR (Ku-band, baseline:10m)	Size: 0.5m x 5.0m Antenna type: Phased array (for higher transmit power)	similar to WSOA; phase stable Ku-band T/R modules	Enhancing Technology (E. Rodriguez, 01-29-04)
Sea ice extent/motion	90	Real aperture radar (scatterometer) Ku-band	Size: > 3m Antenna type: Spinning antenna or phased array	Similar to SeaWinds; No new technology required	Technology Mature
Sea ice motion and deformation (high resolution)	C1	Wide-swath Sea Ice Motion SAR (C-band, dual polarization HH & VV)	Size: 15m X 3m Antenna type: Phased array	Similar to Radarsat; 10MHz BW DCG >4KW peak transmit power (60% efficiency C-band T/R mod) ScanSAR	Enhancing Technology (R. Kwok, 1/29/04)
Sea ice thickness	97	Single pass interferometric SAR (Ka-band (35 GHz)	Size: 0.5m x 5.0m Antenna type: Reflectarray 10m interferometric baseline	200 MHz BW chirp 1.5 KW peak Tx power (EIKA) 4dB Sys NF 4-bit, 500MHz ADC Phase stability to 0.1 deg over 1 min On-board range compression Radiation & Life: <20kRad, 5 yrs	Enhancing Technology (E. Rodriguez, 01-29-04)
Sea ice thickness	161A	Space and frequency domain interferometic bistatic radar (Ku-band and dual frequency VHF (137 and 157 MHz), and dual-polarization)	Size: 10m x 5m Antenna type: Reflector antenna with dual frequency and dual polarization phased array feed (scanning angle range?) Ku-band phased array feed	low loss, low power Ku-band phase shifters	Enhancing Technology
Sea ice thickness	161B	Ultra wideband radar (formation flying UAV's, UHF and VHF)	Ultra wideband antenna (airborne) (example: 50 to 250 MHz and 300-1300 MHz)	Airborne technology exists Wideband chirp generator & ADC	Enhancing Technology
Snow thickness	161C	Ultra wideband radar (formation flying UAV's, L-, S-, and C-bands)	Ultra wideband antenna (airborne) (example: 1-8 GHz)	Airborne radar technology exists. Wideband chirp generator & ADC	Enhancing Technology

Solid Earth & Carbon					
Surface deformation and stress	44a	LEO Interferometric SAR (L-band, single polarization, polarimetric desired)	Size: 15m x 3m Antenna type: Phased array (steering of +/- 15deg) 6-8 kg/m2	80 MHz DCG 3-8KW transmit power (T/R mod) 3dB system NF 8-10-bit, 250 MHz ADC Data: digital filters, M:N BFPQ Radiation & Life: <60kRad, 5 yrs	Enhancing Technology (S. Madsen, 1/29/04)
Land Surface Topography	44b	Two formation flying LEO L-band synthetic aperture radars (single polarization, polarimetric desired)	Size: 15m x 3m Antenna type: Phased array (steering of +/- 15deg) 6-8 kg/m2	Local oscillator synch by GPS 80MHz BW DCG 3-8KW transmit power (T/R mod)3dB system NF 8-10-bit, 250MHz ADC Digital filters, M:N BFPQ <60Krad	Enhancing Technology (S. Madsen, 1/29/04)
Surface deformation and stress, Land Surface Topography	45	MEO L-band InSAR (formation flying for topography, single polarization, polarimetric desired))	Size: 40m x 10m Antenna type: Phased array (flatness: wavelength/20, elevation steering: +/- 40 deg., azimuth steering: +/- 10-30 deg. desired) 2-3 kg/m2 Radiation protection (T/R modules and antenna electronics) Metrology	80MHz BW low power, single chip DCG 20KW peak transmit power (integrated, high eff, low cost, rad-hard T/R modules) 3dB system NF 8-10 bit, 250MHz ADC Digital filters, M:N BFPQ TTD elements, digital beamforming processor >1Mrad, 10 years life thermal management	Enabling Technology (S. Madsen, 1/29/04)
Surface deformation and stress, Land Surface Topography	46	Constellation of L-band geosynchronous InSAR (single polarization, quad polarization (optional))	Size: ~30m x 30m (>700 meter square) Antenna type: Phased array or reflector with scanning capability (flatness: wavelength/20, +/-8 steering in 2-D 1-2 kg/m2 Radiation protection Digital beam-forming Metrology	80MHz BW low power, single chip DCG >65KW peak transmit power (integrated, high eff, low cost, rad-hard T/R modules) 3dB system NF 8-10 bit, 250MHz ADC Digital filters, M:N BFPQ TTD elements, digital beamforming processor thermal management >1Mrad, 10 years life	Enabling Technology (S. Madsen, 01-21-04)

Surface deformation and stress, Land Surface Topography	47	Airborne InSAR (L-band, single polarization, polarimetric desired, UAV)	Size: 2m x 0.5m Antenna type: Phased array (flatness: wavelength/20, azimuth steering of +/- 15 deg.) Peak transmit power: >10kW	80-160MHz bandwidth AWG, 2KW peak Tx power (50-100W T/R modules) 12-bit, >300 MHz ADC digital filters, 12:4 BFPQ precision flight path (10m tube)	Enhancing Technology (S. Madsen, 1/29/04)
Land Surface Topography	163	X-band single pass InSAR (100m baseline, 100-200MHz bandwidth, and single polarization)	Size: 15m x 1m Antenna type: Phased array (flatness: wavelength/20, elevation steering of +/- 15 deg., azimuth steering for beam alignment), Peak transmit power: 2-5 kW, 100m lightweight stable boom	300MHz low power DCG 2-5KW peak transmit power (10W T/R modules) 3dB sys NF 8-10 bit, 1GHz ADC Interferometric calibration Antenna flatness and baseline metrology Data: digital filters, M:N BFPQ Radiation & Life: <20Krad, 5yrs	Enabling Technology (S. Madsen, 1/29/04)
Biomass	19	P-band SAR	Size 10m X 3-5m Antenna type: Phased array or reflector (steering angle?)	6MHz bandwidth AWG to enable frequency notching or alternative waveforms for RFI mitigation. High dynamic range ADC (>10-bits) and digital filters. Feasible now but expensive.	Enhancing Technology (S. Madsen, 1/29/04)
Biomass	157	Airborne repeat-pass interferometric L-band polarimetric SAR (multiple altitude, UAV)	Antenna size: 2 m x 0.5 m Antenna type: Phased array (azimuth steering up to +/- 15º)	80-160MHz bandwidth AWG, 2KW peak Tx power (50-100W T/R modules) 12-bit, >300 MHz ADC digital filters, 12:4 BFPQ precision flight path (10m tube)	Enhancing Technology (S. Madsen, 01-21-04)

APPENDIX 4D: ACTIVE MICROWAVE TECHNOLOGY CHALLENGES

				S/C Technology					Antenna Technologies								Radar Electronics Technologies								Radar System Technologies									Precision Control			Advanced Comm	
Measurement Parameter	Measuremen Scenario	Radar Utility	Radar approach	Efficient Power Generation	Large onboard data storage	Real time onboard processing	High performance RHP	Processing algorithms	Lightweight Antenna Structure	Lightweight deployables (delete)	B. Antenna Radiator: Lighweight Phase Array	Hi.eff. reflectarray	Phase array feed for reflector-type antennas	Multiple Feeds	Large deployable rotating reflector	Multiple Frequency antenna	High efficiency T/R modules (P, L, C, Ku, Ka, W-band)	Adaptive wavefront sensing and correction technology	Low power, high speed, rad-hard arbitrary waveform generator	High power transmitter from P-band to W-band	MMIC Devices: PA, LNA, phase shifter, switches	RF, Power, Control Distribution for Phased Arrays	Low power, high speed ADC	Thermal control for phased arrays	2D electronic beam scanning and multiple beams	Digital beam forming, multiple phase centers, and per panel A/D	Mechanical beam scanning	Polarimetric calibration/channel isolation (ionospheric correction)	Interferometric calibration/channel isolation (ionospheric and tropospheric correction)	Metrology, Antenna deformation compensation techniques	Formation flying of multiple radar platforms	Multi-static radar	Active/passive integrated microwave, aperture sharing	Precision attitude knowledge/cross track	Precision Nav, Orbit Determination	Precision Antenna Pointing	Multi-platform comm	High rate downlink
Freeze-thaw	22	1	L-band dual polarization SAR						CR	CR	CR		CR				CR		CR			CR	CR				CR	CR										
River stage height, River discharge rate	100	1,2	Ka-band along/across track interferometric SAR							CR	CR						E		CR	E	E	CR		E	E	CR	E		E									
Snow cover, accumulation, and water equivalent	102	1,2	Ku-band polarimetric scatterometer							CR					CR					CR							CR	CR					CR					
Snow cover, accumulation, and water equivalent	103	1,2	Ku-band polarimetric interferometric SAR						CR	CR	CR	CR	CR				E		CR		CR	CR	CR	E	CR		E		E				CR					
Snow cover, accumulation, and water equivalent	104	1,2	Ku-band polarimetric interferometric SAR+L-band polarimetric SAR						CR	CR	CR	CR	CR			CR	E		CR		CR	CR	CR	E	CR		CR		E				CR					
Snow cover, accumulation, and water equivalent	105	1,2	Ku/L-band Polarimetric SAR						CR	CR	CR	CR	CR			CR	E		CR			CR	CR	CR	CR		CR	CR					CR					
Snow cover, accumulation, and water equivalent, Sea ice thickness	151	1	Radar for rover													CR																						

APPENDIX 4D: RADAR TECHNOLOGY CHALLENGE

				S/C Technology					Antenna Technologies								Radar Electronics Technologies								Radar System Technologies									Precision Control			Advanced Comm	
Measurement Parameter	Measuremen Scenario	Radar Utility	Radar approach	Efficient Power Generation	Large onboard data storage	Real time onboard processing	High performance RHP	Processing algorithms	Lightweight Antenna Structure	Lightweight deployables (delete)	B. Antenna Radiator: Lighweight Phase Array	Hi.eff. reflectarray	Phase array feed for reflector-type antennas	Multiple Feeds	Large deployable rotating reflector	Multiple Frequency antenna	High efficiency T/R modules (P, L, C, Ku, Ka, W-band)	Adaptive wavefront sensing and correction technology	Low power, high speed, rad-hard arbitrary waveform generator	High power transmitter from P-band to W-band	MMIC Devices: PA, LNA, phase shifter, switches	RF, Power, Control Distribution for Phased Arrays	Low power, high speed ADC	Thermal control for phased arrays	2D electronic beam scanning and multiple beams	Digital beam forming, multiple phase centers, and per panel A/D	Mechanical beam scanning	Polarimetric calibration/channel isolation (ionospheric correction)	Interferometric calibration/channel isolation (ionospheric and tropospheric correction)	Metrology, Antenna deformation compensation techniques	Formation flying of multiple radar platforms	Multi-static radar	Active/passive integrated microwave, aperture sharing	Precision attitude knowledge/cross track	Precision Nav, Orbit Determination	Precision Antenna Pointing	Multi-platform comm	High rate downlink
Soil moisture (deep)	112	1,2	UHF/VHF polarimetric SAR						E	E	E		E	E		CR	CR										CR	E			CR		CR					
Atmospheric water vapor, Ozone vertical profile	68	1,2	Atmospheric occultation													CR					E																	
Cloud system structure, Cloud particle properties and distribution	142	1	94GHz Cloud Profiling Radar							CR										E	CR																	
Global precipitation	75	1,2	14/35GHz Precipitation Radar						E	E	E		E			E	E		CR	CR	CR	CR			E		E											
Global precipitation	76	1,2	14/35/94GHz Precipitation Radar						E	E	E		E			E	E		CR	CR	E	CR			E	CR	E											
Global precipitation	154	1,2	35GHz Differential Frequency Precipitation Radar							CR	CR		CR			CR	CR		E	CR			CR		CR		CR											
Global precipitation, Storm cells properties	160	1	35GHz Doppler rain profiling radar						E	E			E	E				E	CR	CR	CR				E													

APPENDIX 4D: RADAR TECHNOLOGY CHALLENGE

				S/C Technology					Antenna Technologies								Radar Electronics Technologies								Radar System Technologies									Precision Control			Advanced Comm	
Measurement Parameter	Measuremen Scenario	Radar Utility	Radar approach	Efficient Power Generation	Large onboard data storage	Real time onboard processing	High performance RHP	Processing algorithms	Lightweight Antenna Structure	Lightweight deployables (delete)	B. Antenna Radiator: Lighweight Phase Array	Hi.eff. reflectarray	Phase array feed for reflector-type antennas	Multiple Feeds	Large deployable rotating reflector	Multiple Frequency antenna	High efficiency T/R modules (P, L, C, Ku, Ka, W-band)	Adaptive wavefront sensing and correction technology	Low power, high speed, rad-hard arbitrary waveform generator	High power transmitter from P-band to W-band	MMIC Devices: PA, LNA, phase shifter, switches	RF, Power, Control Distribution for Phased Arrays	Low power, high speed ADC	Thermal control for phased arrays	2D electronic beam scanning and multiple beams	Digital beam forming, multiple phase centers, and per panel A/D	Mechanical beam scanning	Polarimetric calibration/channel isolation (ionospheric correction)	Interferometric calibration/channel isolation (ionospheric and tropospheric correction)	Metrology, Antenna deformation compensation techniques	Formation flying of multiple radar platforms	Multi-static radar	Active/passive integrated microwave, aperture sharing	Precision attitude knowledge/cross track	Precision Nav, Orbit Determination	Precision Antenna Pointing	Multi-platform comm	High rate downlink
Global precipitation, Storm cells properties	155	1,2	Dual freq mmw precipitation and cloud profiling UAV radar													CR																						
Cloud system structure, Cloud particle properties and distribution, Aerosol properties	156	1,2	Cloud Profiling Radar (94 GHz, constellation of stratospheric long-duration balloons)																																			
Cloud system structure, Cloud particle properties and distribution	159	1,2	94/140GHz scanning cloud profiling radar								E		E			E	E		CR		E	CR			CR													
Ocean surface topography	28	1	Ka-band synthetic aperture altimeter																E																			
Ocean surface topography	29	1	Ku-band interferometric altimeter							CR		CR							CR										CR	CR								
Ocean surface topography	30	2	GPS reflection (L1 and L2)						CR	CR			CR	CR									CR		CR													
Ocean surface winds	61	1,2	Ku-band polarimetric scatterometer																																			
Ocean surface winds	148	1,2	Ku-band polarimetric scatterometer at MEO							CR					E				CR	CR	CR		CR										CR					

APPENDIX 4D: RADAR TECHNOLOGY CHALLENGE (CONTINUED)

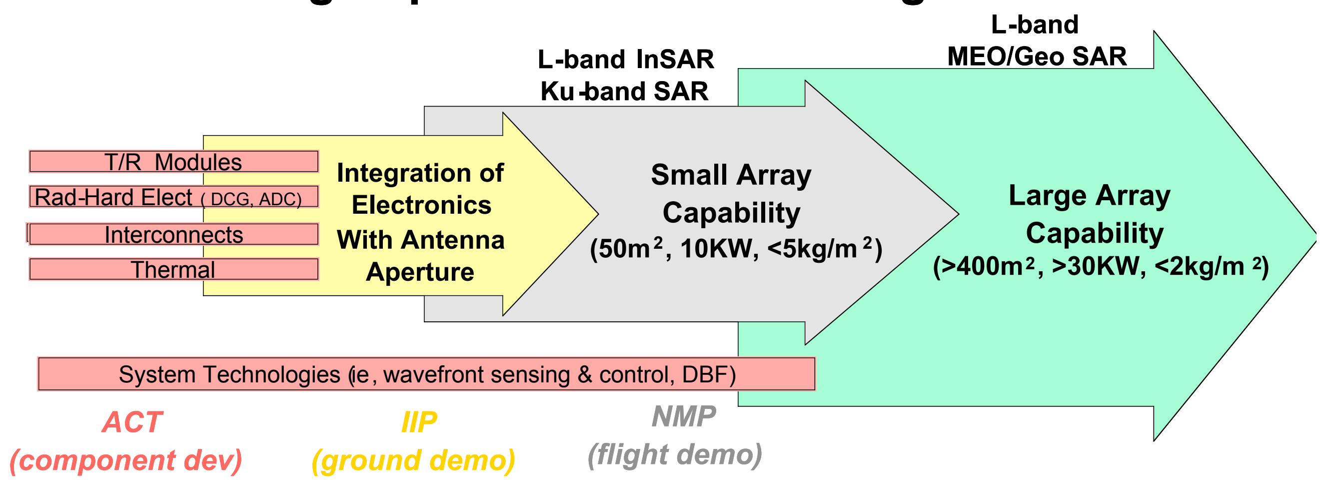
				S/C Technology					Antenna Technologies								Radar Electronics Technologies								Radar System Technologies									Precision Control			Advanced Comm	
Measurement Parameter	Measuremen Scenario	Radar Utility	Radar approach	Efficient Power Generation	Large onboard data storage	Real time onboard processing	High performance RHP	Processing algorithms	Lightweight Antenna Structure	Lightweight deployables (delete)	B. Antenna Radiator: Lighweight Phase Array	Hi.eff. reflectarray	Phase array feed for reflector-type antennas	Multiple Feeds	Large deployable rotating reflector	Multiple Frequency antenna	High efficiency T/R modules (P, L, C, Ku, Ka, W-band)	Adaptive wavefront sensing and correction technology	Low power, high speed, rad-hard arbitrary waveform generator	High power transmitter from P-band to W-band	MMIC Devices: PA, LNA, phase shifter, switches	RF, Power, Control Distribution for Phased Arrays	Low power, high speed ADC	Thermal control for phased arrays	2D electronic beam scanning and multiple beams	Digital beam forming, multiple phase centers, and per panel A/D	Mechanical beam scanning	Polarimetric calibration/channel isolation (ionospheric correction)	Interferometric calibration/channel isolation (ionospheric and tropospheric correction)	Metrology, Antenna deformation compensation techniques	Formation flying of multiple radar platforms	Multi-static radar	Active/passive integrated microwave, aperture sharing	Precision attitude knowledge/cross track	Precision Nav, Orbit Determination	Precision Antenna Pointing	Multi-platform comm	High rate downlink
Sea ice extent/motion	90	1,2	Ku-band real aperture scatterometer							CR					CR																							
Sea ice motion and deformation	C1	1,2	Wide-swath Sea Ice Motion C-Band SAR						CR	CR	CR						CR		CR			CR	CR	CR	CR		CR											
Sea ice thickness	97	1,2	Ka-band single pass interferometric SAR							CR	CR								CR	E	CR		CR	E					E									
Sea ice thickness	161A	1,2	VHF/Ku-band space and frequency domain interferometic bistatic radar						CR	CR			CR	CR		CR	CR		CR		CR								E			E	E					
Sea ice thickness	161B	1,2	VHF/UHF ultra wideband bistatic radar (formation flying UAV's)													CR			CR				CR									E						
Snow thickness	161C	1,2	L/S/C-Band ultra wideband bistatoc radar (formation flying UAV's)													CR			CR				CR									E						
Surface deformation and stress	44a	1	LEO L-band InSAR						CR	CR	CR						CR		CR			CR	CR	CR	CR	CR	CR		CR									
Land Surface Topography	44b	1,2	Two formation flying LEO L-band SAR						CR	CR	CR						CR		CR			CR	CR	CR	CR	CR	CR		CR		E							
Surface deformation and stress, Land Surface Topography	45	1	MEO L-band InSAR						E	E	E						E	E	E		E	E	E	E	CR	E	CR		CR	E								
Surface deformation and stress, Land Surface Topography	46	1	Constellation of L-band geosynchronous InSAR						E	E	E						E	E	E		E	E	E	E	E	E	E		E	E								

Surface deformation and stress, Land Surface Topography	47	1	Airborne L-band InSAR														CR		CR										CR									
Land Surface Topography	163	1,2	X-band single pass InSAR						CR	CR	CR						CR		E			CR	E		CR	CR	CR		CR	CR								
Biomass	19	1,2	P-band polarimetric SAR						CR	CR	CR						CR		CR						CR		CR	CR										
Biomass	157	1,2	Airborne repeat-pass L-band InSAR , quad-pol														CR		CR										CR									
Biomass	158	1,2	LEO repeat-pass interferometric L-band SAR, quad polarization						CR	CR	CR						CR		CR			CR	CR	CR	CR	CR	CR		CR									
Land cover and land use	162	1,2	L-band polarimetric SAR						CR	CR	CR						CR		CR			CR	CR	CR	CR		CR	CR										
Surface deformation and stress, Terrestrial reference frame	51	1	GPS ground network																		CR																	

APPENDIX 4E: ACTIVE ELECTRONICS TECHNOLOGY ROADMAPS

Below are the individual technology roadmaps active electronics.

Large Aperture SAR Technologies

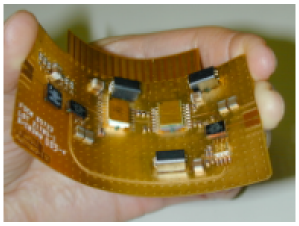


- Large aperture Electronically Steered Arrays (ESAs) require lightweight, low power, highly integrated electronics compatible with lightweight apertures and structures (e.g., membrane antennas and inflatable structures).
- Specific components include high-efficiency membrane compatible T/R modules and other electronics distributed on the array, technologies to attach and interconnect these components as well as thermal management technologies compatible with lightweight antennas.
- System technologies include digital beamforming and wavefront sensing and adaptive control to compensate for deformations of the large array
- Address integration of electronics by combining all component and system technologies (e.g., membrane T/R, interconnects, thermal with aperture and demonstrate DBF).

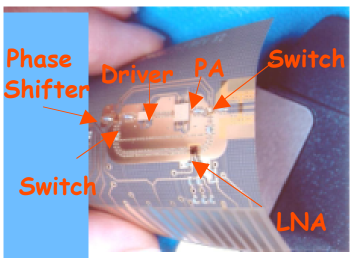
Figure 4E1

Membrane L -band T/R Modules

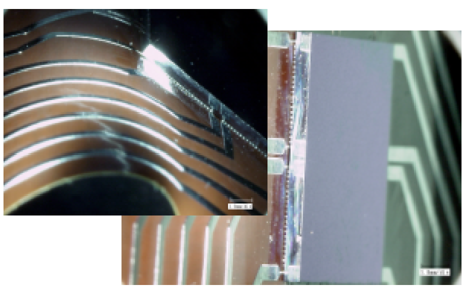
(for large array MEO/Geo SAR with antenna mass densities <2kg/m²)



ACT: Flex T/R using packaged parts (functional)



ACT: T/R using flip chip attachment (non functional prototype for flip chip development)



ACT: Test die flip chip attachment reliability testing

Current Status:

- Commercial SOA: does not exist
- Current ACT: 1W T/R using GaAs packaged parts, TRL 2
  - 1st Prototype demo (T/R only) in FY04
  - 2nd Prototype (T/R+controls) in FY05 (TRL 3 anticipated)

Tasks needed:

Develop membrane compatible T/R modules including attachment/packaging techniques and manufacturing techniques for low costs and high reliability

1. Address circuit design for membrane T/R
2. Improve T/R packaging and/or attachment
   a- die inside a low profile package
   b- direct attachment of die (i.e. flip chip)
3. Address radiation (through packaging) (>1MRad)
4. Increase transmit power (to 5 -10W)
5. Increase efficiency (s.a. incorporating High -Eff PA)
6. Address thermal management
7. Address manufacturability, reliability
8. Add BIT and telemetry
9. Reduce cost <$500 per module

NOTE: Tasks 1 -9 are not yet funded

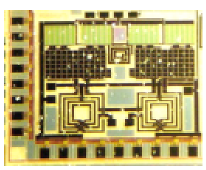
Figure 4E3

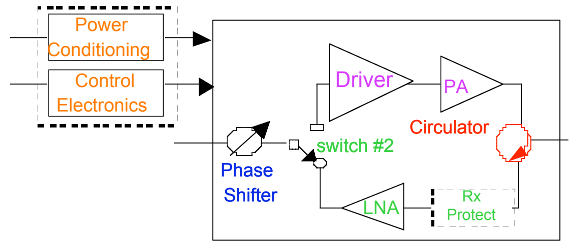
Single-Chip MMIC L-band T/R Modules

(for moderate to large SAR array applications)

Current Status:

Most T/R modules consist of multiple (5-6) MMICs plus discrete passives in a hybrid microcircuit. Cost is typically $1 - 5K in large quantities. Limited work is being done commercially to develop single chip L-band T/R modules. RF functions are being integrated into a single chip but some key components remain off-chip (circulators, control & power). Work is being done in CMOS for integrating the controls and GaAs for integrating the RF.





T/R module

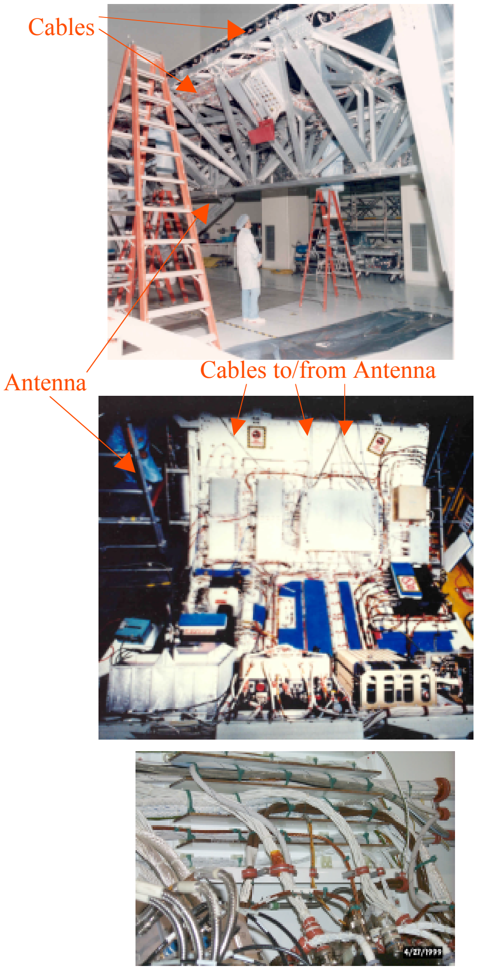
Tasks needed:

Develop a fully integrated MMIC T/R module:

1. Develop individual RF components (PA, LNA, P/S, switches) using a rad-hard semiconductor process (e.g., GaAs, SOI CMOS, SiGe).
2. Develop digital control components, BIT and telemetry.
3. Integrate into a single MMIC chip.
4. Improve RF performance (inc power, efficiency, reduce NF)
5. Address radiation hardness (with minimal shielding)

Figure 4E4

Signal Distribution & Interconnect



Current SOA: Cable Bundles

Current Status:

Large cable bundles distribute RF, power and control signals. These heavy cables are not compatible with ultra -lightweight antennas (i.e. -membrane). They are also expensive requiring extensive manual labor to build and integrate.

Tasks needed:

Development of technologies to simplify the interconnection of thousands of unit cells of ESA; significantly reduce mass and volume; develop reliable RF, control, power, and data distribution.

Sample Candidate Technologies:

1- Printed interconnects:

Challenges: Amount of current on printed lines, providing redundancy

2- Wireless interconnects:

Challenges: Bandwidth to support the amount of data, Possible RF interference

3- Optical interconnects:

Challenges: Large mass and power consumption of optical components, reliability

4- Signal multiplexing

Figure 4E5

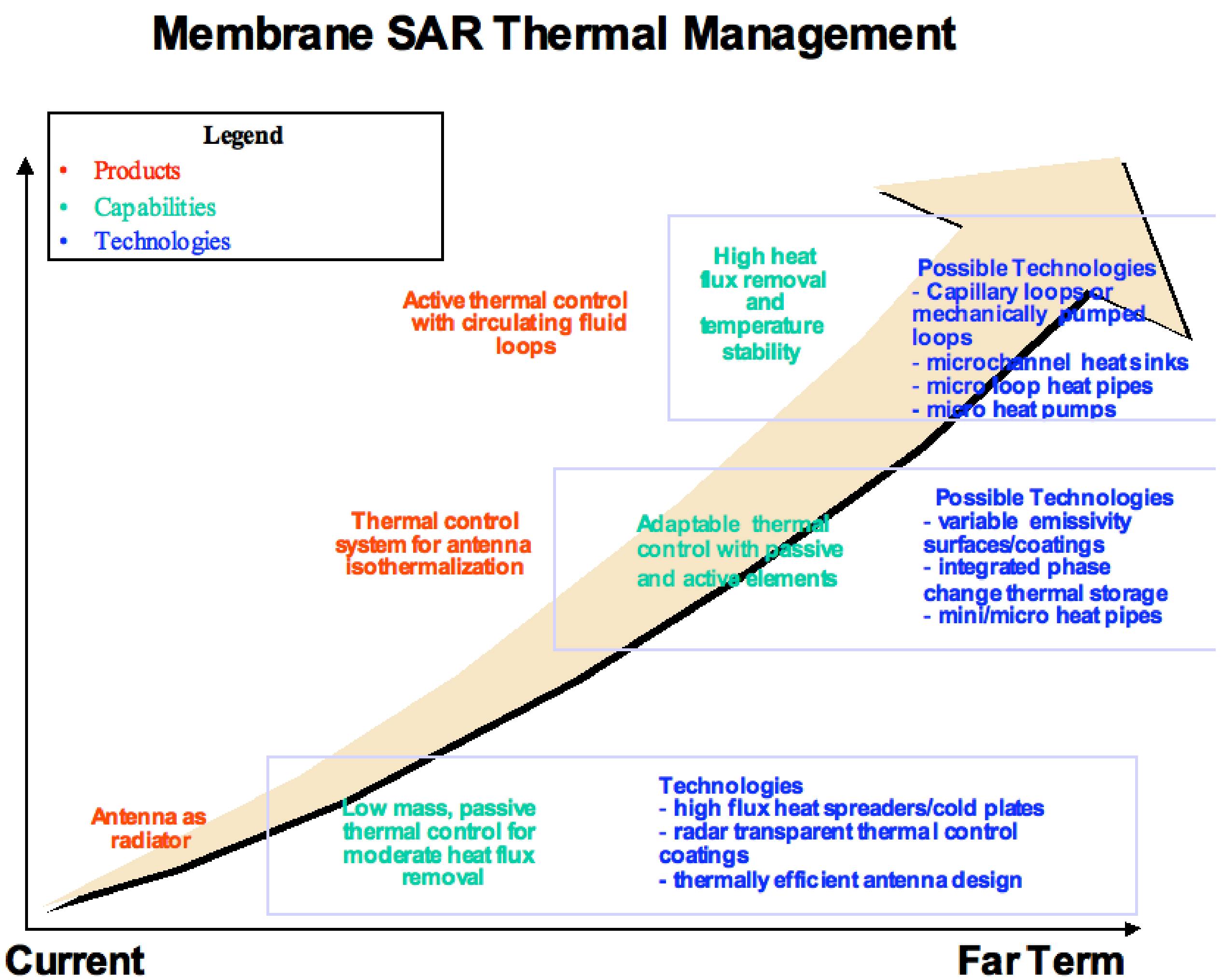

Membrane SAR Thermal Management
Legend
Products
Capabilities
Technologies
Active thermal control with circulating fluid loops
High heat flux removal and temperature stability
Possible Technologies
- Capillary loops or mechanically pumped loops
- microchannel heat sinks
- micro loop heat pipes
- micro heat pumps
Thermal control system for antenna isothermalization
Adaptable thermal control with passive and active elements
Possible Technologies
- variable emissivity surfaces/coatings
- integrated phase change thermal storage
- mini/micro heat pipes
Antenna as radiator
Low mass, passive thermal control for moderate heat flux removal
Technologies
- high flux heat spreaders/cold plates
- radar transparent thermal control coatings
- thermally efficient antenna design
Current
Far Term

Figure 4E6

Digital Beamforming (DBF)

(for large array MEO/Geo SAR applications)

Current Status

- **Hardware:** Mixed-signal (ADC) and reconfigurable (FPGA) IC technology at TRL 4-5.
- ? **Firmware:** Algorithm development at TRL 3.
- **Proof-of-concept demonstrated:** STAR radiometry, SBR, next-generation DSN array (TRL 3-5).

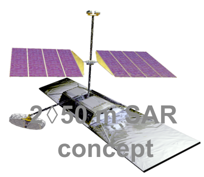
Tasks Needed

Build a hardware prototype of multi-channel L-band DBF system:

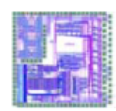
1. Rad-hard, low power, high-speed A/D conversion applied near antenna sub-system (at panel or element level).
2. Distributed microwave coaxial cables replaced with phase-stable digital fiber-optic network.
3. Address SEU immunity using "Rad-Hard by design" techniques

Instrument/Platform Requirements

- **Large antenna:** 20–50 m antenna span (rectangular panel array or circular aperture).
- **Direct RF A/D conversion:** 1.26 GHz carrier frequency, 80 MHz bandwidth, 4-8 bit resolution.
- **High data throughput:** Electronic beam steering, combining >30 phase center channels.
- **Phase stability:** 10–100 millidegree phase precision over wide thermal gradients.
- **On-board processing rate:** 10–100 billion op/s.



2◊50m SAR concept



High-speed GaAs and SiGe ADCs (up to 6 GHz input bandwidth)

High density FPGAs (up to 8 million gates)

Technology path toward single-chip receivers for a SAR array.

Figure 4E7

Wavefront Sensing and Control

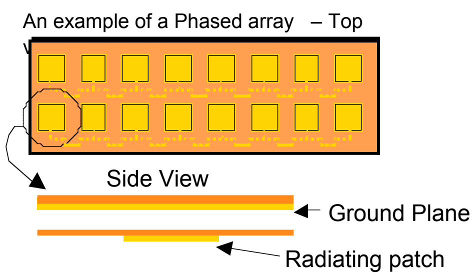
(for large array MEO/Geo SAR applications)

Description

- SAR measurements require the precise knowledge of the phase of the signal received. Therefore, precise knowledge of the antenna shape (surface flatness and layer separation) and phase of electronics are critical for these arrays. Thermal gradients, spacecraft motion, aging of electronics etc. all contribute to this uncertainty. Technologies for wavefront sensing and control are critical for realization of large phased arrays.

Current Status

- Some of the component technologies for sensing and control are mature however as an integrated metrology, calibration, and control system the TRL is at 1-2
- A proper ground validation system needs to be investigated for this technology



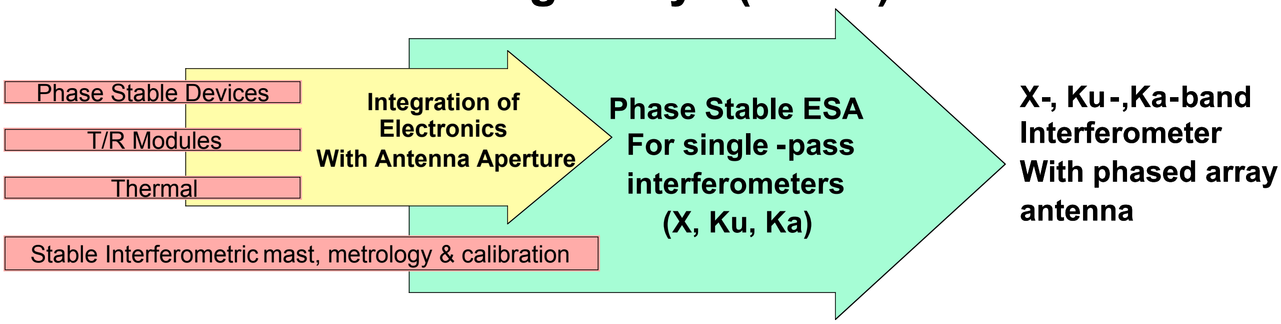
Array Flatness	l/20 (1.3cm)
Layer separation	1/10 of separation (1.3mm)

Tasks Needed

- Active & adaptive systems for controlling structural geometry and dynamics including measuring and correcting surface flatness, antenna to ground plane separation (See table below). Also wavefront sensing and correction due to electronics.
- Methods of creating stable wavefront & maintaining it over environmental changes such as temperature, S/C vibrations etc.
- This includes: system models, metrology, wavefront sensing and control, algorithm development
- Develop a ground validation system demonstration

Figure 4E8

X-, Ku-, Ka-band
Single-Pass Interferometers using Electronically Steering Arrays (ESAs)



Millimeter Wave
Atmospheric Radar using ESAs

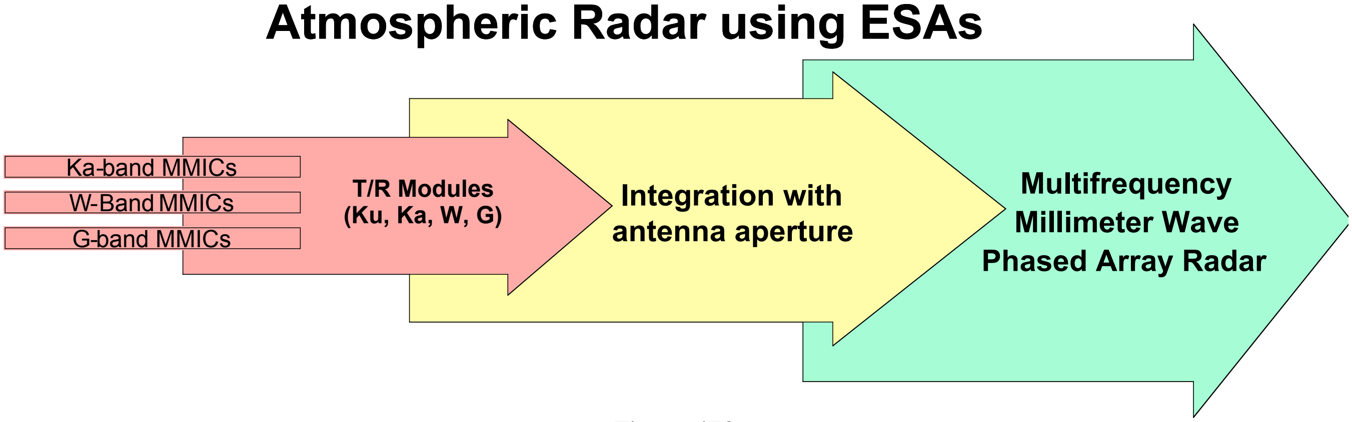
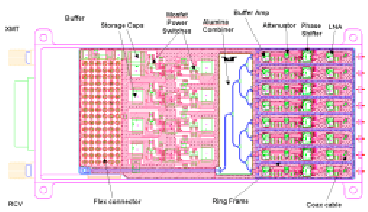


Figure 4E9

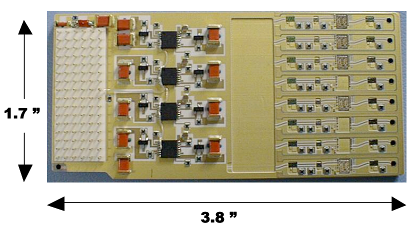
Ka-band T/R Modules

(similar roadmap for Ku-band or X-band)

Layout of Receive side of
8-channel MSL T/R module



Photograph of receive side of
8-channel MSL T/R module



Current Status:

- 1 W transmit chain, 20% efficiency demonstrated (using Triquint 2W chip) (TRL 3)
- 8-channel LTCC module w/ GaAs MMICs
    - 17 dBm output power, 4GHz BW
    - Low power -added efficiency (low power module)
    - 30 g/channel mass
- Developed under ATIP and Mars Focused Tech Program
    - Multi-module brassboard demonstrated circuitry (TRL 4)
- There are no equivalent commercial products

Tasks needed:

1. Improvement in efficiency to 30% (by 2006) to 50% (by 2010)
2. Increase power to 3W (by 2006) to 10W (by 2010) (Triquint 6W MMIC chip recently available)
3. Address phase stable receive electronics (for interferometers)
4. Further miniaturization and application specific packaging (ie, 2D array)
5. Reduced mass and cost
6. Add BIT and telemetry

Figure 4E10

W-band & G-band Devices for T/R modules

(MMIC development at 95GHz and 140GHz)

Current Status:

- W-band (95 GHz) components:
  - 0.25W PA, 6dB NF LNA
- G-band (140 GHz) components:
  - T/R components (particularly PA) do not exist

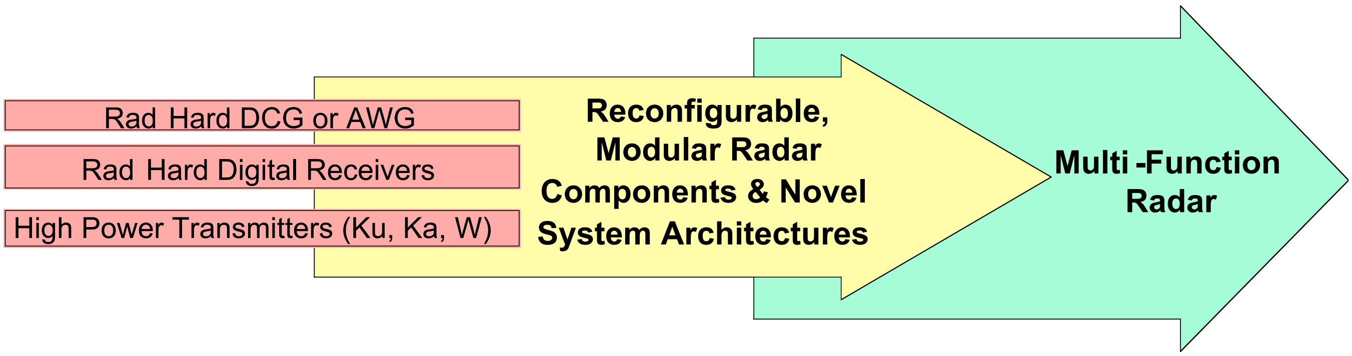
Tasks needed:

Basic research to develop new MMIC devices using GaAs, GaN, InP, MEMS (or other emerging semiconductor technologies) at 95 GHz and 140 GHz for future T/R modules

1. Develop MMIC devices such as power amplifiers (PAs), LNAs, Phase Shifters, switches, filters. Performance goals:
   - W-band MMICs: 1W PA with 20% PAE, <4dB NF LNA, 4-bit phase shifter (<3dB loss)
   - G-band MMICs: 0.5W PA with 10% PAE, 6dB NF LNA
2. Develop low loss power combining and packaging technologies at 95GHz and 140GHz for future T/R modules
3. Address the integration of the MMICs for T/R modules

Figure 4E11

Core Radar Sensor Technologies

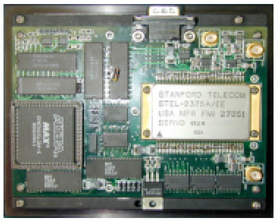


- Develop generic and integrated radar building blocks with the flexibility to be adapted to a variety of near and far-term radar applications.
- Includes core back-end components such as digital chirp or arbitrary waveform generators and digital receivers
- Includes high-power tube amplifiers and high voltage power supplies
- Technology challenges radiation-hardening (particularly for for electronics required for phased-array antennas where shielding is limited), reducing mass and power and increasing flexibility
- Also includes new system architectures that can result in significantly reduced mass, power and cost.

Figure 4E12

Waveform Generators

(applicable to nearly all radar applications)



STEL-2375B high-speed GaAs NCO-based DCG

Current Status:

- STEL-2375B GaAs NCO, 400 MHz max BW, 40 dB SFDR, 15W DC. Currently at TRL 6. Prototype built and tested, airborne validated. OSTM/WSOA will raise TRL from 6 to 9 by 2008.
- AD-9858, CMOS NCO, 325 MHz max BW, 3W DC, no radiation test data available. Currently at TRL 4. In process of prototyping and radiation testing.

Tasks Needed:

Develop low power, high-speed (>300MHz BW), rad-hard (1MRad) integrated chirp generators

- Reduce power consumption <5W by 2006, <2W by 2008, <1W by 2012
- Increase speed (bandwidth) and SFDR (low sidelobes)
- Reduce mass (eg., single chip ASIC)
- Increase flexibility (arbitrary waveform generator)
- Increase radiation hardness (particularly for MEO, Geo applications)

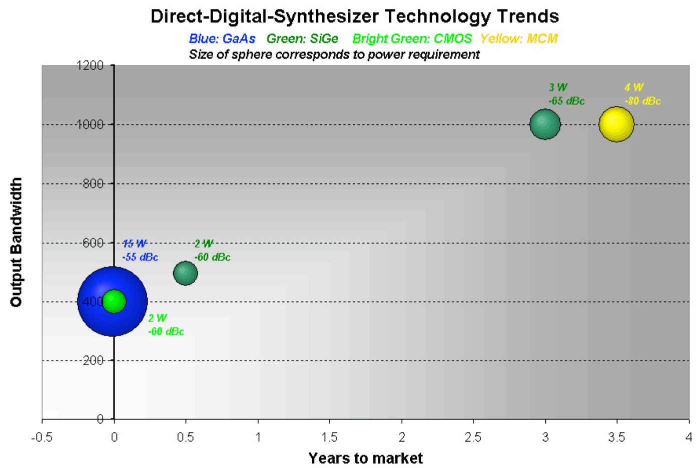
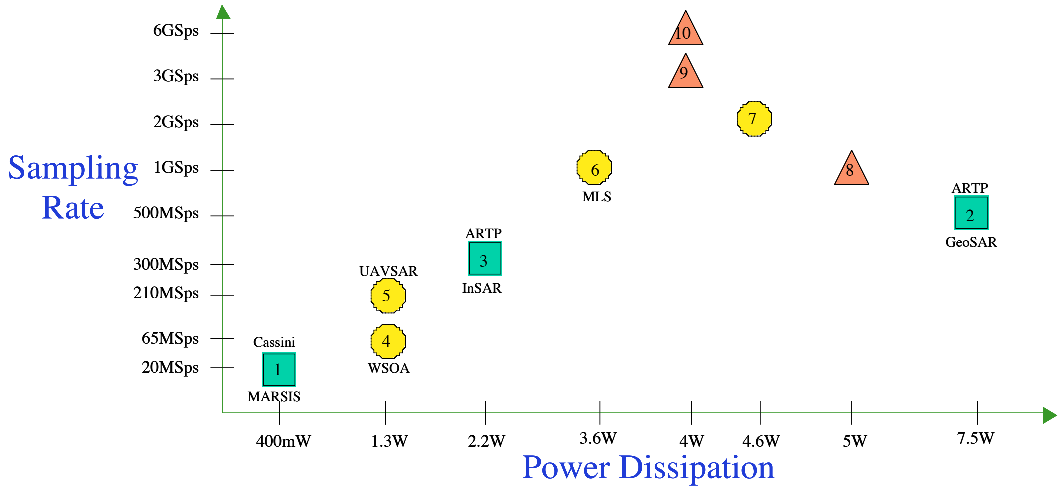


Figure 4E13

Science ADC Trends



Current/past technology, all having designs fully tested in instruments, being implemented in some present instruments.	1	Harris HS9008	8 bits	20MSps max	400 mW	Tested: No latchup TID >100 krad
	2	Maxim MX101	8 bits	500MSps max	7.5 W	Tested: Destructively failed
	3	Fairchild SPT7725	8 bits	300MSps max	2.2 W	Tested: LET > 100 TID >100 krad
Current/future technology, #6 having a design partially tested in an instrument, to be implemented in instruments over the next 5 yrs.	4	ADI AD6640	12 bits	65MSps max	1.3W	Simlarity : No latchup TID >100 krad
	5	ADI AD9430	12 bits	210MSps max	1.3W	Advanced BiCMOS , perhaps TID > 10 krad
	6	Atmel TS8388B	8 bits	1GSps max	3.6 W	Vender data: TID >150 krad
	7	Atmel TS83102G0	10 bits	2GSps max	4.6 W	Vender data: TID >150 krad
Future technology, have not been prototyped at JPL, being implemented in higher BW instruments over the next 10 yrs.	8	Rockwell RAD010	10 bits	1GSps max	5 W	Bi-polar GaAs : s/b TID > 100 krad
	9	Rockwell RAD008	8 bits	3GSps max	4 W	Bi-polar GaAs : s/b TID > 100 krad
	10	Rockwell RAD006	6 bits	6GSps max	4 W	Bi-polar GaAs : s/b TID > 100 krad

Figure 4E14

High-Speed Science ADC

Current Assessment

- ADC trends indicate most Code Y missions will have suitable ADC devices available **EXCEPT**
  - MEO and GEO applications requiring radiation hardening
  - MEO or GEO SAR requiring very low DC power for distributed array architectures
  - Most SAR applications would benefit from higher dynamic range (# bits)

Future Technology Development Tasks

Development of rad-hard, low power, high-speed, >8-bit ADCs.

1. Increased dynamic range: Increase the number of bits (from 8-bit to 12-bit) for moderately high-speed ADC (300MHz)
2. Reduced power consumption for large array applications (<0.5W)
3. Radiation hardening for MEO/Geo:

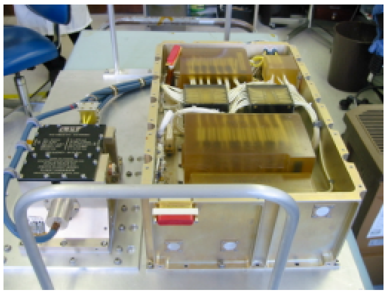
   100kRad (by 2006)

   500 KRad (by 2010)

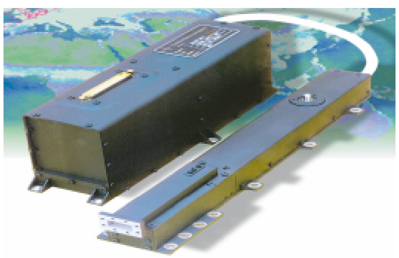
   1MRad (by 2014)

Figure 4E15

High Power Transmitter Technologies
(Ku, Ka, W-band)



Cloudsat
1.5KW EIKA EQM



OVWM/WSOA
120 W TWTA breadboard

Current Status:

- 1.5KW 95GHz EIKA (klystron + high voltage power supply) developed for Cloudsat (TRL >6)
- 120W Ku-band (14GHz) TWTA under development for OVWM and WSOA (TRL 5)

Tasks needed:

- Continue developments of space transmitter tube amplifiers at Ku-band and W-band
  1. Develop a 10KW EIK at 95GHz (W-band) with 20KV HVPS
  2. Develop a >500W TWTA at 14GHz (Ku-band)
- Apply Cloudsat EIKA experience to develop a space-qualified EIKA at Ka-band (35GHz)
  1. Develop a 2-5KW EIK at 35 GHz (Ka-band) with 16-20KV HVPS (based on existing commercial product)

Figure 4E16

APPENDIX 4F: ACTIVE ELECTRONICS TECHNOLOGY CBS

Technology	Measurement Scenarios	Instrument Type	Waveband	Needed Functional Product	Quantitative Requirement	Task	Subtask	Explanation	TRL @ Start	TRL @ End	Development Period (years)	Year Needed (at least 3 years before launch)	POC Name	POC Phone	POC e-mail
High Efficiency T/R Module (L-band)	45, 46, 22, 105, 92, 44a, 44b, 47, 157, 158, 162	L-band SAR	L-band	Freeze-Thaw, SWE, polar ice velocity, surface deformation, biomass, land cover	Efficiency >70% Power 10-100W Bandwidth >80MHz Mass <50g	Develop L-band T/R modules for numerous SAR missions: 5-10W T/R for 1D and 2D full-scan phased array; 20-40W T/R for moderate 1D or 2D scan; 50-100W T/R for limited scan or 1-axis scan	These tasks are follow-on to current ACT project: 1. Improve efficiency >70% 2. Address other output power requirements (10-100W) 3. Reduce mass to <50g 4. Address radiation hardness (by design) 5. Add BIT and telemetry 6. Reduce cost to $1K per module	Required for small array LEO applications with mass densities <10 kg/m2. Current ACT will raise from TRL 3 to TRL 5.	5	6	2	2006	Edelstein	818-354-8746	wendy.edelstein@ jpl.nasa.gov
MMIC T/R module (L-band)	45, 46, 22, 105, 92, 44a, 44b, 47, 157, 158, 162	L-band SAR	L-band	Surface deformation and land topography	single chip T/R; 5-10W, 70% eff, 2dB NF, rad hard >1MRad	Develop a fully integrated (single chip) MMIC T/R modules: 1. Single chip T/R <5W; 2. Single chip T/R >5W; 3. Rad hard T/R (>1MRad);	1. Develop individual T/R RF components 2. Develop control input, BIT and telemetry 3. Integrate into single MMIC 4. Improve RF performance (increase power & eff, reduce NF) 5. Address radiation hardness (with minimal shielding)	Required for large aperture systems with mass densities <2kg/m2 with requirement for high volume T/R modules	2	6	4	2008	Edelstein	818-354-8746	wendy.edelstein@ jpl.nasa.gov
Membrane High-Efficiency T/R modules (L-band)	45, 46, 22, 105, 92, 44a, 44b, 47, 157, 158, 162	L-band SAR	L-band	Surface deformation and land topography	5-10W, 70% eff, membrane attached, rad hard >1MRad	Develop T/R modules that are compatible with membrane antennas: 1. Attachment/packaging techniques; 2. Manufacturing techniques; 3. Thermal management; 4. Unit cell demonstration.	These tasks are follow-on to current ACT project to address system integration issues of active electronics on membrane antennas: 1. Address circuit design for membrane compatible T/R 2. Improve T/R packaging and/or attachment 3. Increase transmit power 4 Increase efficiency (s.a. incorporating High-Eff PA) 5. Address thermal management 6. Address radiation hardening (through packaging) 7. Add BIT and telemetry 8. Reduce cost to $500 per module	Required for large aperture systems with mass densities <2kg/m2. Once this has been developed at L-band, the technology could be developed for higher frequencies. Current ACT will raise from TRL 1 to TRL 3.	3	5	4	2008	Edelstein	818-354-8746	wendy.edelstein@ jpl.nasa.gov

Technology	Measurement Scenarios	Instrument Type	Waveband	Needed Functional Product	Quantitative Requirement	Task	Subtask	Explanation	TRL @ Start	TRL @ End	Development Period (years)	Year Needed (at least 3 years before launch)	POC Name	POC Phone	POC e-mail
Manufacturing, integration, and assembly of active membrane antennas electronic subsystems	45, 46	L-band SAR	L-band	Surface deformation and land topography	integrated subarray fabrication (>64 element subarray)	Develop technologies and techniques for large-scale integration of electronics with membrane antennas 1. Subarray demonstration 2. Integration of subarrays	These tasks combine all the component technologies required for membrane antennas (ie, membrane compatible T/R, interconnects, thermal)	Required for large aperture systems with mass densities <2kg/m2. Once this has been developed at L-band, the technology could be developed for higher frequencies.	2	6	4	2010	Edelstein	818-354-8746	wendy.edelstein@jpl.nasa.gov
Ku-Band MMIC devices (PAs, LNAs, P/S, switches)	93, 161A	Ku-band interferometric SAR	Ku-band	SWE, ice surface topography	Phase stable (0.1 deg) receive components (LNA, phase shifters, switches, filters). Rad hard with minimal shielding.	Develop Ku-band phase stable devices required for T/R modules of interfometric SAR phased-array antennas.	LNAs, Phase shifters, switches, filters	Required for phase stable receivers in phased-array antennas used for interferometry	3	6	3 years (IIP)	2007	Edelstein	818-354-8746	wendy.edelstein@jpl.nasa.gov
T/R Module (Ku-band)	105, 93, 75, 76, 161A	Ku-band SAR, Ku-band rain radar	Ku-band	SWE, precipitation, ice surface topography	1-20W Ku-Band T/R Modules, with LNA, HPA, phase shifters (5-6 bit), low loss T/R switches, receive channel digital attenuators, DC power and communication interfaces, BIT capability.	Develop Ku-band T/R modules for scanning antennas: 1W T/R for 1D and 2D full-scan phased array; 8W T/R for moderate 1D or 2D scan; 20W T/R for limited scan or 1-axis scan	Address the following improvements to SOA: Power Out = 1-20W (application specific), Efficiency>45%, Noise Figure<1.5 dB, >50KRad TID, Mass <30 gm, phase-stable (0.1deg) receive chain, application specific packaging	High Power Ku-Band applications for phased or line arrays with electronic scan capability.	3	6	3 years (IIP)	2007	Salisbury	303-939-6838	gsalisbu@ball.com
Ku-band TWTA	102, 75, 76, 148	Ku-band scatterometers, Ku-band interferometers	Ku-band	snow cover, precip, ocean surface topography, sea ice	500W TWT, >40% efficiency, HVPS	Space qualification of >500W TWTA		500W TWTA technology similar to existing 200W TWTA under development for OVWM & WSOA	4	6	3	2007	Edelstein	818-354-8746	wendy.edelstein@jpl.nasa.gov
Ka-Band MMIC devices (PAs, LNAs, P/S, switches)	100, 75, 76, 154, 160, 97	Ka-band SAR, Ka-band rain radar	Ka-band	river discharge, precipitation, ocean topography	2-12W PA with >30% PAE, <3dB NF LNA, 4-bit phase shifter (<3dB loss), phase-stable receive components.	Develop new MMIC devices using GaAs, GaN, SiGe, InP, MEMS technologies (or other emerging semiconductor technologies)	Power amplifiers, LNAs, Phase shifters, switches, filters. Receive components must be phase stable to 0.1 deg for interferometer applications.	Development of basic Ka-band devices required for future T/R modules.	2	4	3	2008	Edelstein	818-354-8746	wendy.edelstein@jpl.nasa.gov

Technology	Measurement Scenarios	Instrument Type	Waveband	Needed Functional Product	Quantitative Requirement	Task	Subtask	Explanation	TRL @ Start	TRL @ End	Development Period (years)	Year Needed (at least 3 years before launch)	POC Name	POC Phone	POC e-mail
T/R Module (Ka-band)	100, 75, 76, 154, 97	Ka-band SAR, Ka-band rain radar	Ka-band	river discharge, precipitation, ocean topography	1-12W Ka-Band T/R Module with HPA, LNA, phase shifters (5-6 bit), low loss T/R switches, receive channel digital attenuators, DC power and communication interfaces, BIT capability.	Develop Ka-band T/R modules for scanning antennas: 1W T/R for 1D and 2D full-scan phased array; 6W T/R for moderate 1D or 2D scan; 12W T/R for limited scan or 1-axis scan	The following improvements to SOA to be addressed: Power out=1-12 (application specific), Efficiency>30%, Noise Figure< 2.8 dB, phase-stable receive chain, >50KRad TID, mass<30g, application specific packaging	For high power Ka-Band phased array or line arrays with electronic scan capability. Past ATIP raised from TRL 2 to TRL 4.	4	6	3 years (IIP)	2008	Salisbury	303-939-6838	gsalisbu@ball.com
Ka-band tube amplifiers (EIKA)	100, 154, 160, 97	Ka-band SAR	Ka-band	river discharge	2-5KW EIK, >30% efficiency, 16-20KV HVPS	Space qualification of 2-5KW Ka-band EIKA and HVPS		Similar technology to Cloudsat EIKA (Ka-band has more relaxed requirements)	4	6	3	2008	Edelstein (Rodriguez)	818-354-8746	wendy.edelstein@jpl.nasa.gov
W-band MMIC devices (PAs, LNAs, P/S, switches)	142, 76, 159	Cloud radar	W-band	cloud profiling	1W PA with 20% PAE, <4dB NF LNA, 4-bit phase shifter (<3dB loss)	Develop new MMIC devices using GaAs, GaN, InP, MEMS technologies (or other emerging semiconductor technologies)	Power amplifiers, LNAs, Phase shifters, switches, filters	Development of basic W-band devices required for future T/R modules.	2	4	4	?	Edelstein (Eastwood Im)	818-354-8746	wendy.edelstein@jpl.nasa.gov
T/R Module (W-Band)	76, 159	Cloud radar	W-band	cloud profiling	1W W-band T/R modules with integrated PA, LNA, phase shifter (4-bit), low loss T/R switches.	Basic research to develop low loss power combining and packaging technologies at 95GHz		Addresses the integration of MMICs. Requires MMIC devices developed separately.	2	4	4	?	Edelstein (Eastwood Im)	818-354-8746	wendy.edelstein@jpl.nasa.gov
W-band EIKA (10KW)	142	Cloud radar	W-band	cloud profiling	10KW EIK, >30% PAE, >20KV HVPS	Development and space qualification of 10 KW EIKA		Further development of Cloudsat EIKA for increased power	3	6	3	?	Edelstein (Eastwood Im)	818-354-8746	wendy.edelstein@jpl.nasa.gov
G-Band (140, 183 GHz) MMICs (PAs, LNAs, P/S, switches)	159, 68	Cloud radar	140, 183 GHz	cloud profiling	0.5W PA, 10%PAE, 6dB NF LNA	Basic research to develop 140GHz MMICs particularly power amplifiers and low noise amplifiers.	Power amplifiers and low noise amplifiers	Development of basic G-band devices required for future T/R modules.	1	3	6	?	Edelstein (Eastwood Im)	818-354-8746	wendy.edelstein@jpl.nasa.gov

Technology	Measurement Scenarios	Instrument Type	Waveband	Needed Functional Product	Quantitative Requirement	Task	Subtask	Explanation	TRL @ Start	TRL @ End	Development Period (years)	Year Needed (at least 3 years before launch)	POC Name	POC Phone	POC e-mail
T/R Module (G-band) (140 GHz)	159	Cloud radar	140GHz	cloud profiling	0.5W W-band T/R modules with integrated PA, LNA, phase shifter (4-bit), low loss T/R switches	Basic research to develop low loss power combining and packaging technologies at 140GHz		Addresses the integration of MMICs. Requires MMIC devices developed separately.	1	3	6	?	Edelstein (Eastwood Im)	818-354-8746	wendy.edelstein@jpl.nasa.gov
Waveform Generators	45, 46, 22, 100, 105, 75, 76, 159, 148, 92, 93, C1, 97, 161A, 161B, 161C, 44A, 44B, 47, 163, 157, 158, 162, 112, 154, 160, O2, 28, 29, 19	SAR, scatterometers, altimeters, atmospheric radars	UHF/P-band, L-band, C-band, X-band, Ku-band, Ka-band, W-band	Primarily for surface deformation and land topography	>300MHz max BW, >50dB SFDR, <2W, Rad-Hard (>1MRad)	Development of low power, high-speed, rad-hard integrated chirp generators. Reduce DC power to <5W by 2006, <2W by 2008, <1W by 2012	1. Reduce power consumption; 2. Increase speed (bandwidth) and SFDR (low sidelobe); 3. Reduce mass (eg, single chip ASIC); 4. Increase flexibility (arbitrary waveform generator); 5. Increase radiation hardness (particularly for MEO/GEO applications)	Enhancing for nearly all radar applications; low power single-chip DCG is enabling for large array applications.	3	6	4	2010	Edelstein	818-354-8746	wendy.edelstein@jpl.nasa.gov
Analog to Digital Converters	45, 46, 22, 105, 148, 92, C1, 161B, 161C, 44A, 44B, 163, 157, 154, 162, O2, 30, 97	SAR	L-band, C-band, X-band, Ku-band,Ka-band	Primarily for surface deformation and land topography	MEO and GEO applications requiring radiation hardening; MEO and GEO SAR requiring very low DC power; most SAR applications would benefit from higher dynamic range (# bits)	Development of rad-hard, low power, high-speed, >8-bit ADCs	1. Increase dynamic range (increase # bits from 8-bit to 12-bit) for moderately high speed ADC (300MHz); 2. Reduce power consumption for large array applications (<0.5W); 3. Rad-hard to 1MRad	ADC trends indicate most Code Y missions will have suitable ADC devices available except MEO/GEO SAR which has a unique set of requirements	3	6	4	2010	Edelstein	818-354-8746	wendy.edelstein@jpl.nasa.gov
RF, Control & Power Distribution for Phased Arrays	45, 46, 22, 100, 105, 75, 76, 159, 92, 93, C1, 44a, 44b, 163, 158, 162	SAR	L-band	Primarily for surface deformation and land topography	Technologies to simplify the interconnection of thousands of unit cells on a phased array; reliable RF, control, power and data distribution. Lightweight, low loss, membrane-compatible interconnects for RF, data and power distribution.	Development of technologies that will significantly reduce the mass and volume of cabling and interconnects particularly for large arrays	Candidate technologies 1. Printed interconnects; 2. Wireless interconnects; 3. Optical interconnects; 4. Signal multiplexing;	While all Phased-Array antennas would be enhanced by improved sig dist technology, large aperture SARs require it	2	6	4	2008	Edelstein	818-354-8746	wendy.edelstein@jpl.nasa.gov

Technology	Measurement Scenarios	Instrument Type	Waveband	Needed Functional Product	Quantitative Requirement	Task	Subtask	Explanation	TRL @ Start	TRL @ End	Development Period (years)	Year Needed (at least 3 years before launch)	POC Name	POC Phone	POC e-mail
Thermal Management for membrane antennas	45, 46, 22, 105, 92, C1, 44A, 44B, 158, 162	InSAR	L-band	Surface deformation and land topography	passive and active thermal management, high heat flux removal, temperature stability	Development of local thermal management technologies required for lightweight membrane antennas such as radar transparent thermal coatings, variable emissivity surfaces/coatings; integrated micro heat-pipes, heat spreaders, thermally efficient antenna design	1. Low mass, passive thermal control for moderate heat flux removal; 2. Thermal control system for antenna isothermalization; 3. Active thermal control with circulating fluid loops	applies to thermal management and control of high power, large aperture membrane antennas with integrated electronics	1	6	4	2010	Edelstein	818-354-8746	wendy.edelstein@jpl.nasa.gov
Thermal Control for Interferometric SAR	100, 93, 97, 163	Single Pass Interferometric SAR	X,-band, Ku-band & Ka-band	land, ice, ocean topography	precise thermal control for phase stability of phased-array antennas	Develop thermal control system for phased array antenna. Demonstrate in laboratory environment.		Applies to single-pass interferometers using active phased array antennas.	2	6	4	2010	Edelstein	818-354-8746	wendy.edelstein@jpl.nasa.gov
Adaptive waveform sensing and correction technology	45, 46, 160	InSAR	L-band, UHF/VHF & Ka-Band		aperture flatness to 1/20 wavelength, aperture separation accuracy to 1/10 of separation	Develop technologies to sense and correct for deformations in large aperture reflector or phased array membrane antennas		applies to large aperture membrane antennas	2	6	6	2010	Edelstein	818-354-8746	wendy.edelstein@jpl.nasa.gov

APPENDIX 4G: CBS FOR COMBINED ACTIVE/PASSIVE ANTENNAS

The table below summarizes the passive antenna technology challenges

Technology	Measurement Scenario	Instrument Type	Waveband	Needed Functional Product
e.g. deployable antenna, high-speed processor, increased data storage, etc.	Applicable Scenario ID Numbers	Real, STAR, LEO, GEO, UAV etc.	frequencies, polarizations	
ANTENNA TECHNOLOGY CHALLENGE AREAS				
Multi-frequency Feeds with High Beam Efficiency	H2, 38, 106, 107, 108, 111, 176, 140, 143, 67, A1, A2, O1, C2	(H2) STAR, LEO; (38) Real, LEO; (106) Real, LEO; (107) 2D-STAR, LEO; (108) 1D-STAR, LEO; (111) Real, LEO; (176) Real, GEO; (140) Real, LEO; (143) Real, LEO; (A1) STAR, LEO or UAV; (A2) STAR, LEO or UAV; (C2) STAR, LEO	(H2) L, 18 & 37, 2-pol; (38) L, 2-3 pol; (106) 18 & 37, 2 pol; (107) 18 & 37, 2 pol; (108) 18 & 37, 2 pol; (111) L, 3-pol; (176) 50 & 183 GHz, 1-2 pol; (140) 180 - 2.5 THz, 1-2 pol; (143) 183 - Far IR, 1-2 pol; (67) 50 & 183 GHz, 1-2 pol; (A1) 10.7 & 36, 2 pol; (A2) 4-10 GHz, 1 or 2-pol; (O1) 6 & 10 GHz, 2-pol; (C2) 18 & 37, 2-pol	The product is a multiple frequency horn that can be used in a linear array. Must exhibit low mutual coupling when placed in closely spaced configuration.
Combined Active Passive Feeds	H1, H2, H3, 34, 38, 107, 108, 111, 177, A1, A2	(H1) STAR, LEO; (H2) STAR, LEO; (H3) STAR, LEO; (34) 2D-STAR, LEO;(38) Real, LEO; (107) 2D-STAR, LEO; (108) 1D-STAR, LEO; (111) Real, LEO; (177) STAR, LEO; (A1) STAR, LEO or UAV; (A2) STAR, LEO or UAV	(H1) L, 2 pol; (H2) L, 18 & 37, 2 pol; (H3) L, 2 pol; (34) L, 2-3 pol; (38) L, 2-3 pol; (107) 18 & 37, 2 pol; (108) 18 & 37, 2 pol; (111) L, 3-pol; (177) L, 2 pol; (A1) 10.7 & 36, 2 pol; (A2) 4-10 GHz, 1 or 2-pol;	(111) L-band feedhorn that can be used with radiometry and radar.
Low Cross Polarization Antennas (feeds) for 3rd and 4th Stokes Parameter Measurements	H2, 106, 107, 108, A1, A2, O1	(H2) STAR, LEO; (106) Real, LEO; (107) 2D-STAR, LEO; (108) 1D-STAR, LEO; (A1) STAR, LEO or UAV; (A2) STAR, LEO or UAV; (O1) Real, LEO	(H2) L, 18 & 37, 2-pol; (106) 18 & 37, 2 pol; (107) 18 & 37, 2 pol; (108) 18 & 37, 2 pol; (A1) 10.7 & 36, 2 pol; (A2) 4-10 GHz, 1 or 2-pol; (O1) 6 & 10 GHz, 2-pol;	
Waveguide Arrays	H1, H2, H3, 108, 177, A1, A2, C2	(H1) STAR, LEO; (108) 1D STAR, LEO; (177) STAR, LEO; (A1) STAR, LEO; (A2) STAR, LEO or UAV; (C2) STAR, LEO	(H1) L, 2-pol; (108) 18 & 37 -2-pol; (177) L, 2-pol; (A1) 10.7 & 36, 2-pol; (A2) 4-10 GHz, 1-2 pol; (C2) 18 & 36, 2-pol	Waveguide arrays to support 1D STAR sensor concepts, e.g. (108) linear feed for cylindrical parabolic reflector; (A1) large linear arrays; (A2) multi-frequency arrays

MEMS RF switches	H1, H2, H3, 34, 38, 107, 108, 111, 177, 143, 67, A1, A2, C2	(H1) STAR, LEO; (H2) STAR, LEO; (H3) STAR, LEO; (34) 2D-STAR, LEO;(38) Real, LEO;(67) STAR, GEO;(107) 2D-STAR, LEO; (108) 1D-STAR, LEO; (111) Real, LEO; (143) Real, LEO; (177) STAR, LEO;(A1) STAR, LEO or UAV; (A2) STAR, LEO or UAV; (C2) STAR, LEO	(H1) L, 2-pol; (H2) L, 19, 37, 2-pol; (H3) L, 2-pol; (34) L, 2-3 pol;(38) L, 2-3 pol; (67) 50, 183 GHz, 1-2 pol;(107) 19, 37 GHz, 1-2 pol; (108) 19, 37 GHz, 1-2 pol; (111) L, 2-3 pol; (143) 183 GHz--far IR, 1-2 pol; (177) L, 2-3 pol; (A1) X, Ka, 2-pol; (A2) 4--10GHz, 1-2 pol; (C2) Ku, Ka, 2-pol	(note: SOA 40 GHZ) low insertion loss & high isolation, small size/mass, high duty cycle/high lifetime switches for radiometer front ends. Package must be convenient to combine w/other MMIC components. Important calibration component.
MEMS filters	H1, H2, H3, 34, 38, 107, 108, 111, 177, 143, 67, A1, A2, C2	(H1) STAR, LEO; (H2) STAR, LEO; (H3) STAR, LEO; (34) 2D-STAR, LEO;(38) Real, LEO;(67) STAR, GEO;(107) 2D-STAR, LEO; (108) 1D-STAR, LEO; (111) Real, LEO; (143) Real, LEO; (177) STAR, LEO;(A1) STAR, LEO or UAV; (A2) STAR, LEO or UAV; (C2) STAR, LEO	(H1) L, 2-pol; (H2) L, 19, 37, 2-pol; (H3) L, 2-pol; (34) L, 2-3 pol;(38) L, 2-3 pol; (67) 50, 183 GHz, 1-2 pol;(107) 19, 37 GHz, 1-2 pol; (108) 19, 37 GHz, 1-2 pol; (111) L, 2-3 pol; (143) 183 GHz--far IR, 1-2 pol; (177) L, 2-3 pol; (A1) X, Ka, 2-pol; (A2) 4--10GHz, 1-2 pol; (C2) Ku, Ka, 2-pol	(note: SOA 1 GHZ) low insertion loss, high Q, good input/output match, small size/mass. Important for RF, LO, and IF filters. Potential for easily-reconfigurable filters. Package must be convenient to combine w/other MMIC components.
analog RFI Mitigation Technology	H1, H2, H3, 34, 38, 106, 107, 108, 111, 177, 176, A1, A2, O1,C2	(H1) STAR, LEO; (H2) STAR, LEO; (H3) STAR, LEO; (34) 2D-STAR, LEO;(38) Real, LEO;(106) Real, LEO; (107) 2D-STAR, LEO; (108) 1D-STAR, LEO; (111) Real, LEO; (177) STAR, LEO; (176) Real, GEO;(A1) STAR, LEO or UAV; (A2) STAR, LEO or UAV; (O1) Real, LEO; (C2) STAR, LEO	(H1) L, 2-pol; (H2) L, 19, 37, 2-pol; (H3) L, 2-pol; (34) L, 2-3 pol;(38) L, 2-3 pol; (106,107, 108) 19, 37 GHz, 1-2 pol; (111) L, 2-3 pol; (177) L, 2-3 pol; (176) 50, 183 GHz, 1-2 pol; (A1) X, Ka, 2-pol; (A2) 4--10GHz, 1-2 pol; (O1) 6, 10 GHz, 2 pol; (C2) Ku, Ka, 2-pol	frequency domain channelization; very high interchannel isolation (high out of band rejection); minimize impact on instrument design (small size, low loss)
combined active/passive system design	H1, H2, H3, 34, 38, 106, 107, 108, 111, 177, A1, A2	(H1) STAR, LEO; (H2) STAR, LEO; (H3) STAR, LEO; (34) 2D-STAR, LEO;(38) Real, LEO;(106) Real, LEO; (107) 2D-STAR, LEO; (108) 1D-STAR, LEO; (111) Real, LEO; (177) STAR, LEO;(A1) STAR, LEO or UAV; (A2) STAR, LEO or UAV;	(H1) L, 2-pol; (H2) L, 19, 37, 2-pol; (H3) L, 2-pol; (34) L, 2-3 pol;(38) L, 2-3 pol; (106,107, 108) 19, 37 GHz, 1-2 pol; (111) L, 2-3 pol; (177) L, 2-3 pol; (A1) X, Ka, 2-pol; (A2) 4--10GHz, 1-2 pol;	System design work and technology development as needed to enable antenna aperture sharing to accommodate active/passive systems; Field demonstration that shared aperture systems are capable of the highest stand-alone quality performance

Lightweight Structural Elements	H1, H2, H3, 34, 38, 111, 177, 176, 140, 67, A2, O1, C2	(H1) STAR, LEO; (H2) STAR, LEO; (H3) STAR, LEO; (34) 2D-STAR, LEO;(38) Real, LEO; (111) Real, LEO; (177) STAR, LEO; (176) Real, GEO; (140) Real, LEO; (67) STAR, GEO; (A2) STAR, LEO or UAV; (O1) Real, LEO; (C2) STAR, LEO	(H1) L, 2-pol; (H2) L, 18 & 37, 2-pol; (H3) L, 2-pol; (34) L, 2-3 pol; (38) L, 2-3 pol; (111) L, 3-pol; (177) L, 2-pol; (176) 50 & 183 GHz, 1-2 pol; (140) 180 - 2.5 THz, 1-2 pol; (67) 50 & 183 GHz, 1-2 pol; (A2) 4-10 GHz, 1 or 2-pol; (O1) 6 & 10 GHz, 2-pol; (C2) 18 & 37, 2-pol	(34, 177) Structures are needed to support 1D or 2D STAR concepts to 25 meter diameter; (34) 6 - 12 meter structural components such as extensible booms and trusses are needed
Precision Deployable/Inflatable Structure (1)	38,111,106,O1	(38), Real, LEO;(111), Real, LEO;(106), Real, LEO;O1 Real, LEO	L-Band to Ka-Band	(a) Large (20x50 m) deployable mesh antennas, highly reflective mesh (>.99), techniques to correct for mesh emission (b) Various classes of feeds, including (1) focal line arrays (2) Multiple frequency feeds (3) Thinned array feeds (c) Adaptive sub reflector to (1) correct for phase errors in illuminating the torus (2) switch transparency of sub reflector from 1 to 0 for cold sky calibration
Deployables/Large Aperture	surface salinity (or soil moisture) using a rotating real aperture radiometer with mesh antenna, or by using a parabolic torus reflector with hundred element Focal Plane Array (FPA). (111),Measure surface soil moisture (or sea surface salinity) with 1-10 km spatial resolution using a very large rotating real	(38) Real, LEO; (111) Real, LEO; (O1) Real, LEO;	(38) L, 2-3 pol; (111) L, 3 pol; (O1) 6 & 10 GHz, 2 pol;	(111, and others) Deployable real aperture up to 25 m offset **rotating** parabola with a mesh reflector surface at L- to X-band. Accommodate active (radar) channels sharing same feed and reflector assemblies.

Precision Deployable/Inflatable Structure (2)	38, 111, O1 (same as above)	(38) Real, LEO; (111) Real, LEO; (O1) Real, LEO;	(38) L, 2-3 pol; (111) L, 3 pol; (O1) 6 & 10 GHz, 2 pol;	Deployable/inflatable **non-rotating** antenna mesh or membrane reflector (e.g. torus) up to 50m, with sub-reflector and scanning feed subassembly, at L- to X-band. Accommodate active (radar) channels sharing same feed and reflector assemblies.
Precision Deployable/Inflatable Structure (3)	108	(108) 1D STAR, LEO	18 and 37 GHz, 1-D thinned aperture radiometer	1-dimensional synthesized (STAR) imaging radiometer. Dual polarization at 19 & 37 GHz. Spatial resolution of 5-km with similar imaging performance compared to a real aperture conical imager.
Precision Deployable/Inflatable Structure (4); 2D STAR with receiver elements	H1, H2, H3, 34, 107, 67,	(H1) 2D LEO STAR; (H2) 2D LEO STAR; (H3) 2D LEO STAR; (34) 2D LEO STAR; (107) 2D LEO STAR; (67) 2D GEO STAR	(H1) L, 2-pol; (H2) Ku & Ka 2-pol; (H3) L 2-pol; (34) L, 2-pol; (107) Ku & Ka, 2-pol; (67) 50-60 & 183	Flood beam element patterns with ultra-low mutual coupling, low loss, ultra-stable phase center location vs. temperature. Highly integrated antenna/receiver modules. Low recurring cost for large scale fabrication of identical units
Precision Deployable/Inflatable Structure (5); 2D STAR with tensioned membranes	H1, H2, H3, 34, 177, A2	(H1) STAR, LEO; (H2) STAR, LEO; (H3) STAR, LEO; (34) 2D-STAR, LEO;(177) STAR, LEO; (67) STAR, GEO; (A2) STAR, LEO or UAV; (C2) STAR, LEO	(H1) L, 2-pol; (H2) L, 18 & 37, 2-pol; (H3) L, 2-pol; (34) L, 2-3 pol; (177) L, 2-pol; (176) 50 & 183 GHz, 1-2 pol; (67) 50 & 183 GHz, 1-2 pol; (A2) 4-10 GHz, 1 or 2-pol; (C2) 18 & 37, 2-pol	(34) (STAR) Deployable structural concepts incorporating tensioned rigid panels or membranes are required to meet 10 to 20m aperture size. 6 - 12 meter structural components such as extensible booms and trusses are needed

Millimeter Wave and Submillimeter Wave Antennas	176, 140, 143	(176) Real, GEO; (140) Real, LEO; (143) Real, LEO	(176) 50 & 183 GHz, 1-2 pol; (140) 180 - 2.5 THz, 1-2 pol; (143) 183 GHz - - Far IR, 1-2 pol	(140) Submillimeter antenna
Millimeter Wave and Submillimeter Wave Antennas	176, 140, 143	(176) Real, GEO; (140) Real, LEO; (143) Real, LEO	(176) 50 & 183 GHz, 1-2 pol; (140) 180 - 2.5 THz, 1-2 pol; (143) 183 GHz - - Far IR, 1-2 pol	deployable submillimeter wave antenna
PRECISION CONTROL/SYSTEM TECHNOLOGY CHALLENGES				
Precision Antenna Pointing	67, 143, 176	(67) STAR, GEO; (143) Real, LEO; (176) Real, GEO	(67) 50 & 183 GHz 1-2 pol; (143) 183 GHz - Far IR, 1-2 pol; (176) 50 & 183 GHz, 1-2 pol	The platform must have capability to very accurately scan a large antenna and subreflector
Antenna Metrology	H1, H2, H3, 34, 38, 111, 177, 67	(H1) STAR, LEO; (H2) STAR, LEO; (H3) STAR, LEO; (34) 2D-STAR, LEO; (38) Real, LEO; (111) Real, LEO; (177) STAR, LEO; (67) STAR, GEO;	(H1) L, 2 pol; (H2) L, 18 & 37, 2 pol; (H3) L, 2 pol; (34) L, 2-3 pol; (38) L, 2-3 pol; (111) L, 3-pol; (177) L, 2 pol; (67) 50 & 183 GHz, 1-2 pol	Continuous metrology of large deployable Y-arrays (H1-H3, and others)
Control of spinning large apertures		(111) real, LEO	(111) L, 3-pol 25 m aperture	Control and Stability of spinning large apertures
Antenna Aperture Control	177	(177) STAR, LEO	(177) L, 2 pol	Control and Stability of spinning large apertures
Precision Attitude Knowledge/Cross Track	A1	(A1) STAR, LEO or UAV	(A1) 10.7 & 36 2 pol	(H1, H2, H3) Attitude control of large flexible array in plane parallel to the Earth
Consellation Metrology	A1	(A1) STAR, LEO or UAV	(A1) 10.7 & 36 2 pol	

Control of spinning large apertures		(111) real, LEO	(111) L, 3-pol 25 m aperture	Control and Stability of spinning large apertures
Antenna Aperture Control	177	(177) STAR, LEO	(177) L, 2 pol	Control and Stability of spinning large apertures
Precision Attitude Knowledge/Cross Track	A1	(A1) STAR, LEO or UAV	(A1) 10.7 & 36 2 pol	(H1, H2, H3) Attitude control of large flexible array in plane parallel to the Earth
Consellation Metrology	A1	(A1) STAR, LEO or UAV	(A1) 10.7 & 36 2 pol	
Cryo-coolers	140		(140)180 GHz - 2.5 THz, 1-2 pol	Cryocooler to enable Heb and SIS terahertz detectors at 4 K. Cryo-cooler to reduce the noise temperature of LNA at 20 K for limb sounder

APPENDIX 4H: CBS FOR COMBINED ACTIVE/PASSIVE ELECTRONICS

Technology	Measurement Scenario	Instrument Type	Waveband	Needed Functional Product
High Frequency LNAs >160 GHz	140, 143, 67, 176	(140) Real, LEO; (143) Real, LEO; (67) STAR GEO; (176) Real, GEO	(140) 180 GHz--2.5 THz, 1-2 pol; (143) 183 GHz--far IR, 1-2 pol;(67) 50, 183 GHz, 1-2 pol; (176) 50, 183 GHz, 1-2 pol;	wideband low noise amplifiers
High Frequency Downconversion Techniques >900 GHz	140, 143	(140) Real, LEO; (143) Real, LEO	(140) 180 GHz--2.5 THz, 1-2 pol; (143) 183 GHz--far IR, 1-2 pol	mixers and other downconverters
High Frequency >= 50GHz Sources (LO)	140, 143, 67, 176	(140) Real, LEO; (143) Real, LEO; C20 (176) Real, GEO	(140) 180 GHz--2.5 THz, 1-2 pol; (143) 183 GHz--far IR, 1-2 pol;(67) 50, 183 GHz, 1-2 pol; (176) 50, 183 GHz, 1-2 pol;	narrowband, tunable, but stable sources powerful enough to drive corresponding downconverters, but low input power & small size
mmw/smmw detectors	140, 143, 67, 176	(140) Real, LEO; (143) Real, LEO; (67) STAR GEO; (176) Real, GEO	(140) 180 GHz--2.5 THz, 1-2 pol; (143) 183 GHz--far IR, 1-2 pol;(67) 50, 183 GHz, 1-2 pol; (176) 50, 183 GHz, 1-2 pol;	broadband heterodyne low-noise receivers, mixers, & compact LOs needed for the 50-900 GHz range.
MMIC/Miniature Radiometers & Low Mass/Power Receiver Elements (COMBINED these 2 challenges)	H1, H2, H3, 34, 106, 107, 108, 177, 143, 67, A1, A2, 38, 111, O1, C2/// H1, H2, H3, 34, 107, 108, 177, 67, A1, A2, 38, 111,	(H1) STAR, LEO; (H2) STAR, LEO; (H3) STAR, LEO; (34) 2D-STAR, LEO;(38) Real, LEO;(67) STAR, GEO;(106) Real, LEO; (107) 2D-STAR, LEO; (108) 1D-STAR, LEO; (111) Real, LEO; (143) Real, LEO; (177) STAR, LEO;(A1) STAR, LEO or UAV; (A2) STAR, LEO or UAV; (O1) Real, LEO; (C2) STAR, LEO///(H1) STAR, LEO; (H2) STAR, LEO; (H3) STAR, LEO; (34) 2D-STAR, LEO;(38) Real, LEO;(67) STAR, GEO; (107) 2D-STAR, LEO; (108) 1D-STAR, LEO; (111) Real, LEO; (177) STAR, LEO;(A1) STAR, LEO or UAV; (A2) STAR, LEO or UAV	(H1) L, 2-pol; (H2) L, 19, 37, 2-pol; (H3) L, 2-pol; (34) L, 2-3 pol;(38) L, 2-3 pol; (67) 50, 183 GHz, 1-2 pol;(106,107, 108) 19, 37 GHz, 1-2 pol; (111) L, 2-3 pol; (143) 183 GHz--far IR, 1-2 pol; (177) L, 2-3 pol; (A1) X, Ka, 2-pol; (A2) 4--10GHz, 1-2 pol; (O1) 6, 10 GHz, 2 pol; (C2) Ku, Ka, 2-pol////(H1) L, 2-pol; (H2) L, 19, 37, 2-pol; (H3) L, 2-pol; (34) L, 2-3 pol;(38) L, 2-3 pol; (67) 50, 183 GHz, 1-2 pol;(107) 19, 37 GHz, 1-2 pol; (108) 19, 37 GHz, 1-2 pol; (111) L, 2-3 pol; (177) L, 2-3 pol; (A1) X, Ka, 2-pol; (A2) 4--10GHz, 1-2 pol	Compact radiometers for instrument configurations with large numbers of and/or closely-spaced radiometers (e.g. STAR, focal line/plane arrays), or cases where radiometer must be located right at feed for lowest possible loss. For some applications, want MMIC/miniature radiometer integrated right at feed for low loss.

MEMS RF switches	H1, H2, H3, 34, 38, 107, 108, 111, 177, 143, 67, A1, A2, C2	(H1) STAR, LEO; (H2) STAR, LEO; (H3) STAR, LEO; (34) 2D-STAR, LEO;(38) Real, LEO;(67) STAR, GEO;(107) 2D-STAR, LEO; (108) 1D-STAR, LEO; (111) Real, LEO; (143) Real, LEO; (177) STAR, LEO;(A1) STAR, LEO or UAV; (A2) STAR, LEO or UAV; (C2) STAR, LEO	(H1) L, 2-pol; (H2) L, 19, 37, 2-pol; (H3) L, 2-pol; (34) L, 2-3 pol;(38) L, 2-3 pol; (67) 50, 183 GHz, 1-2 pol;(107) 19, 37 GHz, 1-2 pol; (108) 19, 37 GHz, 1-2 pol; (111) L, 2-3 pol; (143) 183 GHz--far IR, 1-2 pol; (177) L, 2-3 pol; (A1) X, Ka, 2-pol; (A2) 4--10GHz, 1-2 pol; (C2) Ku, Ka, 2-pol	(note: SOA 40 GHZ) low insertion loss & high isolation, small size/mass, high duty cycle/high lifetime switches for radiometer front ends. Package must be convenient to combine w/other MMIC components. Important calibration component.
MEMS filters	H1, H2, H3, 34, 38, 107, 108, 111, 177, 143, 67, A1, A2, C2	(H1) STAR, LEO; (H2) STAR, LEO; (H3) STAR, LEO; (34) 2D-STAR, LEO;(38) Real, LEO;(67) STAR, GEO;(107) 2D-STAR, LEO; (108) 1D-STAR, LEO; (111) Real, LEO; (143) Real, LEO; (177) STAR, LEO;(A1) STAR, LEO or UAV; (A2) STAR, LEO or UAV; (C2) STAR, LEO	(H1) L, 2-pol; (H2) L, 19, 37, 2-pol; (H3) L, 2-pol; (34) L, 2-3 pol;(38) L, 2-3 pol; (67) 50, 183 GHz, 1-2 pol;(107) 19, 37 GHz, 1-2 pol; (108) 19, 37 GHz, 1-2 pol; (111) L, 2-3 pol; (143) 183 GHz--far IR, 1-2 pol; (177) L, 2-3 pol; (A1) X, Ka, 2-pol; (A2) 4--10GHz, 1-2 pol; (C2) Ku, Ka, 2-pol	(note: SOA 1 GHZ) low insertion loss, high Q, good input/output match, small size/mass. Important for RF, LO, and IF filters. Potential for easily-reconfigurable filters. Package must be convenient to combine w/other MMIC components.
analog RFI Mitigation Technology	H1, H2, H3, 34, 38, 106, 107, 108, 111, 177, 176, A1, A2, O1,C2	(H1) STAR, LEO; (H2) STAR, LEO; (H3) STAR, LEO; (34) 2D-STAR, LEO;(38) Real, LEO;(106) Real, LEO; (107) 2D-STAR, LEO; (108) 1D-STAR, LEO; (111) Real, LEO; (177) STAR, LEO; (176) Real, GEO;(A1) STAR, LEO or UAV; (A2) STAR, LEO or UAV; (O1) Real, LEO; (C2) STAR, LEO	(H1) L, 2-pol; (H2) L, 19, 37, 2-pol; (H3) L, 2-pol; (34) L, 2-3 pol;(38) L, 2-3 pol; (106,107, 108) 19, 37 GHz, 1-2 pol; (111) L, 2-3 pol; (177) L, 2-3 pol; (176) 50, 183 GHz, 1-2 pol; (A1) X, Ka, 2-pol; (A2) 4--10GHz, 1-2 pol; (O1) 6, 10 GHz, 2 pol; (C2) Ku, Ka, 2-pol	frequency domain channelization; very high interchannel isolation (high out of band rejection); minimize impact on instrument design (small size, low loss)
combined active/passive system design	H1, H2, H3, 34, 38, 106, 107, 108, 111, 177, A1, A2	(H1) STAR, LEO; (H2) STAR, LEO; (H3) STAR, LEO; (34) 2D-STAR, LEO;(38) Real, LEO;(106) Real, LEO; (107) 2D-STAR, LEO; (108) 1D-STAR, LEO; (111) Real, LEO; (177) STAR, LEO;(A1) STAR, LEO or UAV; (A2) STAR, LEO or UAV;	(H1) L, 2-pol; (H2) L, 19, 37, 2-pol; (H3) L, 2-pol; (34) L, 2-3 pol;(38) L, 2-3 pol; (106,107, 108) 19, 37 GHz, 1-2 pol; (111) L, 2-3 pol; (177) L, 2-3 pol; (A1) X, Ka, 2-pol; (A2) 4--10GHz, 1-2 pol;	System design work and technology development as needed to enable antenna aperture sharing to accommodate active/passive systems; Field demonstration that shared aperture systems are capable of the highest stand-alone quality performance

3 or 4 stokes-polarimeteric receiver design	H1, H2, H3, 34, 38, 106, 107, 108, 111, A2, C2	(H1) STAR, LEO; (H2) STAR, LEO; (H3) STAR, LEO; (34) 2D-STAR, LEO;(38) Real, LEO;(106) Real, LEO; (107) 2D-STAR, LEO; (108) 1D-STAR, LEO; (111) Real, LEO; (A2) STAR, LEO or UAV; (C2) STAR, LEO	(H1) L, 2-pol; (H2) L, 19, 37, 2-pol; (H3) L, 2-pol; (34) L, 2-3 pol;(38) L, 2-3 pol; (106,107, 108) 19, 37 GHz, 1-2 pol; (111) L, 2-3 pol; (A2) 4--10GHz, 1-2 pol; (C2) Ku, Ka, 2-pol	bring up to TRL 6 level both polarimetric combining hybrid and direct <VH> correlating approaches to measuring the 3rd and 4th Stokes TBs
correlation radiometer calibration subsystem	H1, H2, H3, 34, 38, 106, 107, 108, 111, 177, 140, 143, 67, A1, A2, 176, C2, O1	(H1) STAR, LEO; (H2) STAR, LEO; (H3) STAR, LEO; (34) 2D-STAR, LEO;(38) Real, LEO;(67) STAR GEO;(106) Real, LEO; (107) 2D-STAR, LEO; (108) 1D-STAR, LEO; (111) Real, LEO; (177) STAR, LEO; (176) Real, GEO;(A1) STAR, LEO or UAV; (A2) STAR, LEO or UAV; (O1) Real, LEO; (C2) STAR, LEO;(140) 180 GHz--2.5 THz, 1-2 pol; (143) 183 GHz--far IR, 1-2 pol	(H1) L, 2-pol; (H2) L, 19, 37, 2-pol; (H3) L, 2-pol; (34) L, 2-3 pol;(38) L, 2-3 pol;(67) 50, 183 GHz, 1-2 pol; (106,107, 108) 19, 37 GHz, 1-2 pol; (111) L, 2-3 pol; (177) L, 2-3 pol; (176) 50, 183 GHz, 1-2 pol; (A1) X, Ka, 2-pol; (A2) 4--10GHz, 1-2 pol; (O1) 6, 10 GHz, 2 pol; (C2) Ku, Ka, 2-pol;(140) 180 GHz--2.5 THz, 1-2 pol; (143) 183 GHz--far IR, 1-2 pol;	track variations in critical signal processing stages of modern radiometers, e.g. polarimetric hybrid combining networks, cross-correlators, spectrometer baselines; stable noise diodes,
on-board RF signal distribution	H1, H2, H3, 34, 38 107, 108, 111, 177, 67, A1, A2, C2	(H1) STAR, LEO; (H2) STAR, LEO; (H3) STAR, LEO; (34) 2D-STAR, LEO;(38) Real, LEO;(67) STAR, GEO;(107) 2D-STAR, LEO; (108) 1D-STAR, LEO; (111) Real, LEO; (177) STAR, LEO;(A1) STAR, LEO or UAV; (A2) STAR, LEO or UAV; (C2) STAR, LEO	(H1) L, 2-pol; (H2) L, 19, 37, 2-pol; (H3) L, 2-pol; (34) L, 2-3 pol;(38) L, 2-3 pol; (67) 50, 183 GHz, 1-2 pol;(107,108) 19, 37 GHz, 1-2 pol; (111) L, 2-3 pol; (177) L, 2-3 pol; (A1) X, Ka, 2-pol; (A2) 4--10GHz, 1-2 pol; (C2) Ku, Ka, 2-pol	Coherent (phase locked) local oscillators need to be distributed over electrically and physically large areas to enable future STAR systems. Correlated broadband RF noise sources need to be distributed over electrically and physically large areas to enable future STAR systems.

ultrastable low loss radiometers	H1, H3, 34, 38, 107, 108, 111, 177, 67, A1, A2, C2, O1	(H1) STAR, LEO; (H2) STAR, LEO; (H3) STAR, LEO; (34) 2D-STAR, LEO;(38) Real, LEO;(67) STAR, GEO;(107) 2D-STAR, LEO; (108) 1D-STAR, LEO; (111) Real, LEO; (177) STAR, LEO;(A1) STAR, LEO or UAV; (A2) STAR, LEO or UAV; (O1) Real, LEO; (C2) STAR, LEO	(H1) L, 2-pol; (H2) L, 19, 37, 2-pol; (H3) L, 2-pol; (34) L, 2-3 pol;(38) L, 2-3 pol; (67) 50, 183 GHz, 1-2 pol;(107,108) 19, 37 GHz, 1-2 pol; (111) L, 2-3 pol; (177) L, 2-3 pol; (A1) X, Ka, 2-pol; (A2) 4--10GHz, 1-2 pol; (O1) 6, 10 GHz, 2 pol; (C2) Ku, Ka, 2-pol	stable radiometer components & subsystems, as well as stable system design techniques subject to satellite resource constraints; likely to be closely linked to trades with respect to calibration approach

APPENDIX 4I: TECHNOLOGY ROADMAPS FOR RADIOMETER ELECTRONICS

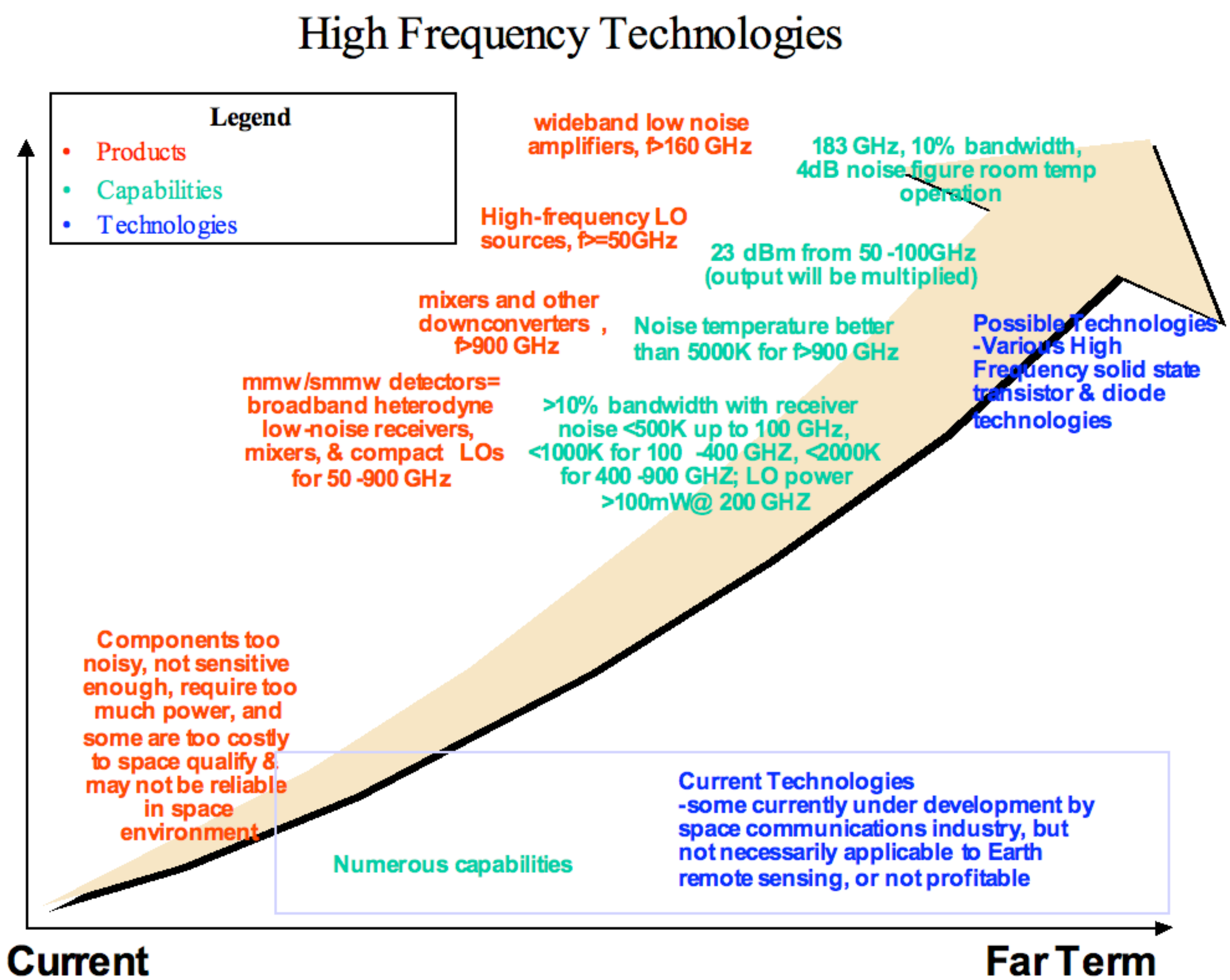


Figure 4I1

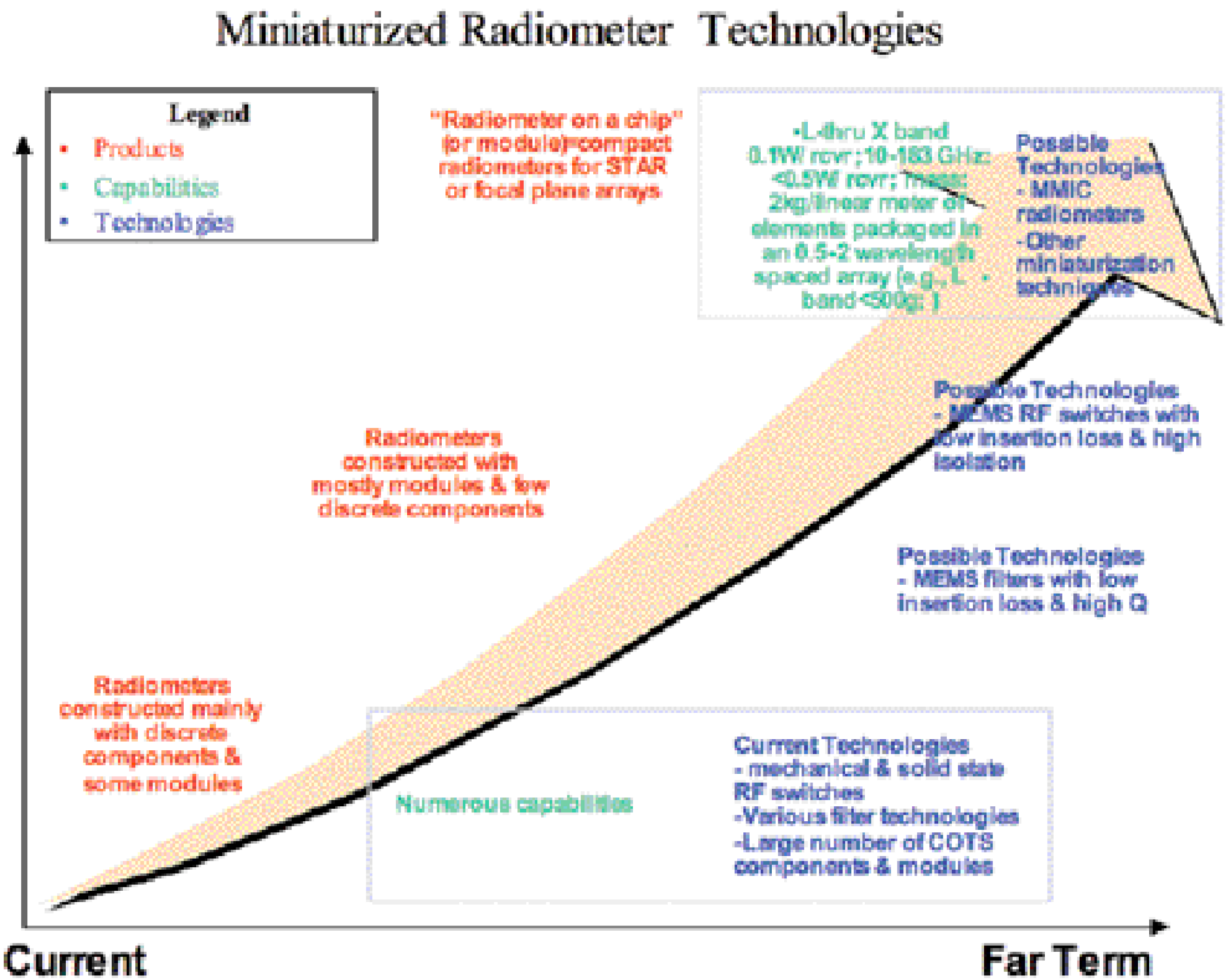

Miniaturized Radiometer Technologies
Legend
Products
Capabilities
Technologies
"Radiometer on a chip" (or module)=compact radiometers for STAR or focal plane arrays
Possible Technologies
- MMIC radiometers
-Other miniaturization techniques
Possible Technologies
- MEMS RF switches with low insertion loss & high isolation
Radiometers constructed with mostly modules & few discrete components
Possible Technologies
- MEMS filters with low insertion loss & high Q
Radiometers constructed mainly with discrete components & some modules
Numerous capabilities
Current Technologies
- mechanical & solid state RF switches
-Various filter technologies
-Large number of COTS components & modules
Current
Far Term

Figure 412

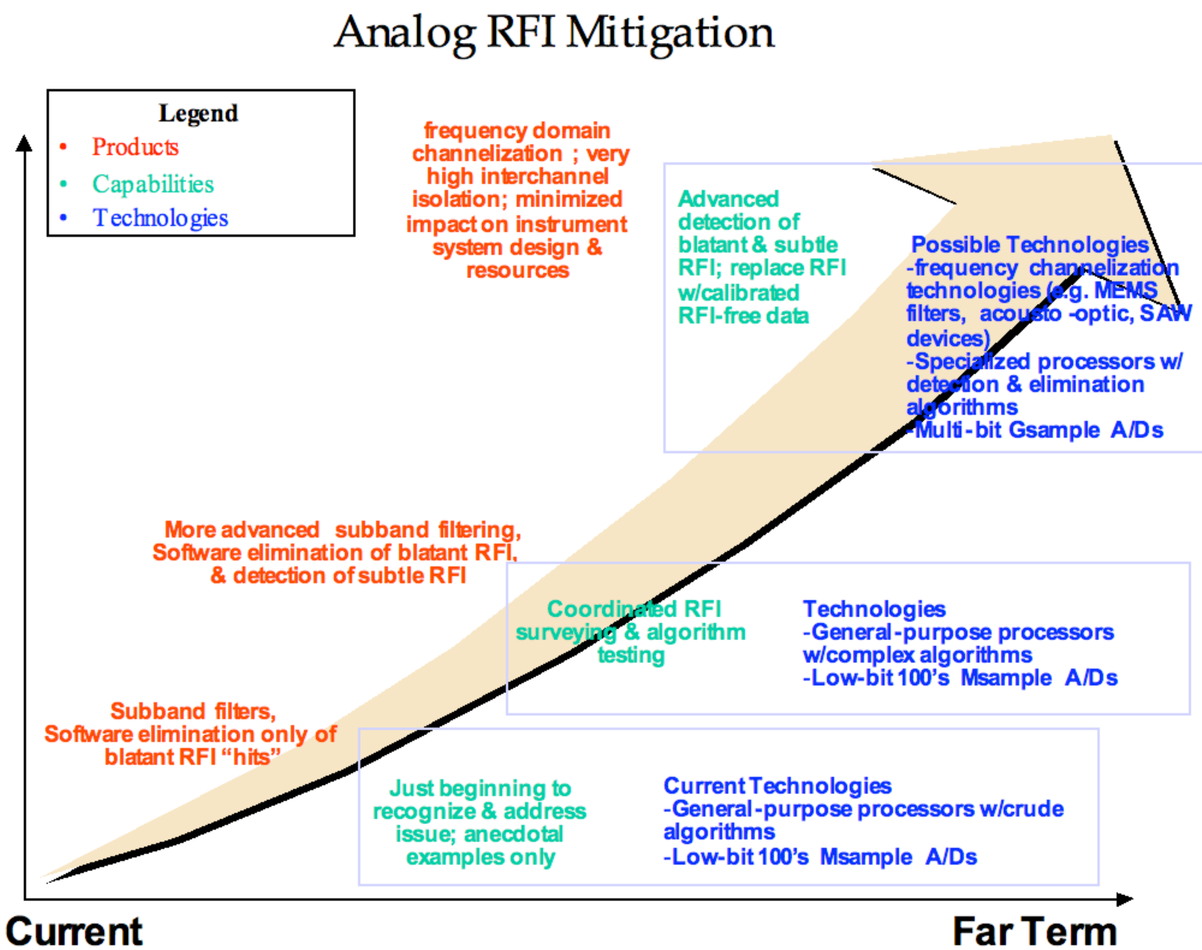

Analog RFI Mitigation
Legend
Products
Capabilities
Technologies
frequency domain channelization ; very high interchannel isolation; minimized impact on instrument system design & resources
Advanced detection of blatant & subtle RFI; replace RFI w/calibrated RFI-free data
Possible Technologies
-frequency channelization technologies (e.g. MEMS filters, acousto -optic, SAW devices)
-Specialized processors w/ detection & elimination algorithms
-Multi-bit Gsample A/Ds
More advanced subband filtering, Software elimination of blatant RFI, & detection of subtle RFI
Coordinated RFI surveying & algorithm testing
Technologies
-General-purpose processors w/complex algorithms
-Low-bit 100's Msample A/Ds
Subband filters, Software elimination only of blatant RFI "hits"
Just beginning to recognize & address issue; anecdotal examples only
Current Technologies
-General-purpose processors w/crude algorithms
-Low-bit 100's Msample A/Ds
Current
Far Term

Figure 4I3

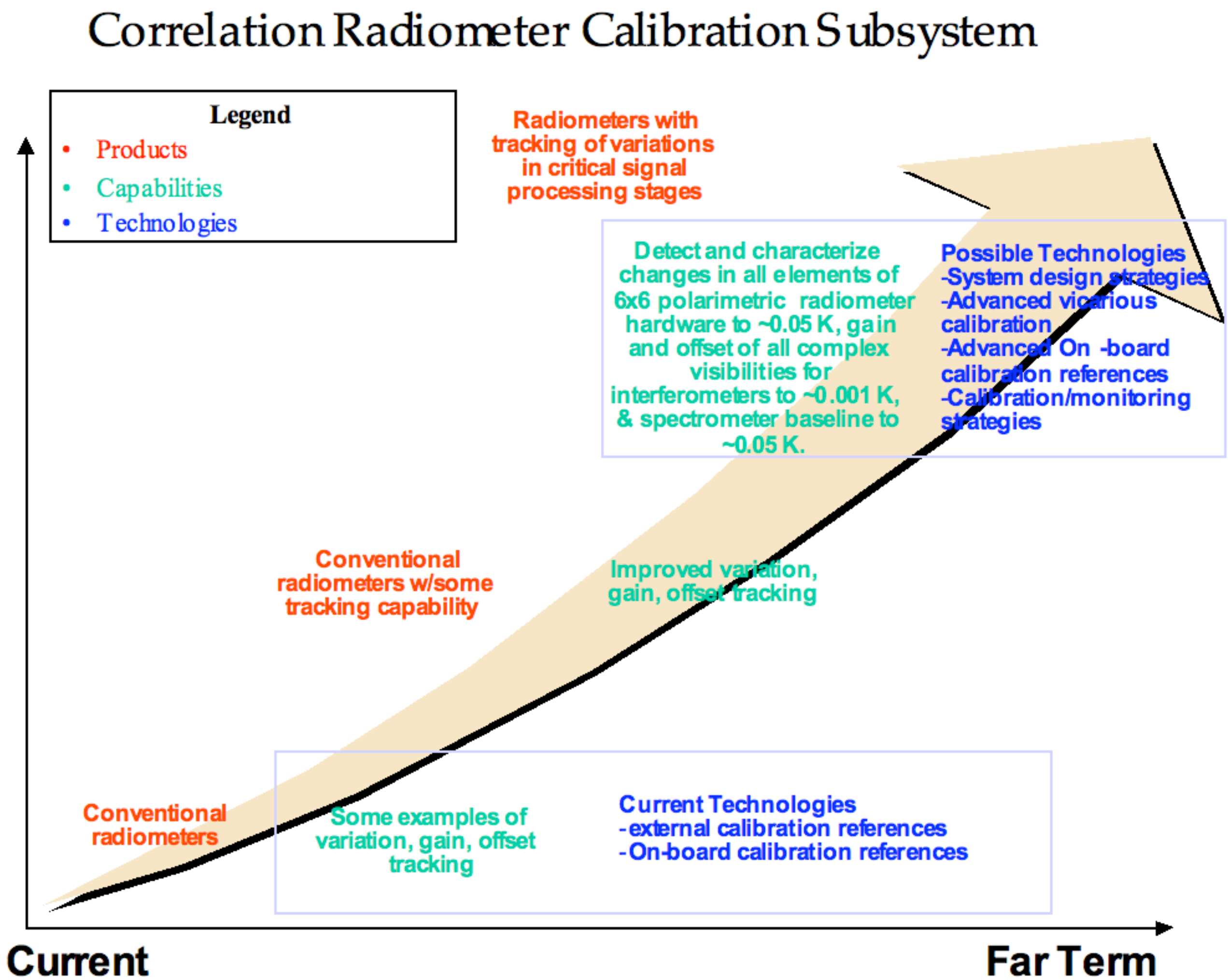

Correlation Radiometer Calibration Subsystem
Legend
Products
Capabilities
Technologies
Radiometers with tracking of variations in critical signal processing stages
Detect and characterize changes in all elements of 6x6 polarimetric radiometer hardware to ~0.05 K, gain and offset of all complex visibilities for interferometers to ~0.001 K, & spectrometer baseline to ~0.05 K.
Possible Technologies
-System design strategies
-Advanced vicarious calibration
-Advanced On -board calibration references
-Calibration/monitoring strategies
Conventional radiometers w/some tracking capability
Improved variation, gain, offset tracking
Conventional radiometers
Some examples of variation, gain, offset tracking
Current Technologies
-external calibration references
-On-board calibration references
Current
Far Term

Figure 4I4

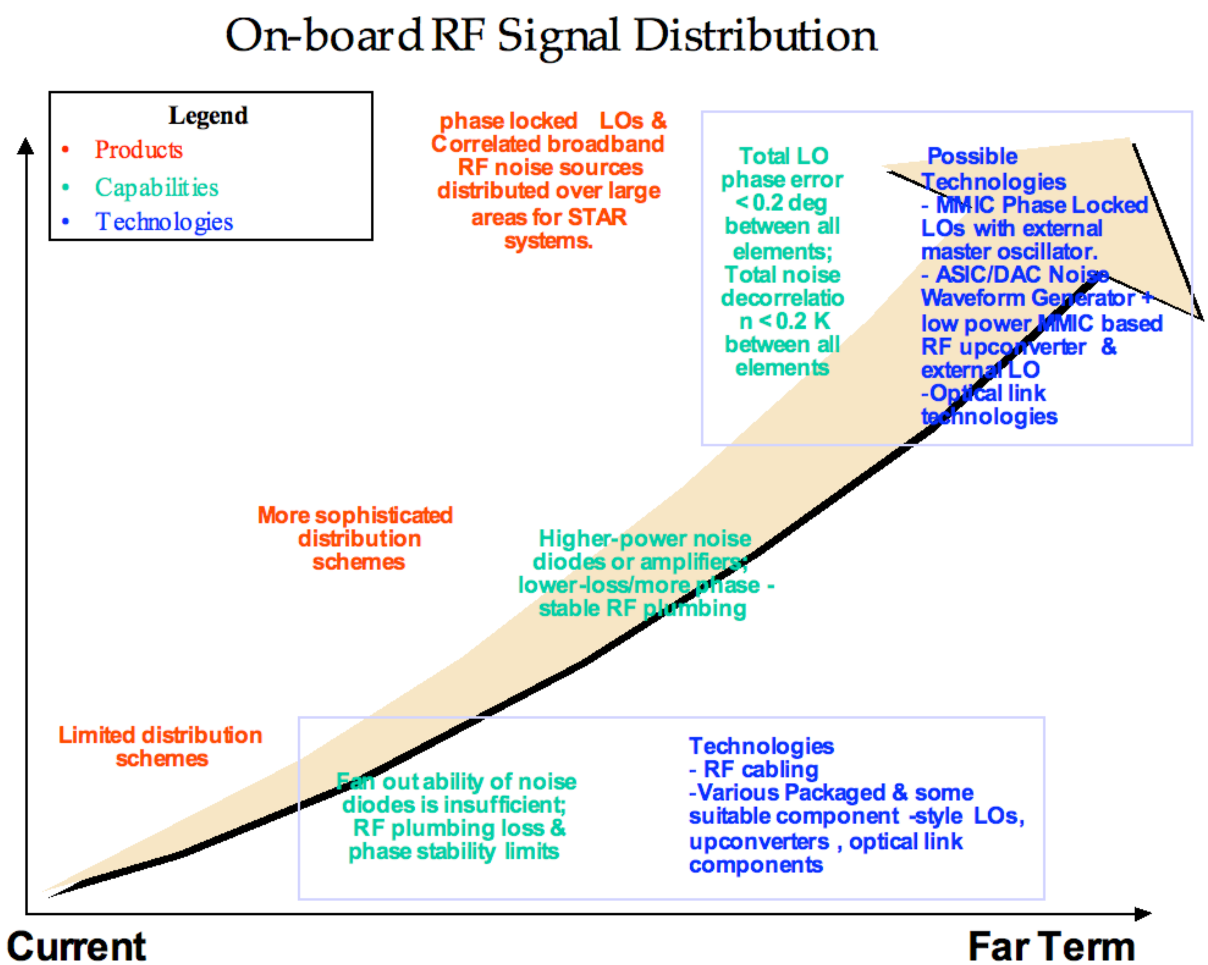

On-board RF Signal Distribution
Legend
Products
Capabilities
Technologies
phase locked LOs & Correlated broadband RF noise sources distributed over large areas for STAR systems.
Total LO phase error < 0.2 deg between all elements; Total noise decorrelation < 0.2 K between all elements
Possible Technologies
- MMIC Phase Locked LOs with external master oscillator.
- ASIC/DAC Noise Waveform Generator + low power MMIC based RF upconverter & external LO
-Optical link technologies
More sophisticated distribution schemes
Higher-power noise diodes or amplifiers; lower-loss/more phase - stable RF plumbing
Limited distribution schemes
Fan out ability of noise diodes is insufficient; RF plumbing loss & phase stability limits
Technologies
- RF cabling
-Various Packaged & some suitable component -style LOs, upconverters , optical link components
Current
Far Term

Figure 4I5

3 or 4 Stokes-Polarimetric Receiver Design

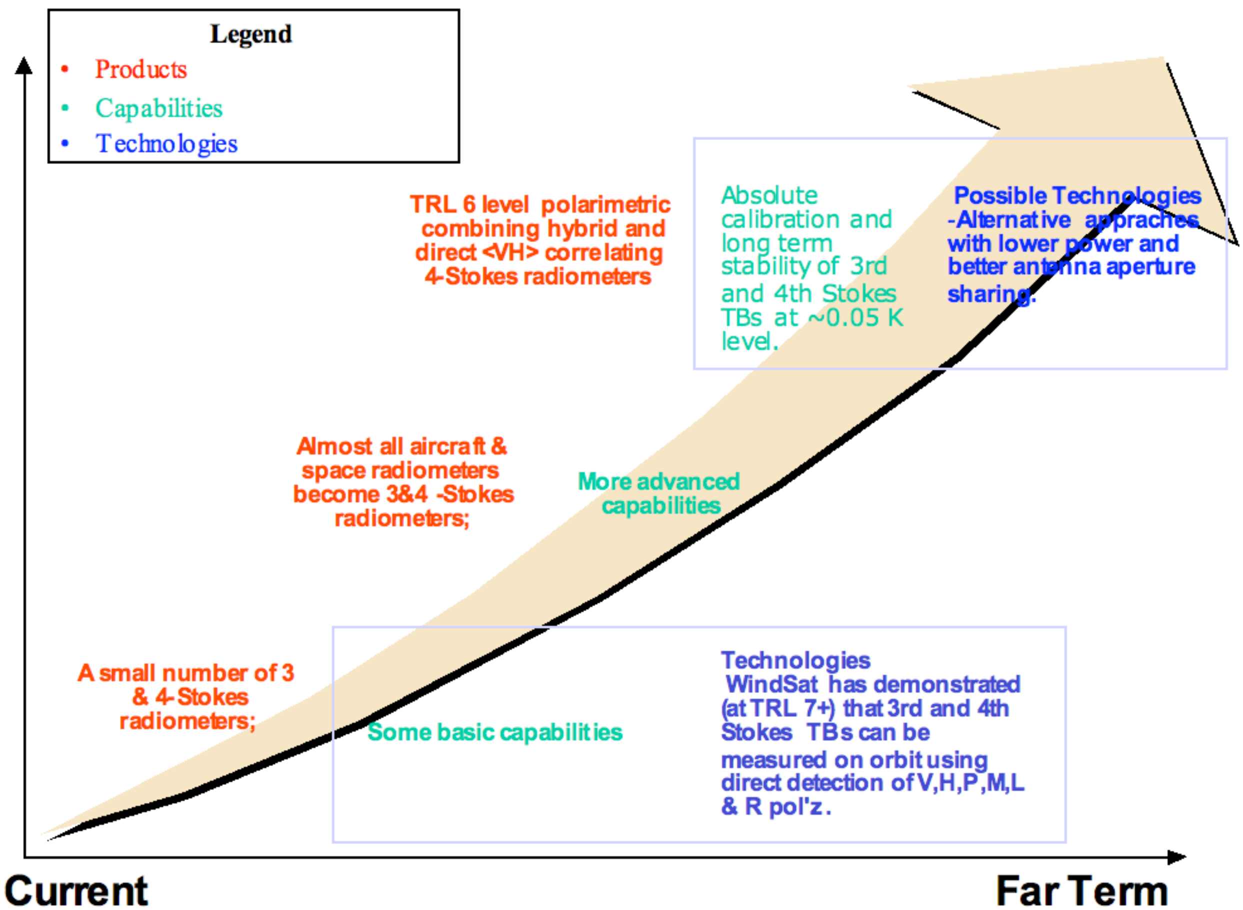


Figure 4I6

Ultrastable Low Loss Radiometers

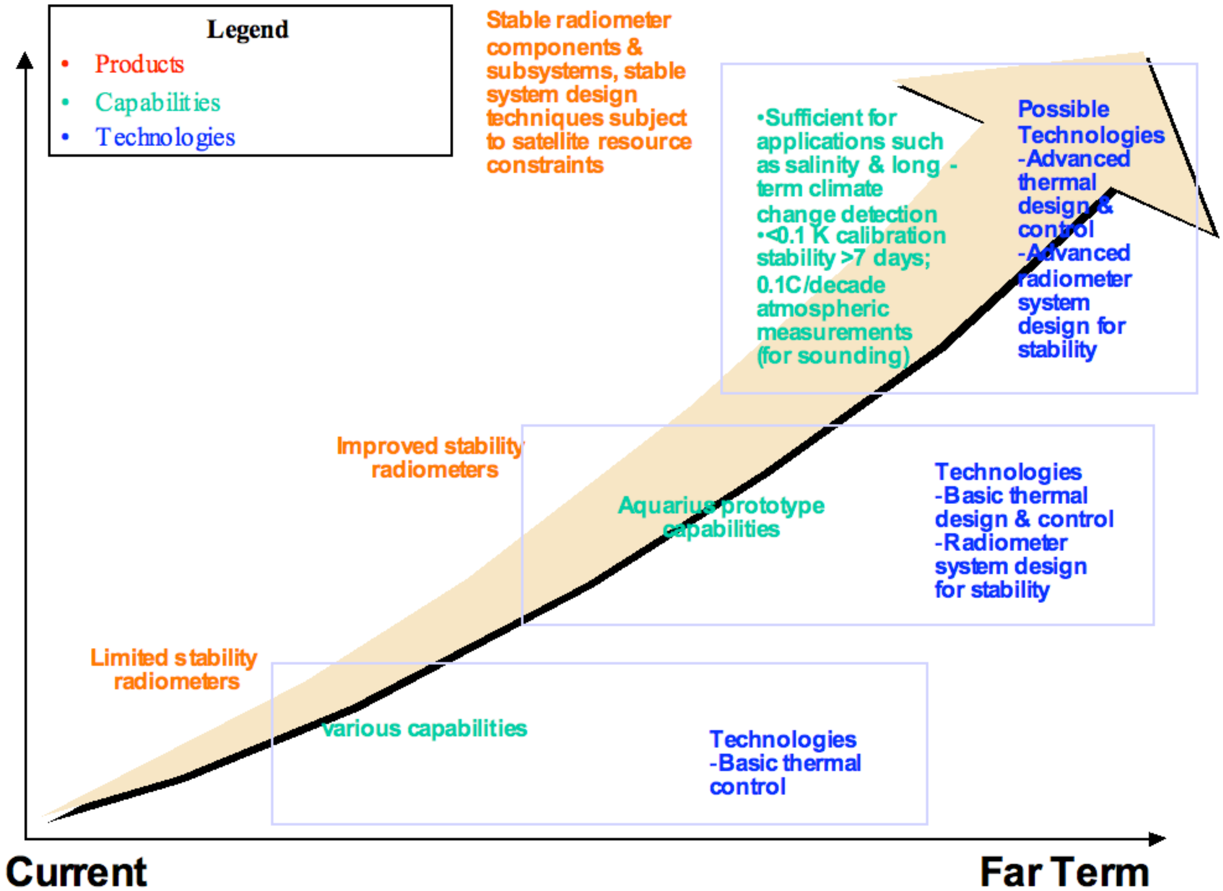


Figure 4I7

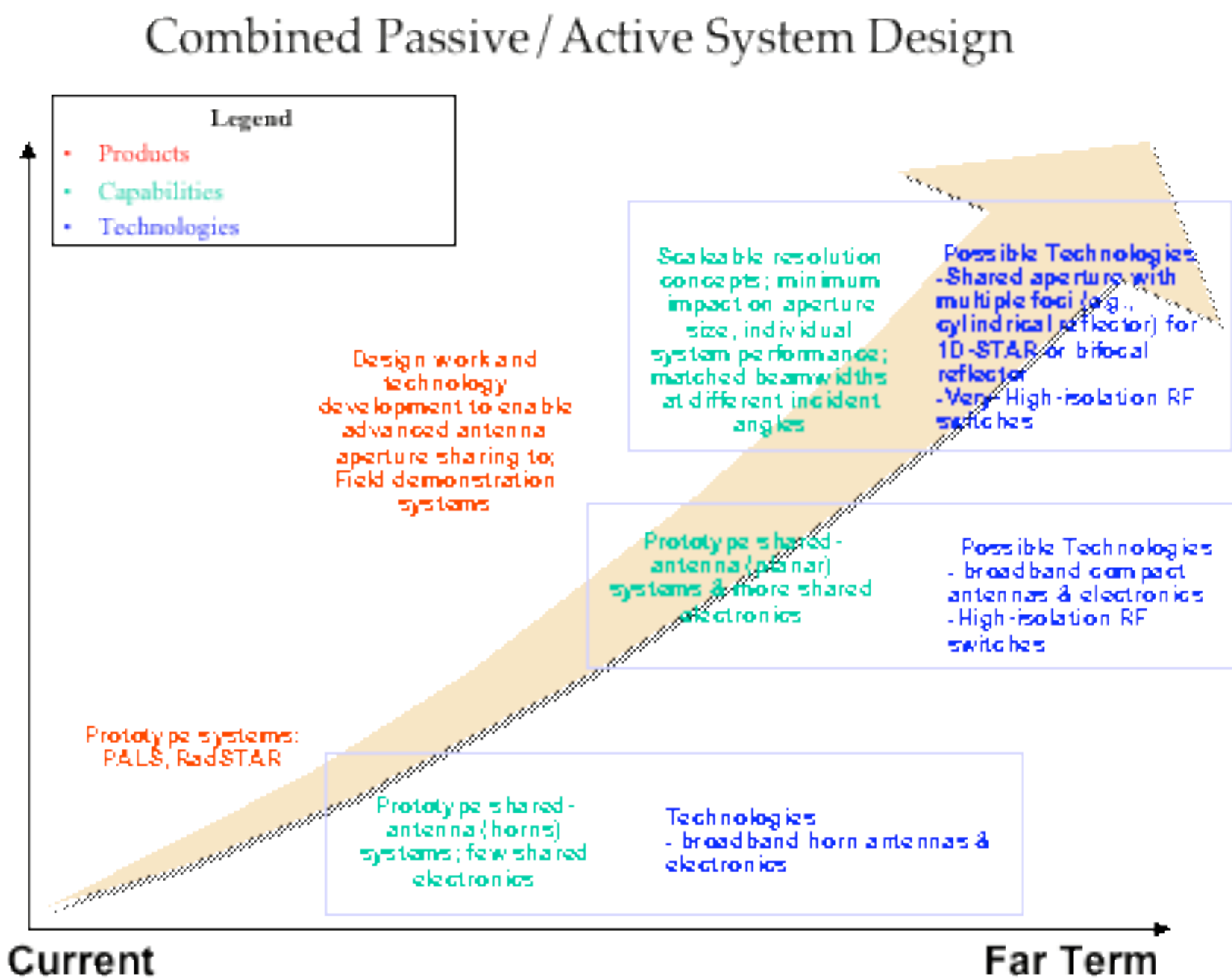

Combined Passive / Active System Design
Legend
Products
Capabilities
Technologies
Scalable resolution concepts; minimum impact on aperture size, individual system performance; matched beamwidths at different incident angles
Possible Technologies
-Shared aperture with multiple foci (e.g., cylindrical reflector) for 1D-STAR or bifocal reflector
-Very High-isolation RF switches
Design work and technology development to enable advanced antenna aperture sharing to; Field demonstration systems
Prototype shared-antenna (planar) systems & more shared electronics
Possible Technologies
- broadband compact antennas & electronics
- High-isolation RF switches
Prototype systems: PALS, RadSTAR
Prototype shared-antenna (horns) systems; few shared electronics
Technologies
- broadband horn antennas & electronics
Current
Far Term

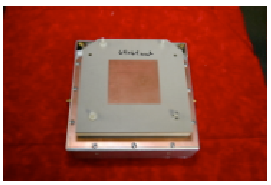
Figure 4.15

Appendix 4J: Technology Roadmaps for Passive Antennas

Below are the individual passive antenna roadmaps.

Low Profile Lightweight Low-Loss Array Feeds

For STAR and Pushbroom arrays



Current Status

1. L-band single elements and small arrays of dual-polarization patch antennas with good bandwidth and polarization properties have been demonstrated. However, these utilize relatively heavy standard teflon-glass laminates, and are not viable for 25 m length linear arrays for 2 -pol and 3-pol operation.
2. X-, Ku-, and Ka-band STAR or pushbroom arrays require novel antenna designs that can provide low loss dual-polarization conical scan.

Tasks needed

1. Demonstrate performance of sub -array configurations using lightweight laminations of multiple stacked patches on thin substrates with foam or other low relative dielectric constant layers, adaptable to 1D or 2D STAR arrays.
2. POC hybrid patch arrays on thin substrates excited by waveguide crossed -slot arrays and combined with shaped reflectors need to be developed and demonstrated.
3. Expand on current waveguide array (WGA) designs (e.g. LRR airborne instrument) with higher frequencies, wider bandwidths, dual -polarization and conically -scanned versions
4. Model and trade cross polarization levels of Microstrip (MS) patch and WGA elements with other parameters during development
5. Develop and demonstrate antenna feed system that meets L-band bandwidth 1.26 – 1.4 GHz, isolation and beam efficiency requirements for shared active/passive aperture

Current TRLs: (3) Array performance
(2) Lightweight materials
Exit TRL: (6)

Figure 4J1

Steerable Subreflectors
For Calibration of Large Apertures Radiometers

Concept

MEMS-switched frequency selective surface (FSS) dual frequency sub-reflector

Provides the ability to electrically steer large focal plane and focal line arrays away from main reflector and to cold space for end-to-end system calibration

Apply to FPA for torus antenna – and/or other antenna concepts

Tasks needed

1. Adapt existing MEMS-based Frequency Selective Surface technique to RSS application (TRL 2 – 3).
2. Develop a prototype RSS based subreflector antenna system. Characterize loss, reflectivity, impact on other radiometer figures of merit.
3. Develop a focal line array using RSS subreflector (TRL 3–4).
4. Combine RSS focal line array with laboratory radiometer and verify system calibration and stability (TRL 4 to 5).
5. Build field deployable instrument and use in science campaign. Verify ability to retrieve Level 2 EDRs with acceptable accuracy and uncertainty. (TRL 5 to 6).

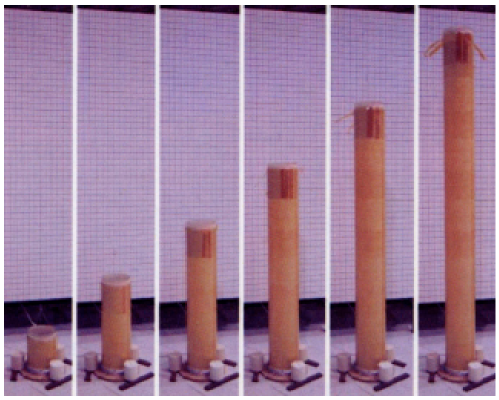
Status

1. Frequency/reflectivity selective surface (RSS) concept applied to radiometry: TRL 2
2. Other concepts needed for end-to-end calibration

Current TRL: 2
Exit TRL: 6

Figure 4J2

Lightweight Structural Elements



Tasks needed

1. Trade study involving best candidate concepts for support elements integrated with the desired electronics/antenna elements
2. Develop the structural support arm concept, build a nondeployable version and test structural characteristics
3. Develop deployable arm/column
4. Deployment test and structural characteristics test/verification

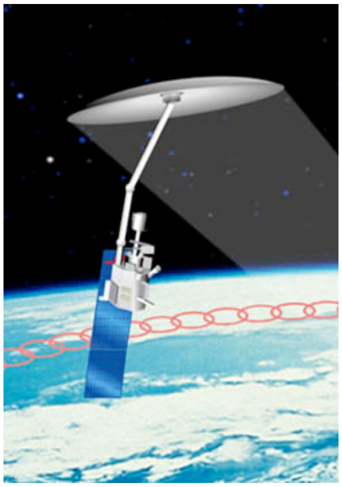
Requirements

1. Less than 0.1 kg/m and must be able to support distributed science sensing element mass, data and power cabling integrated into the structure
2. Self Correcting to ? /20RMS surface distortion

Current TRL: 3
Exit TRL: 6

Figure 4J3

Large Rotating Reflector



Tasks needed for 6 – 20 m rotating reflector

1. Develop optimal system design based on science requirements
2. Lightweight deployable reflector
3. Design reflector boom feed stowage relative to projected designs and capabilities
4. Develop and test multi frequency multi -polarization horn or patch feed design matched to reflector geometry to meet overall beamwidth, beam efficiency and cross polarization requirements
5. Design and test momentum compensation and balancing
6. Analyze thermal and mechanical distortions, calibration system, and overall system error budget and performance
7. In support of #3 develop antenna metrology and compensation techniques to ensure minimum performance can be met

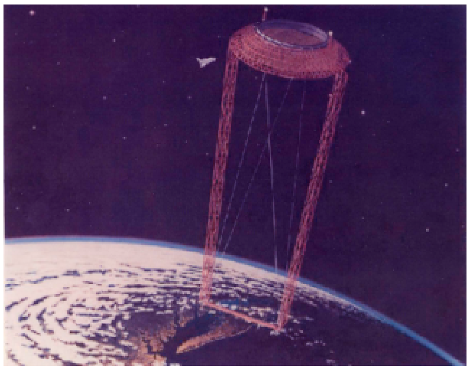
Current Status

1. HYDROS – 6m rotating aperture: scheduled for launch in 2009
2. Feedback suggests 20 – 25 m may be upper range of feasibility for rotating aperture – for larger apertures should consider stationary parabolic torus antenna – system trades involving industry are needed

Current TRL: 4
Exit TRL: 6

Figure 4J4

Large Deployable Non-Rotating Reflector Antenna (Torus)



<u>Tasks needed in support of ~50 m parabolic torus</u>

1. Develop optimal system design based on science requirements
2. Design reflector boom feed stowage relative to projected designs and capabilities (50m X 25m parabola)
3. Develop and test multi frequency multi -polarization subreflector and patch array feed design matched to the reflector geometry to meet overall beam width, beam efficiency and polarization requirements
4. Design and test momentum compensation (for the feed system) and balancing
5. Analyze thermal and mechanical distortions, calibration system, and overall system error budget and performance
6. In support of #3 develop antenna metrology and compensation techniques to ensure minimum performance can be met

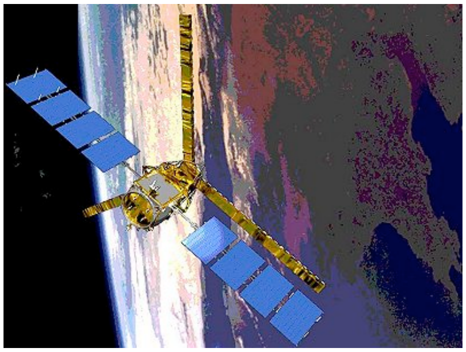
Current Status

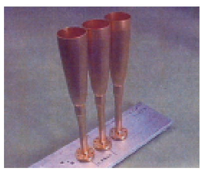
1. HYDROS – 6m rotating aperture: scheduled for launch in 2009
2. Feedback suggests 20 – 25 m may be upper range of feasibility for rotating aperture – for larger apertures should consider stationary parabolic torus antenna – system trades involving industry are needed

Current TRL: 4
Exit TRL: 6

Figure 4J5

2D STAR
With Antenna Feedhorns





Tasks needed to support STAR development

1. Scalability for GEO flight design concepts
2. Extrapolate design to 183 GHz case
3. Low recurring cost for large scale fabrication of identical units
4. Evaluate different feedhorn options: conduct camber test and modify feedhorn design as needed
5. Integrate into laboratory interferometer testbeds
6. Integrate into field deployable prototypes
7. Conduct thermal and mechanical studies in parallel with above

Requirements

1. Flood beam element patterns with ultra-low mutual coupling, low-loss, and ultra stable phase center location vs. temperature
2. < 30dB mutual coupling between immediately adjacent antennas
3. < 0.2dB ohmic losses below 50 GHz; <0.3dB at 50/60, 183 GHz
4. Phase center stability to ?/100 over –40 to +40C temperature range

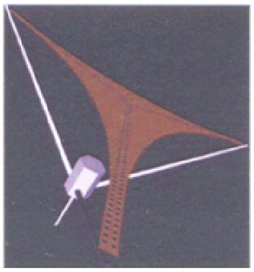
Current Status

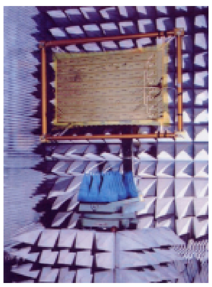
1. Current GEOSTAR prototype has adequate performance for an electrically-small design

Current TRL: 3+
Exit TRL: 6

Figure 4J6

2D STAR
With Ultra-lightweight Elements and Tensioned Membranes





Tasks needed to support STAR antenna development

1. Develop ultra-lightweight deployable antenna technology using tensioned panels and membranes with integrated RF electronics and antenna elements
2. Develop non-deployable test article
3. Develop antenna metrology and aperture control methodology
4. Characterize structural dynamics
5. Integrate low power radiometer electronics onto/into antenna element and structure in a non-deployable scale model
6. Develop flight like tensioned membrane panels
7. Analyze thermal and mechanical distortions and investigate thermal monitoring of micro-miniature electronics

Current Status

1. STI -- Phase 0 studies ongoing
2. One-third scaled test article under development

Requirements

1. l/20 RMS
2. ~20m (full size) diameter
3. Lightweight, low loss integrated arrays

Current TRL: 2+
Exit TRL: 4-5

Figure 4J7

1D STAR
With Lightweight ~3m parabolic cylinder reflector

Tasks needed for 1D STAR development

1. Demonstrate lightweight reflector/feed system deployment and electrical performance.
2. Design reflector and support structure.
3. Design high efficiency, low mutual coupling, lightweight line feed array compatible with antenna structure; dual frequency/dual polarization
4. Lightweight compact 6x12 -m parabolic cylinder reflector
5. Antenna metrology and compensation of reflector distortion

Requirements

1. Dual polarization at 18 & 37 GHz.
2. Spatial resolution of 5 -km with similar imaging performance compared to a real aperture conical imager.
3. Large (>6x12 meter) cylindrical parabolic reflector fed by 1-D STAR linear feed - stowable/deployable.

Status

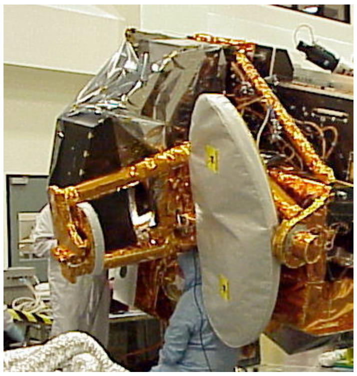
1. Study underway at BATC
2. Measurement scenario 108

Current TRL: 3

Exit TRL: 6

Figure 4J8

Millimeter Wave and Sub-mmw Measurements
for Ozone Profile and Atmospheric Composition



MLS instrument on EOS Aura

Current Status

1. A conceptual design exists to meet the requirements listed in measurement scenario 140

Tasks for reducing schedule/cost risk in development

1. Demonstrate mathematical design (using geometrical and physical optics) that allows very broad scanning in azimuth
2. Develop a structural concept for the scanning antenna system with fabrication of breadboard units

Antenna System Requirements

1. Antenna system for scanning Earth's limb with ~2 km vertical and ~20 km horizontal resolution at 200 GHz
2. Reflector surface accuracy of ~10 micrometers
3. Capability of vertically -scanning ~ 1 degree in ~10 s, and azimuth scanning ~ ±75 degrees in ~0.5 s.

Current TRL: 2
Exit TRL: 4 - 5

Figure 4J9

APPENDIX 4K: PROCESSING TECHNOLOGY CBS

Technology	Measurement Scenario	Instrument Type	Waveband	Needed Functional Product	Quantitative Requirement	Task	Subtask	Explanation	TRL @ Start	TRL @ End	Develop-ment Period (years)	Year Needed (at least 3 years before launch)	Point of Contact		
													POC Name	POC Phone	POC e-mail
e.g. deployable antenna, high-speed processor, increased data storage, etc.	*ID # and a short description*	*e.g. sounder, SAR, STAR, etc.*	*frequency or waveband of measurement scenario*	*describe the final functional product*	*describe the specific levels of performance required by the technology to achieve measurement.*	*identify specific tasks to mature the tech to target TRL*	*if necessary, identify subtasks needed to support task*	*explain how the task contributes to the advancement to the next TRL*	*state the current TRL*	*state the target TRL*	*time required to mature the technology to target TRL*	*state year the tech needs to achieve TRL 6*	*Person responsible for filling in this entry*		
Large onboard data storage	Snow cover,freeze/thaw, accumulation, and water equivalent using electronically scanning radiometer (F), Ocean surface current from dual frequency X-Band correlation Radar (A), Polar ice sheet/glacier velocity from repeat-pass L-band InSAR (92), Ice sheet and glacier absolute elevation and surface relief from SAR altimetery (93), Sea ice extent/motion using Ku-band scatterometer (90), Sea ice motion and deformation by means of C-band SAR (B), Sea ice thickness inferred from freeboard from InSAR (97), Snow cover,freeze/thaw, accumulation, & water equivalent using a Ku-band scatterometer (102), Surface deformation stress using one (or more) SARs (44a), Land surface topography using two SARs in formation (44b), Surface deformation & stress, land surface topography, using a constellation of SARs at MEO (45), Surface deformation, stress, & land using P-band polarimetric SAR (19), Vegitation biomass characteristics using repeat-pass L-band InSAR (158), Land cover types & use using fully polarimetric L-band SAR (162), Freeze-thaw transition & growing season with SAR (22), Snow cover, accumulation & water equivalent using Ku-band scatterometer (102), Snow cover, accumulation & water content using Ku-band InSAR (103), Snow cover, accumulation and water equivalent using Ku/L-band InSAR (104), Snow cover, accumulation & water equivalent using Ku/L-band polarimetric SAR (105), Ocean surface topography using Ka-band SAR (28, also refered to as 26), Ocean Surface Topography using an interferometric radar altimeter at LEO (29, also refered to as 27)	Applicable to SAR, interferometric radar, radar altimeter, scatterometer, etc.	Any Waveband	Large data storage consists of numerous memory modules. Each module consists of several memory chips with necessary EDAC functions.	Radiation tolerance > 300 kRad (LEO, 5 years), 1MRad MEO, Memory clock > 100 MHz, Data volume > 1 Tbit, Power during access < 100 W	Develop memory packaging technology to reduce memory module siz e		Research is required to achieve high packing density of available memory chips to minimize volume while maintaining adequate thermal control	4	6	1.5 ~ 2 years	2006	Frank Stott/JPL	818.354.3070	Frank.Stott@jpl.nasa.gov

Technology	Measurement Scenario	Instrument Type	Waveband	Needed Functional Product	Quantitative Requirement	Task	Sub-task	Explanation	TRL @ Start	TRL @ End	Develop-ment Period (years)	Year Needed (at least 3 years before launch)	Point of Contact		
													POC Name	POC Phone	POC e-mail
Processing Algorithms	I Doppler rain profiling radar in Geostationary orbit (160)	GEO Rain Radar	94 GHz band	Unambiguous rain radar data from GEO	Suppression of surface ambiguities to -60 dB	Research and development into algorithms capable of discriminating off-nadir rain signatures from ground returns at different ranges		Current rain radars are limited to low orbits and nadir profiles because returns from the surface would corrupt off-nadir rain signatures	1	4	4	2010	Paul Rosen	818.354. 0023	Paul.Rosen @jpl.nasa.g ov
	Land surface topography using two SARs in formation (44b), Sea ice thickness inferred from freeboard from InSAR (97)	LEO Land and Ice Surface Topography	1.25-10 GHz	Real-time algorithms for producing accurate topography from either two spacecraft flying tandem or a dual aperture system	DTED-3 global	Real-time algorithms for spaceborne radar interferometry		SRTM showed that DTED-2 mapping using single pass can be done. Algorithms are needed for real-time implementations for dual spacecraft operations, including time transfer and real-time baseline estimation	3	6	3	2008	Paul Rosen	818.354. 0023	Paul.Rosen @jpl.nasa.g ov
	Deformation, stress, and land surface topography employing SAR at MEO (45),Ocean surface winds using scatterometer at MEO (148), Atmospheric temperature & water vapor, global precipitation continuous measurements using a non-scanning microwave radiometer	MEO Surface Deformation	1.25 GHz	Imagery from data taken at high MEO orbits	20 m resolution, 1 m location accuracy	Efficient algorithms to account for along track orbit curvature variability in high MEO orbits.		Strip-map processing algorithms for data taken from high MEO require spot-light mode like algorithms	2	6	3	2010	Paul Rosen	818.354. 0023	Paul.Rosen @jpl.nasa.g ov
	Using a closely-spaced terrestrial network of GPS receivers employing GPS bands L1 and L2 (51)	Real-time GPS	1.25 GHz	Real-time algorithms for position and velocity determination	5 cm real-time in all dimensions, with a goal of 1 cm accuracy	Algorithms to deal with multi-path errors in real-time		Principal limitations of real-time GPS is time-variable multi-path. Mitigation strategies required	2	6	3	2006	Yoaz Bar-Sever /JPL	818.354. 2665	Yoaz.Bar-Sever@jpl.n asa.gov

Technology	Measurement Scenario	Instrument Type	Waveband	Needed Functional Product	Quantitative Requirement	Task	Sub-task	Explanation	TRL @ Start	TRL @ End	Develop-ment Period (years)	Year Needed (at least 3 years before launch)	Point of Contact		
													POC Name	POC Phone	POC e-mail
Processing Algorithms	Using a UHF/VHF polarimetric SAR (112), Generally scenario 161 denotes direct measurement employing formation flying in support of monostatic and bistatic sounding (161A)	UHF/VHF polarimetric SAR	100 MHz - 700 MHz	Polarimetric UHF/VHF imagery from space	100 m resolution, 1 db radiometric accuracy	Algorithms to produce radiometrically accurate polarimetric images from space in the presence of ionospheric contamination and RFI.		Ionosphere and RFI corrupts measurements at low frequencies from space.	2	6	3	2008	Paul Rosen	818.354. 0023	Paul.Rosen @jpl.nasa.gov
High-Performance RHP	1) Profiles of water vapor, temperature, pressure and various atmospheric constituents through absorption (68), Atmospheric temperature & water vapor, global precipitation continuous measurements using a non-scanning microwave radiometer sounder at GEO (67)	Atmospheric sounder, atmospheric profiler, SAR, scatterometer, radar altimeter	Ku, X, S, C, L, P	ATMOSPHERIC PARAMETERS: water vapor, ozone, temperature, pressure profiles.	To ensure uninterrupted data stream for continuous scientific observation and modeling, the High-Performance RHP should constantly process data during the minimum mission lifetime, usually of three years, with graceful degradation thereafter.	(1) DEVICES TECHNOLOGY: radiation hardened at deep-submicron microelectronic technology (0.25, 0.18, 0.15 and 0.09 micron process technology) and microelectronic design tools for ultra-low power ICs, MEMS, ASICs, Gate Arrays, FPGAs, SOCs, DSPs, Microprocessors, Memory (NVRAM, SRAM, SDRAM), using SiGe, InP, InAs, SOI, CMOS processes.	(a) commercial technology characterization; (b) effects of scaling and low-power technology; (c) novel material science investigation; (d) develop hardening techniques for deep-submicron technology; (e) demonstrate deep-submicron technology for gate array, SRAM, FPGAs, DSPs, and microprocessors; (f) develop advanced hardened controller technology for system upset and recovery; (g) develop radiation hardened system-on-chip technology; (h) develop high-density fast, embedded nonvolatile memory technology; (i) develop radiation tolerant technology	Current radiation hardened technology is at 0.35 and 0.25 microns, usually 2 or 3 generations behind commercial technology. Large government investment is needed to satisfy its future high processing needs. As devices ever get denser and tightly integrated (e.g. system on a chip), innovative advanced radiation hardened technology is highly sought. It is also possible to leapfrog the currently acceptable technology in the commercial world, and try to propose something enturely new and daring!	2	3	3	2008	Charles Le	818.354. 4633	Charles.Le @jpl.nasa.gov

Technology	Measurement Scenario	Instrument Type	Wave-band	Needed Functional Product	Quantitative Requirement	Task	Subtask	Explan-ation	TRL @ Start	TRL @ End	Develop-ment Period (years)	Year Needed (at least 3 years before launch)	Point of Contact		
													POC Name	POC Phone	POC e-mail
High-Performance RHP	2) Measure cloud particles and cloud system structure using a mm-wave radar (142)	Atmospheric sounder, atmospheric profiler, SAR, scatterometer, radar altimeter	Ku, X, S, C, L, P	CLOUD PARAMETERS: cloud structure and particles' density and distribution.	The High-Performance RHP should be flexible in terms of programmability and reconfigurability to allow for possible algorithm modifications to be uploaded after launch, and scalability (2X) to permit change in system parameters.	(2) ELECTRONIC DESIGN AUTOMATION TECHNOLOGY: advanced electronic design automation system, advanced rad-hard circuit design automation, advanced modeling and simulation (RHCAD).	(a) develop high-performance simulations in reducing design margins for errors; (b) develop automated toolkit to support system developer in implementing ptotocols; (c) develop electronic design automation tool to enable radiation hardened deep-submicron technology; (d) develop automated tool for radiation hardened system-on-a-chip technology	Having the right tools facilitates the design process, reduces the design cycles, and helps the technology reaching the desired TRL sooner.	2	3	3	2008	Charle s Le	818.354. 4633	Charles.Le @jpl.nasa.g ov
	3) Global precipitation using a dual-frequency radar (75), Global precipitation using a tri-frequency radar (76), Snow cover, freeze/thaw, accumulation, & water equivalent using a Ku-band scatterometer (102), Global precipitation using two closely spaced Ka-band frequencies (154), Doppler rain profiling radar in Geostationary orbit (160), Atmospheric temperature & water vapor, global precipitation continuous measurements using a non-scanning microwave radiometer sounder at GEO (67)	Atmospheric sounder, atmospheric profiler, SAR, scatterometer, radar altimeter	Ku, X, S, C, L, P	PRECIPI-TATION PARAMETERS: snow and water content, rain rate, snow and rain drop size distribution, rainfall velocity, vertical wind and horizontal shear.	The High-Performance RHP should use the latest availabe advanced technology to ensure low mass, size, and power requirements.	(3) FAULT-TOLERANT CIRCUIT DESIGN: incorporate established fault-tolerant strategies (space, time, software, information redundancy) into the rad-hard manufacturing processes.	(a) fault detection and dynamic masking redundancy; (b) algorithm-based fault tolerant; (c) automated fault-tolerant insertion at functional and logic levels; (d) fault injection tools; (e) reconfigurable hardware to switch off faulty element; (f) software implemented fault tolerance; (g) evolvable hardware; (h) commercial component reliability and radiation characterization; (i) component-level package shielding; (j) radiation-tolerant devices	When rad-hard devices are not available to satisfy the throughput, cost, and power consumption requirements, fault-tolerant design can be applied to combat the low-to-moderate radiation environment, using commercially available parts, thus the latest advanced technology. In addition, adding fault-tolerant features into a radiation hardened process can render the devices highly immune from radiation hazards and from any additional faults that may occur.	3	6	3	2008	Charle s Le	818.354. 4633	Charles.Le @jpl.nasa.g ov

Technology	Measurement Scenario	Instrument Type	Wave-band	Needed Functional Product	Quantitative Requirement	Task	Subtask	Explanation	TRL @ Start	TRL @ End	Development Period (years)	Year Needed (at least 3 years before launch)	Point of Contact		
													POC Name	POC Phone	POC e-mail
High-Performance RHP	4) Ocean current from dual frequency X-Band correlation radar (A), Sea ice motion and deformation from C-band Synthetic Aperture Radar (B), Freeze-thaw transition & growing season with SAR (22), Ocean surface topography using Ka-band SAR (26), Ocean Surface Topography using an interferometric radar altimeter at LEO (27), Surface deformation stress using one (or more) SARs (44a), Land surface topography using two SARs in formation (44b), Deformation, stress, and land surface topography employing SAR at MEO (45), Surface deformation, stress & land surface topography using repeat pass InSAR (47), Sea ice extent/motion using Ku-band scatterometer in polar orbit (90), Ice elevation and surface relief of ice sheet and glaciers from SAR altimetery (93), Ocean surface winds using scatterometer at MEO (148)	Atmospheric sounder, atmospheric profiler, SAR, scatterometer, radar altimeter	Ku, X, S, C, L, P	LAND and OCEAN PARAMETERS: ocean current, ice surface topography, sea ice's thickness, extent, motion, deformation, snow cover over sea ice, ocean surface topography, ocean wind	The High-Performance RHP should have a bypass mode and large enough data storage to store raw data for at least one orbit and to download them when requested.	(4) RAD-HARD IC SUPPLIERS: encourage fab-independent radiation-hardened COTS IC suppliers.	solicit proposals from universities and small businesses, and honor intellectual properties	Large participation of experts will bring more innovations and speed up the TRL readiness.	2	3	3	2008	Charles Le	818.354.4633	Charles.Le@jpl.nasa.gov
High Performance A/D Digital Receivers	Generally applicable to transformation of conventional radar to digital radar: Land surface topography, hazard forecasting, soil moisture, vegetation biomass, land cover classification, freeze-thaw transition, polar ice sheet / glacier velocity, sea ice motion and deformation. A, 92, 93, B, 97, 161, 160, 151, 44a, 44b, 45, 47, 163, 19, 157, 158, 162, 22, 104, 105, 112	SAR, repeat pass InSAR	L-, C-, X-, and P-band	All scenarios require digitized signal ADC output (offset/IF video signal or direct sub-harmonically sampled RF signal). In some scenarios, FFT spectral output is needed for channel equalization, sub-band channelization, digital beamforming, and/or digital RFI suppression.	Development of prototype multi-channel digital receiver/beamformer electronic system for use in large aperture SAR instruments.	(System studies and trades to increase sampling bandwidth and reduce power consumption per ADC/digital receiver e.g., reduction in number of bits (precision).		The task would deliver the first functional hardware for the digital receiver/beamformer system in a large aperture spaceborne radar or radiometer. This reduces the risk of this particular subsystem during the test phases in a relevant environment (TRL 5-6) and during the integration and test phases of a mission.	2	3	1	2008	Mark Fischman	818.354.3862	Mark.Fischman@jpl.nasa.gov

Tech-nology	Measurement Scenario	Instrument Type	Wave-band	Needed Functional Product	Quantitative Requirement	Task	Sub-task	Explanation	TRL @ Start	TRL @ End	Develop-ment Period (years)	Year Needed (at least 3 years before launch)	Point of Contact		
													POC Name	POC Phone	POC e-mail
High Performance A/D Digital Receivers	Generally applicable to transformation of conventional radar to digital radar: Land surface topography, hazard forecasting, soil moisture, vegetation biomass, land cover classification, freeze-thaw transition, polar ice sheet / glacier velocity, sea ice motion and deformation. A, 92, 93, B, 97, 161, 160, 151, 44a, 44b, 45, 47, 163, 19, 157, 158, 162, 22, 104, 105, 112	SAR, repeat pass InSAR	L-, C-, X-, and P-band	All scenarios require digitized signal ADC output (offset/IF video signal or direct sub-harmonically sampled RF signal). In some scenarios, FFT spectral output is needed for channel equalization, sub-band channelization, digital beamforming, and/or digital RFI suppression.	Development of prototype multi-channel digital receiver/beamformer electronic system for use in large aperture SAR instruments.	(System studies and trades to increase sampling bandwidth and reduce power consumption per ADC/digital receiver e.g., reduction in number of bits (precision).		The task would deliver the first functional hardware for the digital receiver/beamformer system in a large aperture spaceborne radar or radiometer. This reduces the risk of this particular subsystem during the test phases in a relevant environment (TRL 5-6) and during the integration and test phases of a mission.	2	3	1	2008	Mark Fischman	818.354.3862	Mark.Fischman@jpl.nasa.gov
					.	. Backend algorithm implementation onto FPGAs or microprocessors.			2	6	3	2008	Charles Le	818.354.4633	Charles.Le@jpl.nasa.gov
						Design and test of 1-10 gigabit/s fiber-optic data link from multiple digital receiver modules to a centralized beamforming processor.			2	6	3	2008	Charles Le	818.354.4633	Charles.Le@jpl.nasa.gov

Tech-nology	Measurement Scenario	Instrument Type	Wave-band	Needed Functional Product	Quantitative Requirement	Task	Sub-task	Explanation	TRL @ Start	TRL @ End	Develop-ment Period (years)	Year Needed (at least 3 years before launch)	Point of Contact		
													POC Name	POC Phone	POC e-mail
Real-time On Board Processing	Generally applicable to all synoptic measurements that can reduce data volume before downlink. Profiling radars, scatterometers, low-res wide area multi-look SAR, and single-pass interferometers can significantly reduce data volume with on-board processing, enabling new mission operations scenarios. 68, 142, 75, 76, 154, 160, 155, 156, 159, A, 93, 90, B, 97, 160, 102, 161, 44b, 45, 163, 19,162, 51, 22, 100, 102, 103, 104, 105, 112, 28, 29, 61, 148	SAR, Interferometric SAR (aka InSAR, IFSAR)	L, Ka	Single Look Complex Image, Multi-Look Image, Range Compressed Data	Throughput: 20 - 30 GOPS, Random Access Memory: 1-3 Gbytes, Memory Bandwidth: 3 Gbps	Real Time Onboard Processor Development - Implement current ground based non real-time SAR processing algorithms in space qualifiable hardware that meets requirements for real-time SAR processing. This task can be broken down into three subtasks 1) FPGA design and micro processor programming, 2) Custom board level design, 3) Fault tolerant architecture definition	1) FPGA design / u-processor programming: implement SAR algorithms using a combination of FPGA and microprocessor components. Requires the conversion of floating point SAR algorithms currently described in a high level software language (e.g. C or Fortran) to an equivalent fixed point algorithm described in a low level Hardware Description Language (e.g. verilog or vhdl). Post image processing algorithms (e.g. multi-look, change detection) require programming of space qualifiable microprocessors.	The intermediate product for the task described above is a custom multi FPGA board with built-in fault tolerant architecture for SAR image processing. All aspects of the board including the fault tolerance aspects would be tested in a lab environment. This would bring the real-time onboard processor technology to TRL4. An engineering model development would follow taking the technology to TRL5.	3	5	4	2008	Biren Shah	818.393.6339	Biren.N.Shah@jpl.nasa.gov
							2) Board Level Design: Design and fabricate a multi-FPGA board with interconnected FPGAs, on-board memory, and standardized interface to other boards (e.g. ethernet). Design should support a heterogeneous onboard processor architecture that uses a combination of FPGAs and microprocessors.								
							3) Fault Tolerance: Investigates various approaches to fault detection and (possibly) correction. Trades increased size and power due to redundancy versus fault tolerance algorithm complexity (e.g. module level fault tolerance verus algorithmic level fault tolerance). Propose, design, and implement best fault tolerance strategy for a real-time onboard processor.								

Technology	Measurement Scenario	Instrument Type	Waveband	Needed Functional Product	Quantitative Requirement	Task	Sub-task	Explanation	TRL @ Start	TRL @ End	Development Period (years)	Year Needed (at least 3 years before launch)	Point of Contact		
													POC Name	POC Phone	POC e-mail
1-bit analog to digital conversion for radiometric measurements of the atmosphere, oceans, cryosphere and hydrology	Global precipitation, make pushbroom measurements of rainfall using an electrically scanning microwave radiometer in low earth orbit or on a UAV (C),Hurricane intensity rain rates & ocean surface wind speeds, pushbroom measurements of rainfall and ocean wind speed in cyclones using an electronically scanned stepped frequency LEO or UAV microwave radiometer (D), Snow cover,freeze/thaw, accumulation, and water equivalent using an electronically scanning Ku & Ka-band microwave radiometer in a polar orbit (F), Freeze-thaw transition, Growing Season in high latitudes from LEO STAR (G),Snow cover, accumulation, and water equivalent using 1.4, 19, and 37 GHz STAR at LEO (H), Soil moisture using low frequency STAR at LEO (I), Soil moisturea and Sea Surface salinity using low frequency STAR obsetervations at LEO (34, also refered to as 32), Snow cover, accumulation, and water equivalent using STAR at LEO with at least 5-km resolution (107), Snow cover, accumulation, and water equivalent using STAR at LEO with at least 5-km resolution. Passive system supports active radar systems (108)	STAR sounder/ imager	400 MHz - 183 GHz	Radiation tolerant, high speed, low power, 1-bit, A/D converter	2 GHz, 5mW, 20GHz bandwidth,1 mV/quantum	Develop, fabricate and test A/D ASIC including total-dose and SEU radiation testing			3	6	2.5	2010	Dan Evans	(310) 336-1028	daniel.d.evans@aero.org
2-bit analog to digital conversion for radiometric measurements of the atmosphere, oceans, cryosphere and hydrology	Global precipitation, make pushbroom measurements of rainfall using an electrically scanning microwave radiometer in low earth orbit or on a UAV (C),Hurricane intensity rain rates & ocean surface wind speeds, pushbroom measurements of rainfall and ocean wind speed in cyclones using an electronically scanned stepped frequency LEO or UAV microwave radiometer (D), Snow cover,freeze/thaw, accumulation, and water equivalent using an electronically scanning Ku & Ka-band microwave radiometer in a polar orbit (F), Freeze-thaw transition, Growing Season in high latitudes from LEO STAR (G),Snow cover, accumulation, and water equivalent using 1.4, 19, and 37 GHz STAR at LEO (H), Soil moisture using low frequency STAR at LEO (I), Soil moisturea and Sea Surface salinity using low frequency STAR obsetervations at LEO (34, also refered to as 32), Snow cover, accumulation, and water equivalent using STAR at LEO with at least 5-km resolution (107), Snow cover, accumulation, and water equivalent using STAR at LEO with at least 5-km resolution. Passive system supports active radar systems (108)	STAR sounder/ imager	400 MHz - 183 GHz	Radiation tolerant, high speed, low power, 2-bit, A/D converter	2 GHz, 5mW, 20GHz bandwidth, 1 mV/quantum	Develop, fabricate and test A/D ASIC including total-dose and SEU radiation testing			3	6	2.5	2010	Dan Evans	(310) 336-1028	daniel.d.evans@aero.org

Technology	Measurement Scenario	Instrument Type	Waveband	Needed Functional Product	Quantitative Requirement	Task	Sub-task	Explanation	TRL @ Start	TRL @ End	Development Period (years)	Year Needed (at least 3 years before launch)	Point of Contact		
													POC Name	POC Phone	POC e-mail
3-bit analog to digital conversion for radiometric measurements of the atmosphere, oceans, cryosphere and hydrology	Global precipitation, make pushbroom measurements of rainfall using an electrically scanning microwave radiometer in low earth orbit or on a UAV (C),Hurricane intensity rain rates & ocean surface wind speeds, pushbroom measurements of rainfall and ocean wind speed in cyclones using an electronically scanned stepped frequency LEO or UAV microwave radiometer (D), Snow cover,freeze/thaw, accumulation, and water equivalent using an electronically scanning Ku & Ka-band microwave radiometer in a polar orbit (F), Freeze-thaw transition, Growing Season in high latitudes from LEO STAR (G),Snow cover, accumulation, and water equivalent using 1.4, 19, and 37 GHz STAR at LEO (H), Soil moisture using low frequency STAR at LEO (I), Soil moisturea and Sea Surface salinity using low frequency STAR obsetervations at LEO (34, also refered to as 32), Snow cover, accumulation, and water equivalent using STAR at LEO with at least 5-km resolution (107), Snow cover, accumulation, and water equivalent using STAR at LEO with at least 5-km resolution. Passive system supports active radar systems (108)	STAR sounder/ imager	400 MHz - 183 GHz	Radiation tolerant, high speed, low power, 1-bit, A/D converter	2 GHz, 5mW, 20GHz bandwidth,1 mV/quantum	Develop, fabricate and test A/D ASIC including total-dose and SEU radiation testing			3	6	2.5	2010	Dan Evans	(310) 336-1028	daniel.d.evans@aero.org
High-bandwidth Data Links (Interior to Instrument)	Atmospheric temperature,Atmospheric water vapor,Global precipitation, continuous measurements using a non-scanning microwave radiometeric sounder in geosynchronous orbit (67), Global precipitation (rainfall) make pushbroom measurements of rainfall using an electrically scanning microwave radiometer in low earth orbit or on a UAV (C), Hurricane intensity rain rates & ocean surface wind speeds pushbroom measurements of rainfall and ocean wind speed in cyclones using an electronically scanned stepped frequency LEO or UAV microwave radiometer (D), Soil moisture,Sea surface salinity from low frequency microwave emissions at LEO using a rotating real aperture radiometer (38), Surface soil moisture,Sea surface salinity, 1-10 km resolution from low frequency passive microwave emissions at LEO using a very large rotating real aperture. Supports active radar (111), Snow cover,freeze/thaw, accumulation, and water equivalent using an electronically scanning Ku & Ka-band microwave radiometer in a polar orbit (F), Freeze-thaw transition, Growing Season in high latitudes from LEO STAR (G), Snow cover, accumulation, and water equivalent using 1.4, 19, and 37 GHz STAR at LEO (H), Soil moisture using low frequency STAR at LEO (I), Soil moisture and Sea Surface salinity using low frequency STAR observations at LEO (34, also refered to as 32), Using low frequency STAR obsetervations at LEO (34, also refered to as 32) using STAR at LEO with at least 5-km resolution (107), Snow cover, accumulation, and water equivalent using STAR at LEO with at least 5-km resolution. Passive system supports active radar systems (108), Soil moisture at 10-20 km resolution using an L-band radiometer with beam synthesis from LEO (177).	Radiometers, generally STAR sounder/imagers		High-bandwidth data links	Over copper: >1 Gb/s data link, <20 mW DC power, >3-meter haul.	Identify appropriate technologies and apply to system development of radiometer array		Basic requirements (excluding flight worthiness) may be met with existing TRL-3 hardware, but need to be 1) demonstrated with radiometer system and 2) matured to TRL-6 (tested in relevant environment).	3	6	3	2010	Dan Evans	(310) 336-1028	daniel.d.evans@aero.org

Technology	Measurement Scenario	Instrument Type	Wave-band	Needed Functional Product	Quantitative Requirement	Task	Sub-task	Explanation	TRL @ Start	TRL @ End	Develop-ment Period (years)	Year Needed (at least 3 years before launch)	Point of Contact		
													POC Name	POC Phone	POC e-mail
Digital RFI Mitigation	Sea surface temperature with 15 - 20 km resolution from passive microwave emissions at LEO using rotating real aperture radiometer (E), soil moisture missions (I, 32, 34, 111)	Microwave radiometer	6 GHz and-L band	RFI mitigation algorithms	N/A		Perform spectrum servey with specially fitted radiometer	RFI environment is currently unknown	1	2	0.5 followed by updates to identify new RFI sources	Enhancing for several missions	Dave Kunkee	(310) 336-1125	david.b.kunkee@aero.org
	Sea surface temperature with 15 - 20 km resolution from passive microwave emissions at LEO using rotating real aperture radiometer (E), soil moisture missions (I, 32, 34, 111)	Microwave radiometer	6 GHz and-L band	RFI mitigation algorithms	0.05 K for ocean temperature 0.3 K for land (soil moisture)		Design RF mitigation techniques for interference suppression in RF receivers, design environmental retrievial algorithms to mitigate residual RFI. Design for L-band and C-band environments differently.	Test and verify against known RF environments	2	6	3 to 4	Enhancing for several missions	Dave Kunkee	(310) 336-1125	david.b.kunkee@aero.org
On-board high-rate digital signal distribution	Sea surface salinity &/or soil moisture from low frequency emissions using a synthetic thinned aperture radiometer (34), Soil moisture,sea surface salinity from low frequency emissions using a rotating real aperture radiometer (38),Atmospheric temperature & water vapor, global precipitation continuous measurements using a non-scanning microwave radiometer sounder at GEO (67), Snow cover, accumulation, & water equivalent from low frequency emissions using a very large rotating real aperture (111)	STAR sounder/ imager	1.4, 50-60, 173-193 GHz,	Low power, ultra-wideband digital data interconnect bus	~30 Gbps channel capacity; ~20 W per channel	Build breadboard signal distribution system for laboratory performance characterization	Preface fab with comprehensive assessment of current state-of-the-art commercial options and potential for dedicated ASIC (or other) development to enable necessary subsystem component technologies	breadboard laboratory signal distribution testbed - multiplexing high speed, low bit resolution digital samples onto a common and bus and de-muxing them at the receive end	3	4	1	2006	Chris Ruf	734-764-6561	cruf@umich.edu

Technology	Measurement Scenario	Instrument Type	Wave-band	Needed Functional Product	Quantitative Requirement	Task	Sub-task	Explanation	TRL @ Start	TRL @ End	Develop-ment Period (years)	Year Needed (at least 3 years before launch)	Point of Contact		
													POC Name	POC Phone	POC e-mail
On-board high-rate digital signal distribution	Sea surface salinity &/or soil moisture from low frequency emissions using a synthetic thinned aperture radiometer (34), Soil moisture,sea surface salinity from low frequency emissions using a rotating real aperture radiometer (38),Atmospheric temperature & water vapor, global precipitation continuous measurements using a non-scanning microwave radiometer sounder at GEO (67), Snow cover, accumulation, & water equivalent from low frequency emissions using a very large rotating real aperture (111)	STAR sounder/imager	1.4, 50-60, 173-193 GHz,	Low power, ultra-wideband digital data interconnect bus	~30 Gbps channel capacity; ~20 W per channel	Build benchtop correlating radiometer employing high-rate data bus	Preface fab with extensive system engineering design trade studies	benchtop correlating radiometer testbed employing 30 Gbps bus; verify quality of radiometer's noise correlation statistics (e.g. with respect to clock jitter, sample time synch between channels); perform system design trades to drive power requirements down	4	5	1.5	2008	Chris Ruf	734-764-6561	cruf@umich.edu
On-board high-rate digital signal distribution	Sea surface salinity &/or soil moisture from low frequency emissions using a synthetic thinned aperture radiometer (34), Soil moisture,sea surface salinity from low frequency emissions using a rotating real aperture radiometer (38),Atmospheric temperature & water vapor, global precipitation continuous measurements using a non-scanning microwave radiometer sounder at GEO (67), Snow cover, accumulation, & water equivalent from low frequency emissions using a very large rotating real aperture (111)	STAR sounder/imager	1.4, 50-60, 173-193 GHz,	Low power, ultra-wideband digital data interconnect bus	~30 Gbps channel capacity; ~20 W per channel	Integrate high-rate data bus into field deployed STAR instrument	Include detailed performance characterization studies after field deployment to assess impact of subsystem design on Level 1 and 2 data products	integration of 30 Gbps bus into complete field deployable system; verify end-to-end performance of Level 1 TB images & spectra and Level 2 geophysical retrievals (GDRs)	5	6	2	2010	Chris Ruf	734-764-6561	cruf@umich.edu

Technology	Measurement Scenario	Instrument Type	Wave-band	Needed Functional Product	Quantitative Requirement	Task	Sub-task	Explanation	TRL @ Start	TRL @ End	Develop-ment Period (years)	Year Needed (at least 3 years before launch)	Point of Contact		
													POC Name	POC Phone	POC e-mail
High speed, high resolution Digital Spectrometers for Sounding	Tropospheric ozone and precursors,Ozone vertical profile,Atmospheric properties in the tropopause tropospheric ozone and precursors by observing thermal emissions from the atmospheric limb using a microwave sounder (140), Cloud system structure, measure cloud particles and cloud system structure using a sub-mm wave radiometer in low Earth orbit (143), Atmospheric temperature,Atmospheric water vapor,Global precipitation, continuous measurements using a non-scanning microwave radiometeric sounder in geosynchronous orbit (67)	Radiometer, Sounder,Microwave Sounder,Spectrometer, Microwave/RF Spectrometer,Microwave/RF Radiometer, STAR Imager.	50 GHz to far IR {(140) 180 GHz and 2.5 THz, (67, 143) Bands near 50 GHz and 183 GHz}	Development of digital spectrometers (autocorrelators or polyphase with 4 - 8 GHz bandwidth, low power (a few Watts per spectrometer), and radiation hardening for long duration low- to mid-Earth orbit missions.	Development of hi-speed, hi-res Aanalog to Digital converters (ADCs) and correlators or signal processing hardware. Develop systems design for use in spectrometer. Develop and test ADCs and digital signal processing hardware.	Develop: 1) 4-GHz input bandwidth, 8 GHz sampling rate,8 bits resolution, 5 watts DC power or less. 2) 8-GHz input bandwidth, 16-GHz sampling rate, 1-bit resolution, 5 watts DC power or less.		higher-speeds than currently available will enable more bandwidth of processing, resulting in more science. demonstrate techniques for microwave radiometry and make appropriate for spaceflight	3	6	4	2008	Rafael Rincon	(301) 614-5725	rafael.rincon@nasa.gov
Combined Passive/Active Processing, Distribution	Surface soil moisture,Sea surface salinity, 1-10 km resoltuion from low frequency passive microwave emissions at LEO using a very large rotating real aperture. Supports active radar (111)	Rotating real aperture mesh antenna	L-band: 1.26 and 1.41 GHz	None discerned by several individuals, related issues are data storage and algorithms									Dan Evans	(310) 336-1028	daniel.d.evans@aero.org

Technology	Measurement Scenario	Instrument Type	Wave-band	Needed Functional Product	Quantitative Requirement	Task	Sub-task	Explanation	TRL @ Start	TRL @ End	Develop-ment Period (years)	Year Needed (at least 3 years before launch)	Point of Contact		
													POC Name	POC Phone	POC e-mail
Massively parallel 1-bit cross correlators for radiometric measurements of the atmosphere, oceans, cryosphere and hydrology	Global precipitation, make pushbroom measurements of rainfall using an electrically scanning microwave radiometer in low earth orbit or on a UAV (C),Hurricane intensity rain rates & ocean surface wind speeds, pushbroom measurements of rainfall and ocean wind speed in cyclones using an electronically scanned stepped frequency LEO or UAV microwave radiometer (D), Snow cover,freeze/thaw, accumulation, and water equivalent using an electronically scanning Ku & Ka-band microwave radiometer in a polar orbit (F), Freeze-thaw transition, Growing Season in high latitudes from LEO STAR (G),Snow cover, accumulation, and water equivalent using 1.4, 19, and 37 GHz STAR at LEO (H), Soil moisture using low frequency STAR at LEO (I), Soil moisture and Sea Surface salinity using low frequency STAR obsetervations at LEO (34, also refered to as 32), Snow cover, accumulation, and water equivalent using STAR at LEO with at least 5-km resolution (107), Snow cover, accumulation, and water equivalent using STAR at LEO with at least 5-km resolution. Passive system supports active radar systems (108)	STAR sounder/ imager	As low as 400 MHz and 1.4, 6.7, 10.7, 19.3, 36.5, 50-60, 173-193 GHz	Estimation of partial correlation between many pairs of broadband noise signals by digital cross-correlation (multiply & accumulate) of low bit resolution digitized samples of signals	10,000 (threshold) / 90,000(objective) (multiply-accumulate-MAC)1-bit cross-correlations per ASIC; 0.25 mW(threshold) / 0.1 mW(target) correlator cell at 20 GHz clock rate; Fully scalable interconnect architecture	TRL 2 to 3: Design core correlator cell for 0.1 mW @ 220 MHz operation. TRL 3 to 4: Build prototype massively parallel correlator and fully characterize via evaluation board testing. TRL 4 to 5: Embed prototype correlator in complete benchtop (or ground based) radiometer system and test end-to-end instrument performance. TRL 5 to 6: Field deployment of massively parallel correlator in a science-driven instrument campaign		Prudent design stages from demonstration of individual correlator cells through full instrument integration in massively parallel ASIC	2	6	TRL 2 to 3: 1. TRL 3 to 4: 1.5. TRL 4 to 5: 1.5. TRL 5 to 6: 2.	2011	Chris Ruf	734-764-6561	cruf@umich.edu

APPENDIX 4L: PROCESSING TECHNOLOGY ROADMAPS

In this appendix we provide individual processing challenge roadmaps covering the following areas: large data storage, processing algorithms, high performance RHP, high performance digital receivers, real time on-board processing, 1-, 2-, and 3-bit A/D converters, high-bandwidth data links, digital RFI mitigation, on-board high rate digital distribution, high speed, high resolution spectrometers, and massively parallel 1-bit cross correlators.

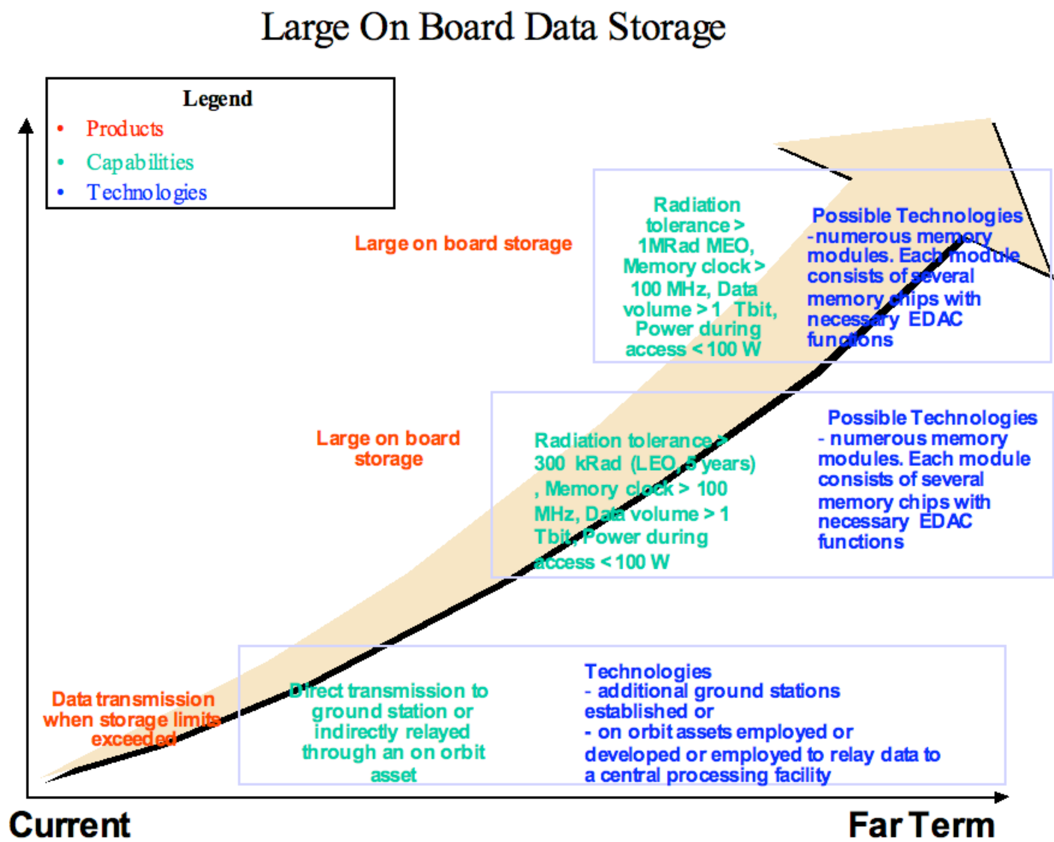


Figure 4L1

Processing Algorithms

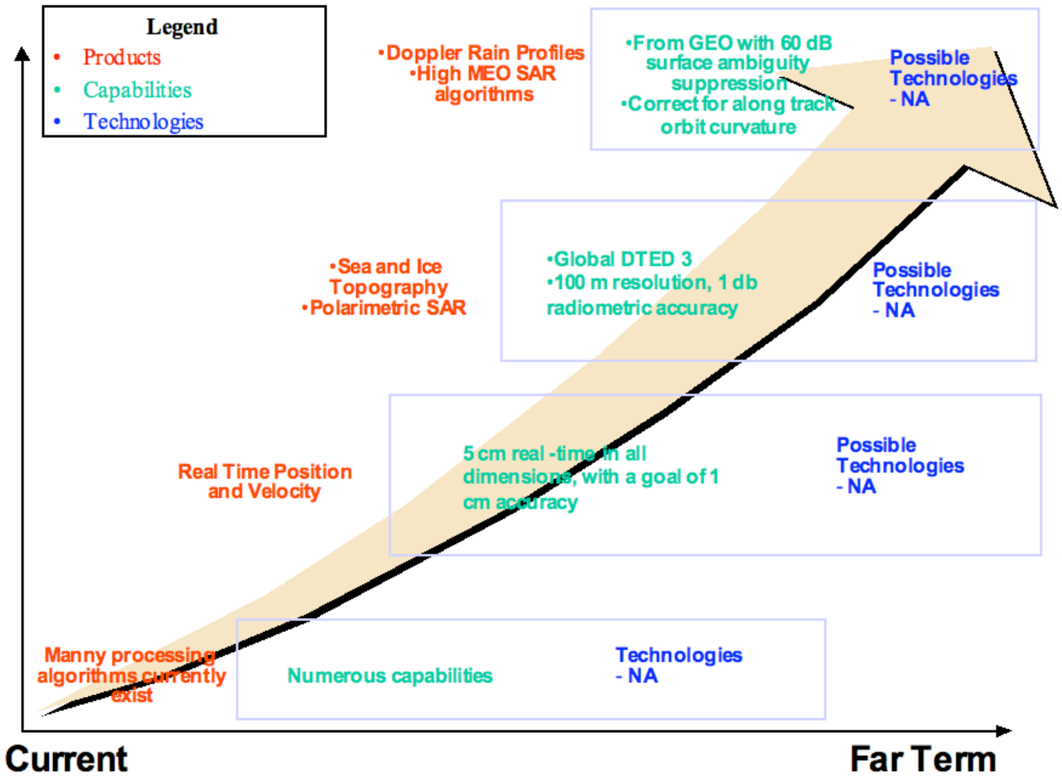


Figure 4L2

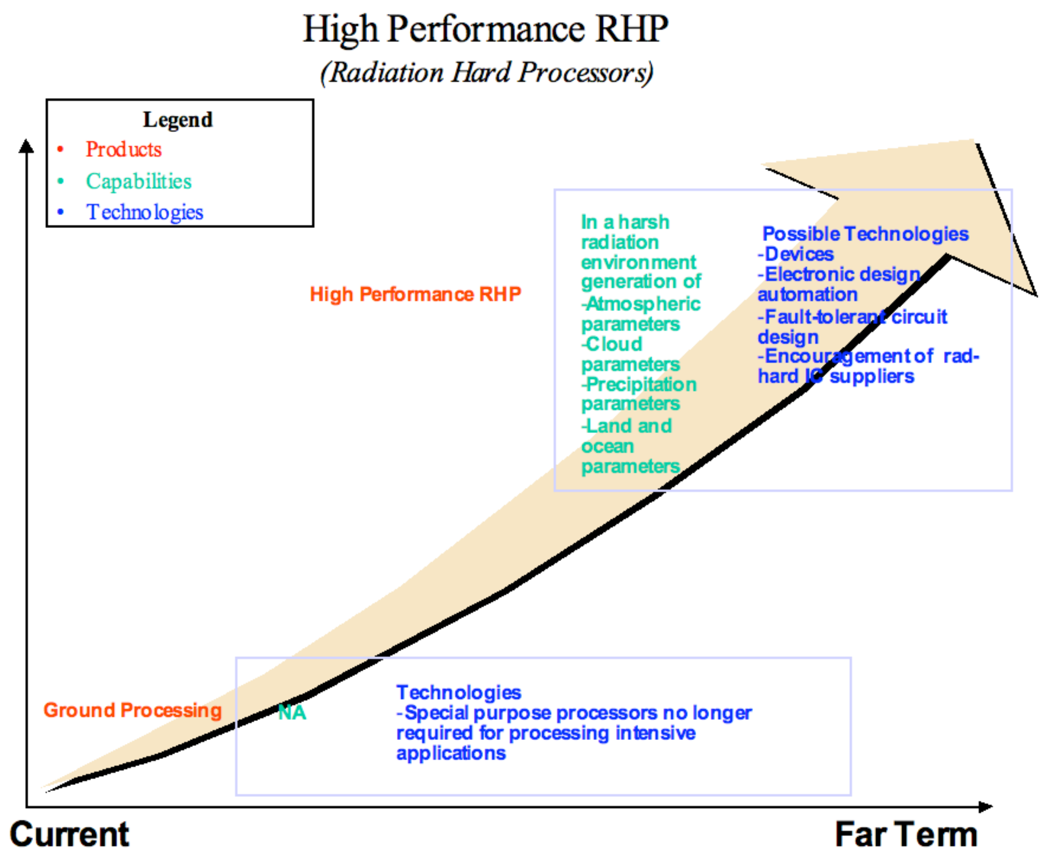

High Performance RHP
(Radiation Hard Processors)
Legend
Products
Capabilities
Technologies
High Performance RHP
In a harsh radiation environment generation of
-Atmospheric parameters
-Cloud parameters
-Precipitation parameters
-Land and ocean parameters
Possible Technologies
-Devices
-Electronic design automation
-Fault-tolerant circuit design
-Encouragement of rad-hard IC suppliers
Ground Processing
NA
Technologies
-Special purpose processors no longer required for processing intensive applications
Current
Far Term

Figure 4L3

High Performance A/D Digital Receivers

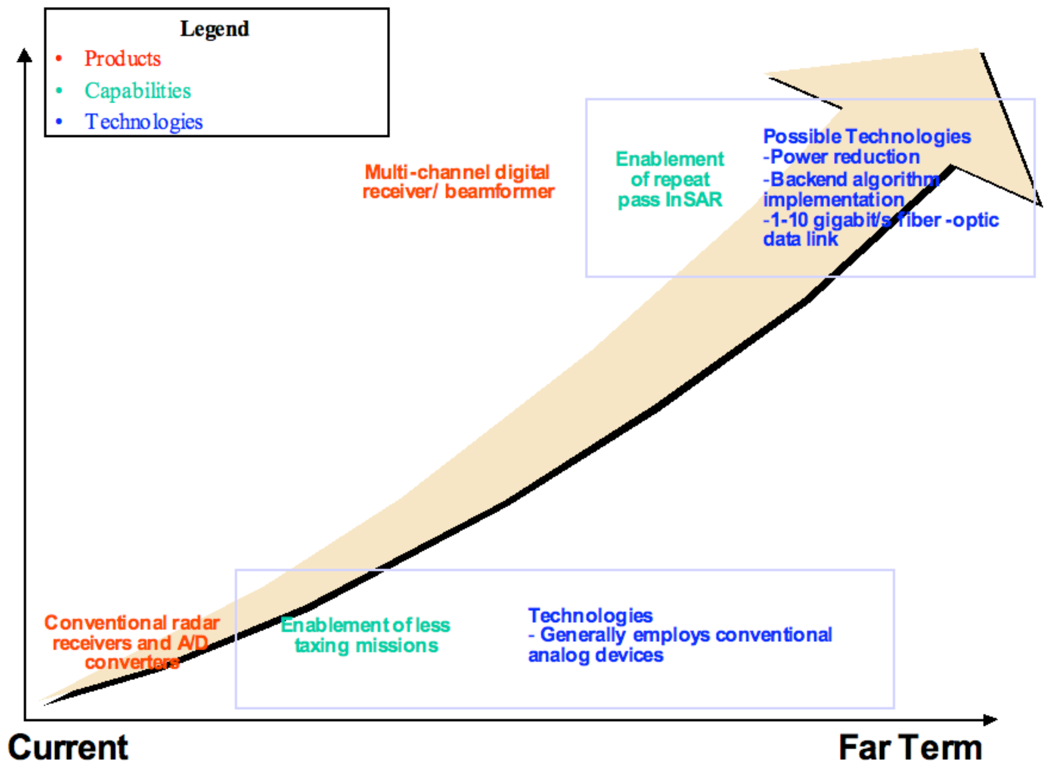


Figure 4L4

Real-time On Board Processing

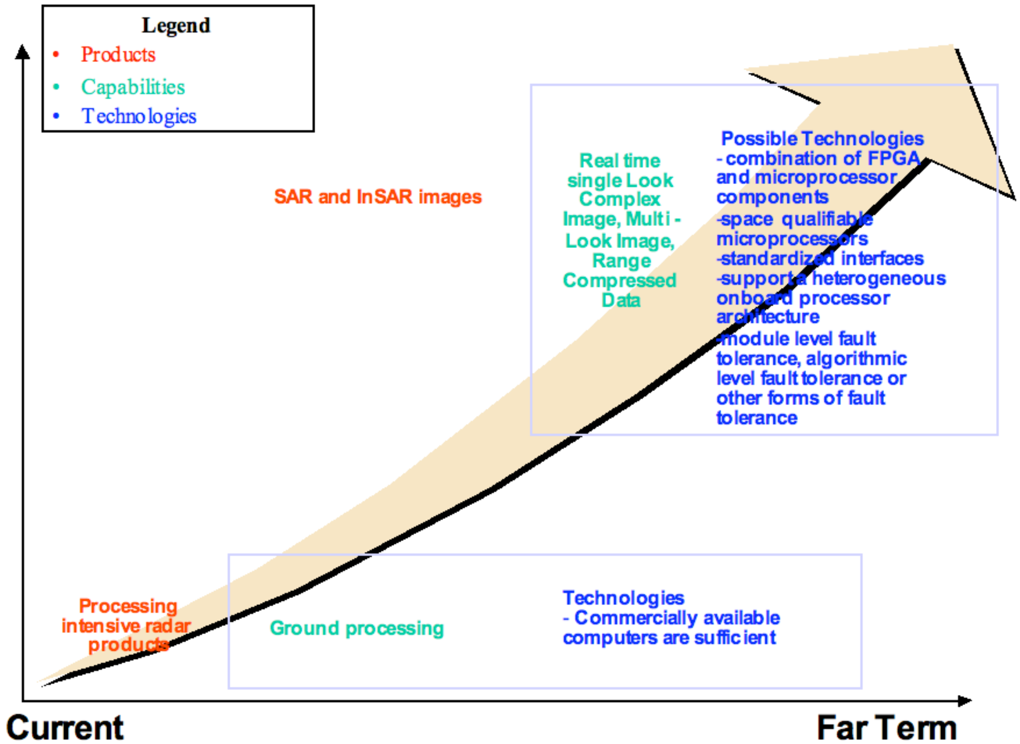
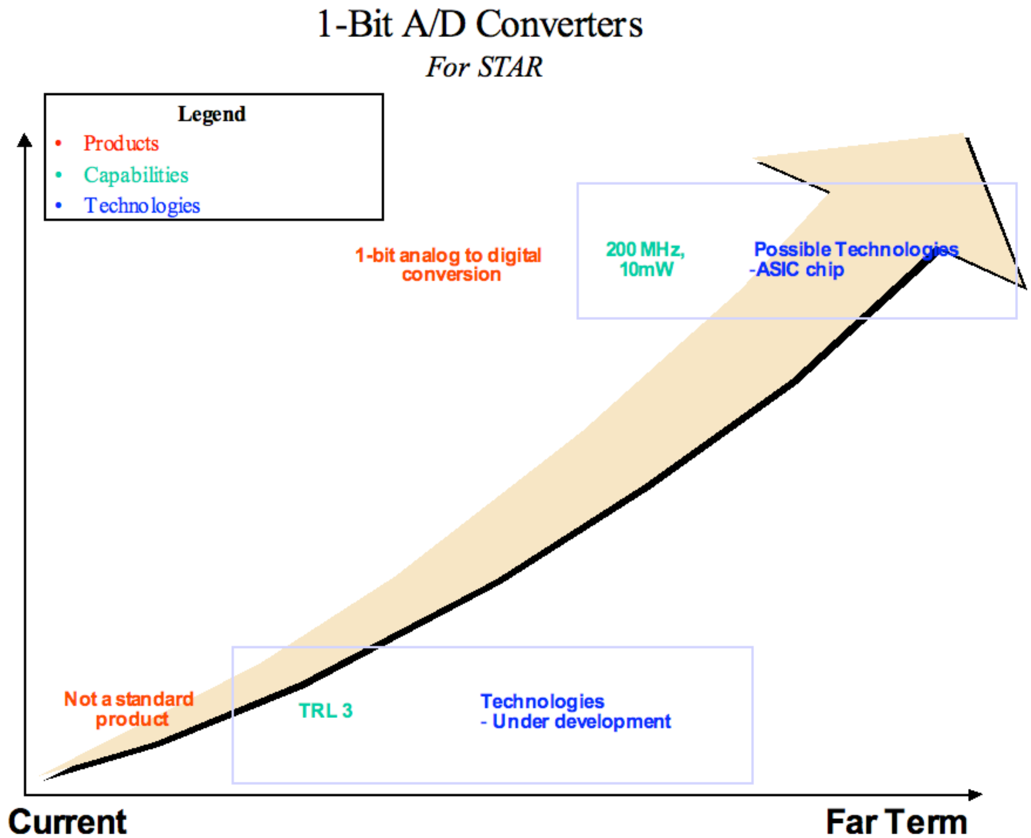


Figure 4L5



1-Bit A/D Converters
For STAR
Legend
• Products
• Capabilities
• Technologies
1-bit analog to digital conversion
200 MHz, 10mW
Possible Technologies
-ASIC chip
Not a standard product
TRL 3
Technologies
- Under development
Current
Far Term

Figure 4L6

2-bit A/D Converters

For STAR

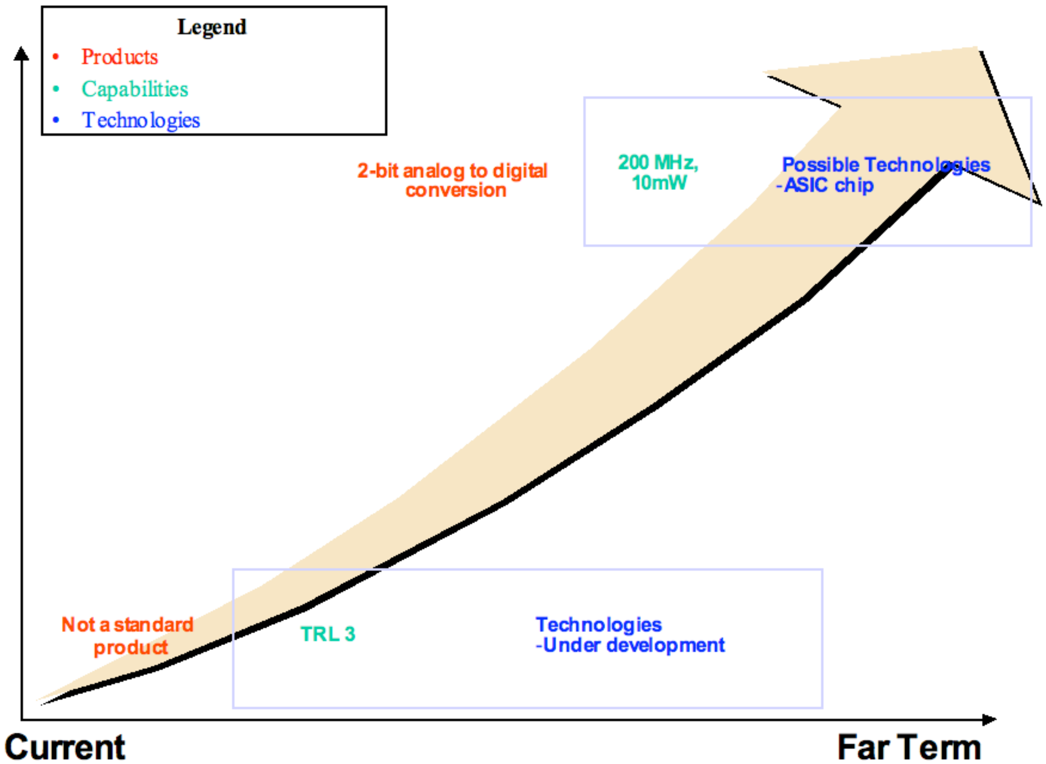
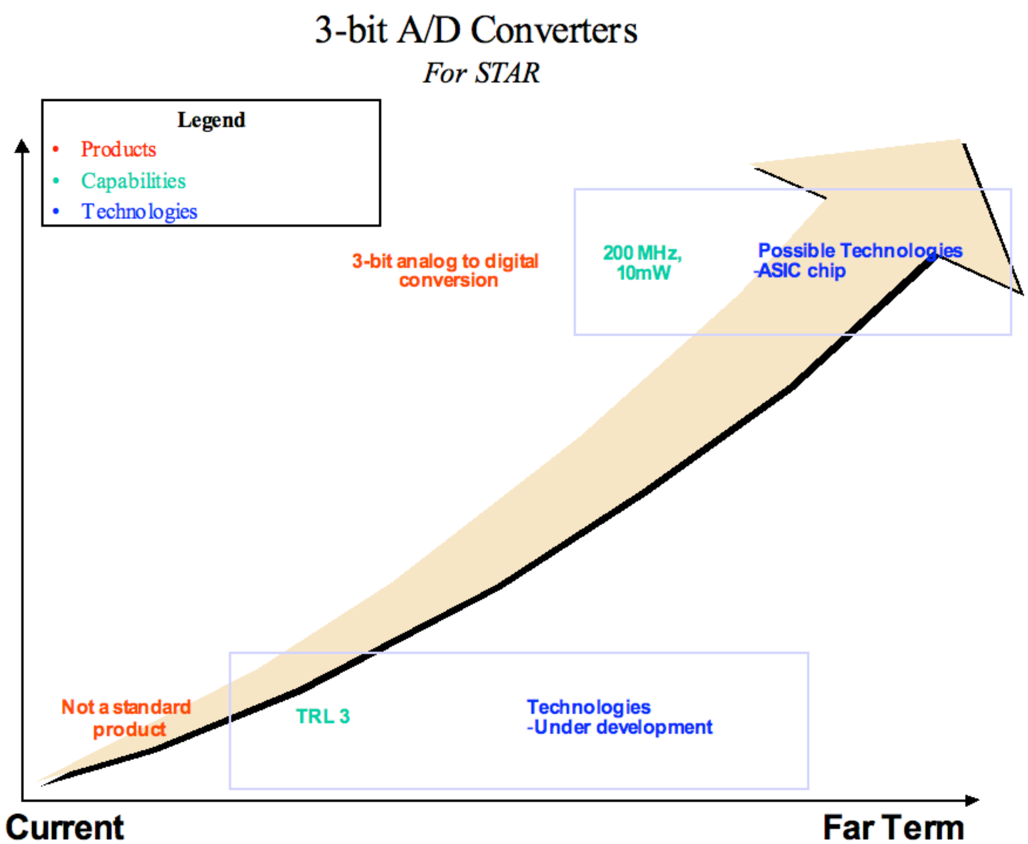


Figure 4L7



3-bit A/D Converters
For STAR
Legend
• Products
• Capabilities
• Technologies
3-bit analog to digital conversion
200 MHz, 10mW
Possible Technologies -ASIC chip
Not a standard product
TRL 3
Technologies -Under development
Current
Far Term

Figure 4L8

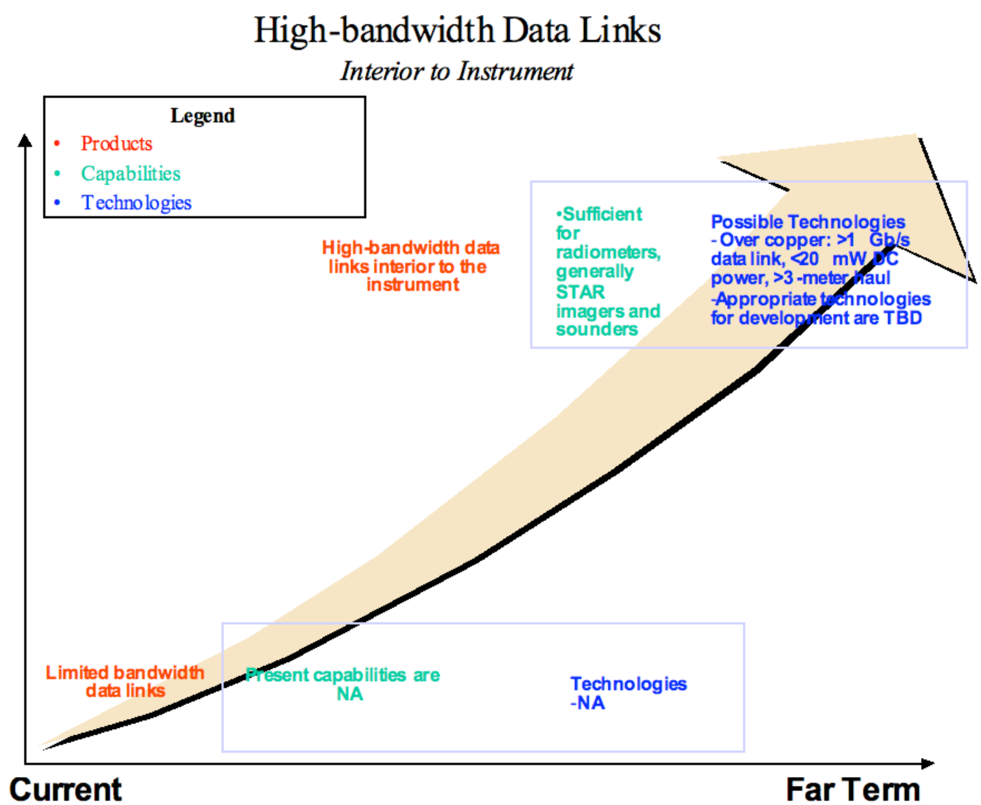

High-bandwidth Data Links
Interior to Instrument
Legend
Products
Capabilities
Technologies
High-bandwidth data links interior to the instrument
•Sufficient for radiometers, generally STAR imagers and sounders
Possible Technologies
- Over copper: >1 Gb/s data link, <20 mW DC power, >3 -meter haul
-Appropriate technologies for development are TBD
Limited bandwidth data links
Present capabilities are NA
Technologies
-NA
Current
Far Term

Figure 4L9

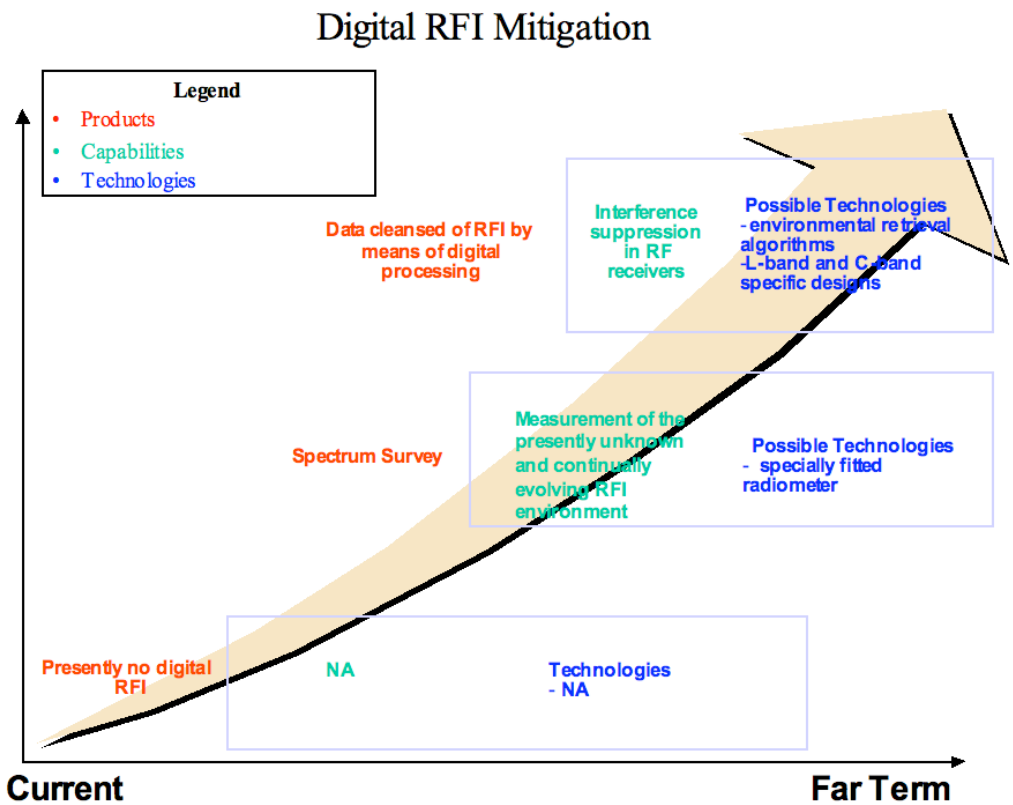

Digital RFI Mitigation
Legend
Products
Capabilities
Technologies
Data cleansed of RFI by means of digital processing
Interference suppression in RF receivers
Possible Technologies
- environmental retrieval algorithms
-L-band and C-band specific designs
Spectrum Survey
Measurement of the presently unknown and continually evolving RFI environment
Possible Technologies
- specially fitted radiometer
Presently no digital RFI
NA
Technologies
- NA
Current
Far Term

Figure 4L10

On Board High Rate Digital Signal Distribution

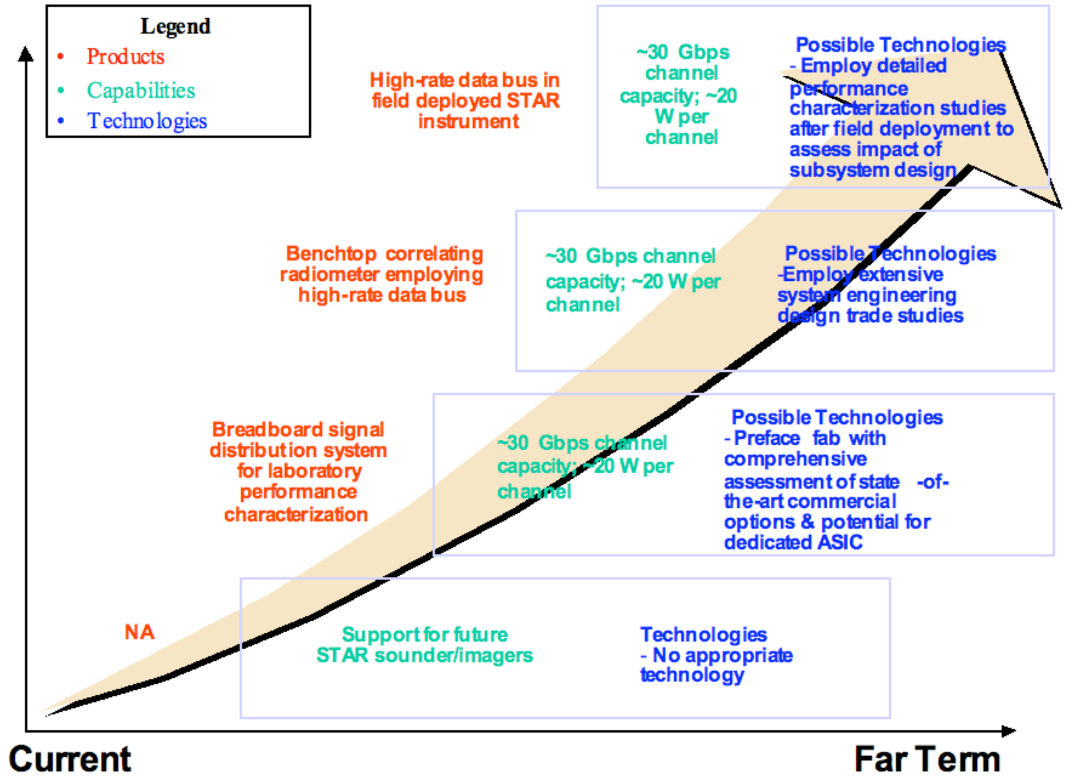


Figure 4L11

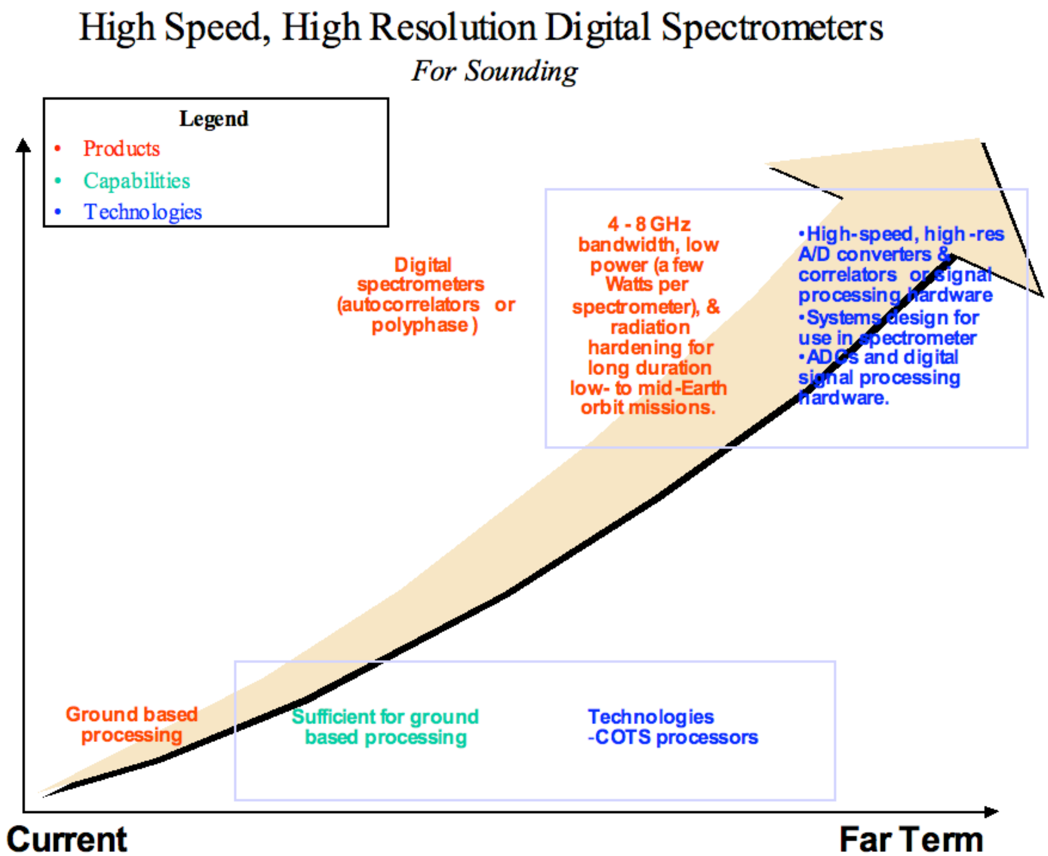

High Speed, High Resolution Digital Spectrometers
For Sounding
Legend
• Products
• Capabilities
• Technologies
Digital spectrometers (autocorrelators or polyphase)
4 - 8 GHz bandwidth, low power (a few Watts per spectrometer), & radiation hardening for long duration low- to mid-Earth orbit missions.
•High-speed, high-res A/D converters & correlators or signal processing hardware
•Systems design for use in spectrometer
•ADCs and digital signal processing hardware.
Ground based processing
Sufficient for ground based processing
Technologies
-COTS processors
Current
Far Term

Figure 4L12

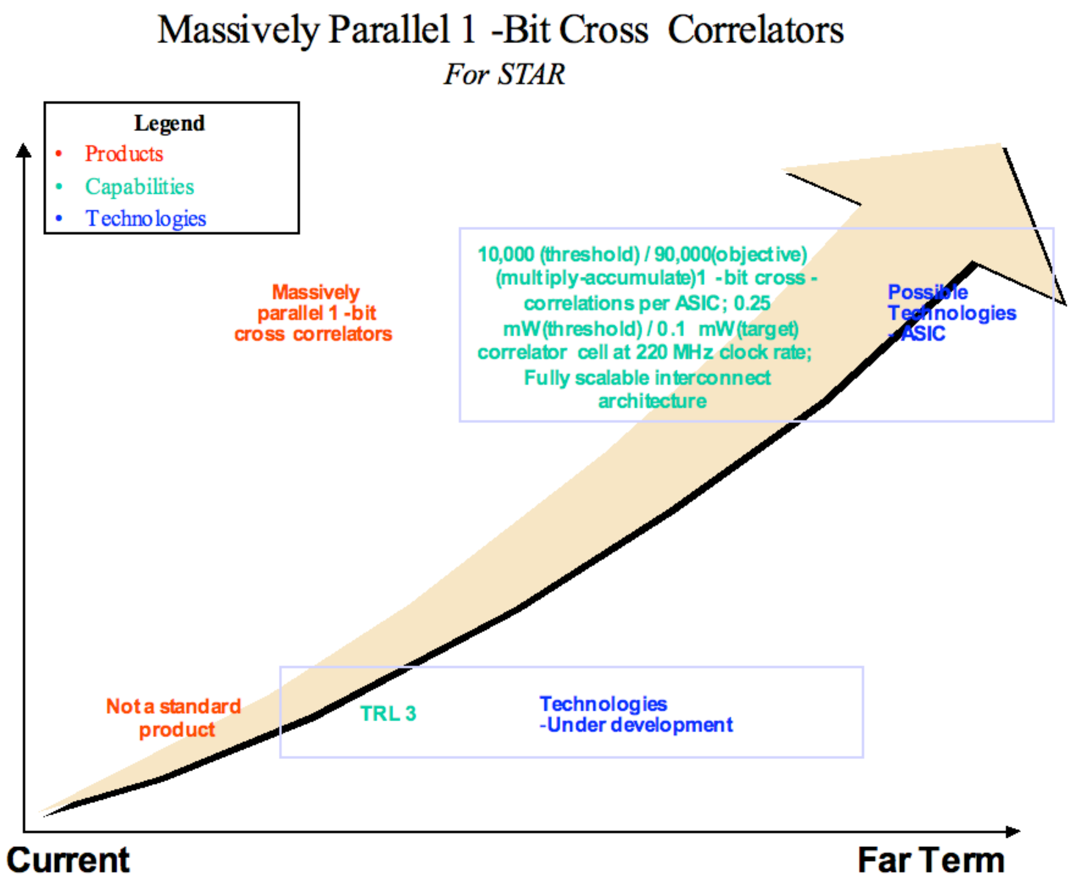
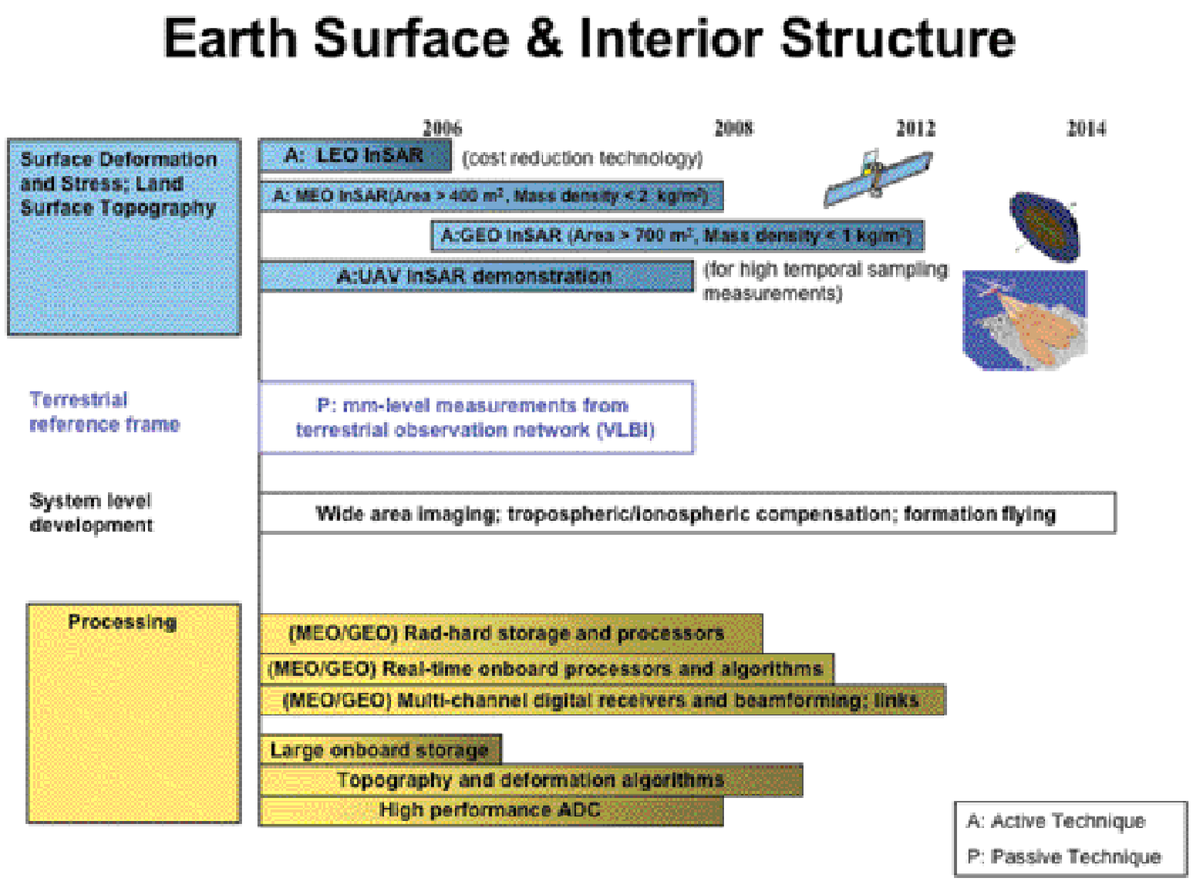
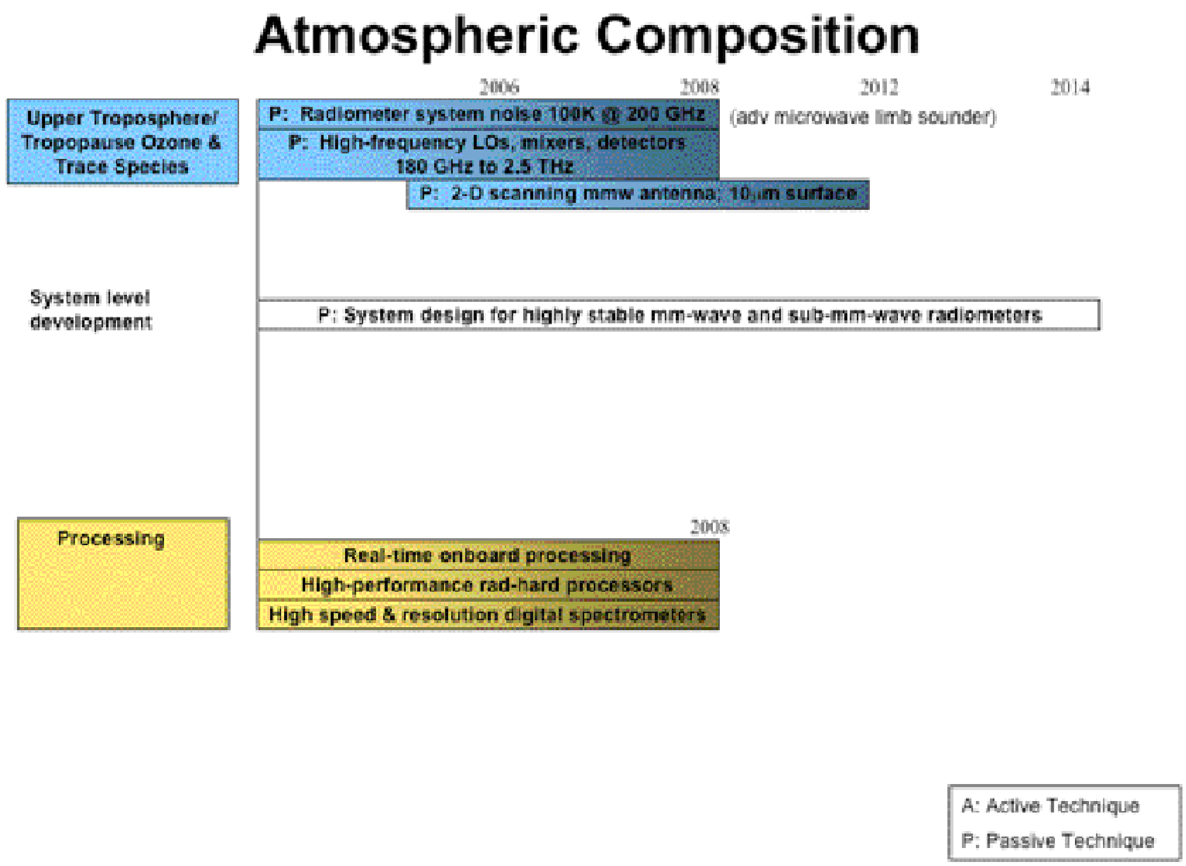
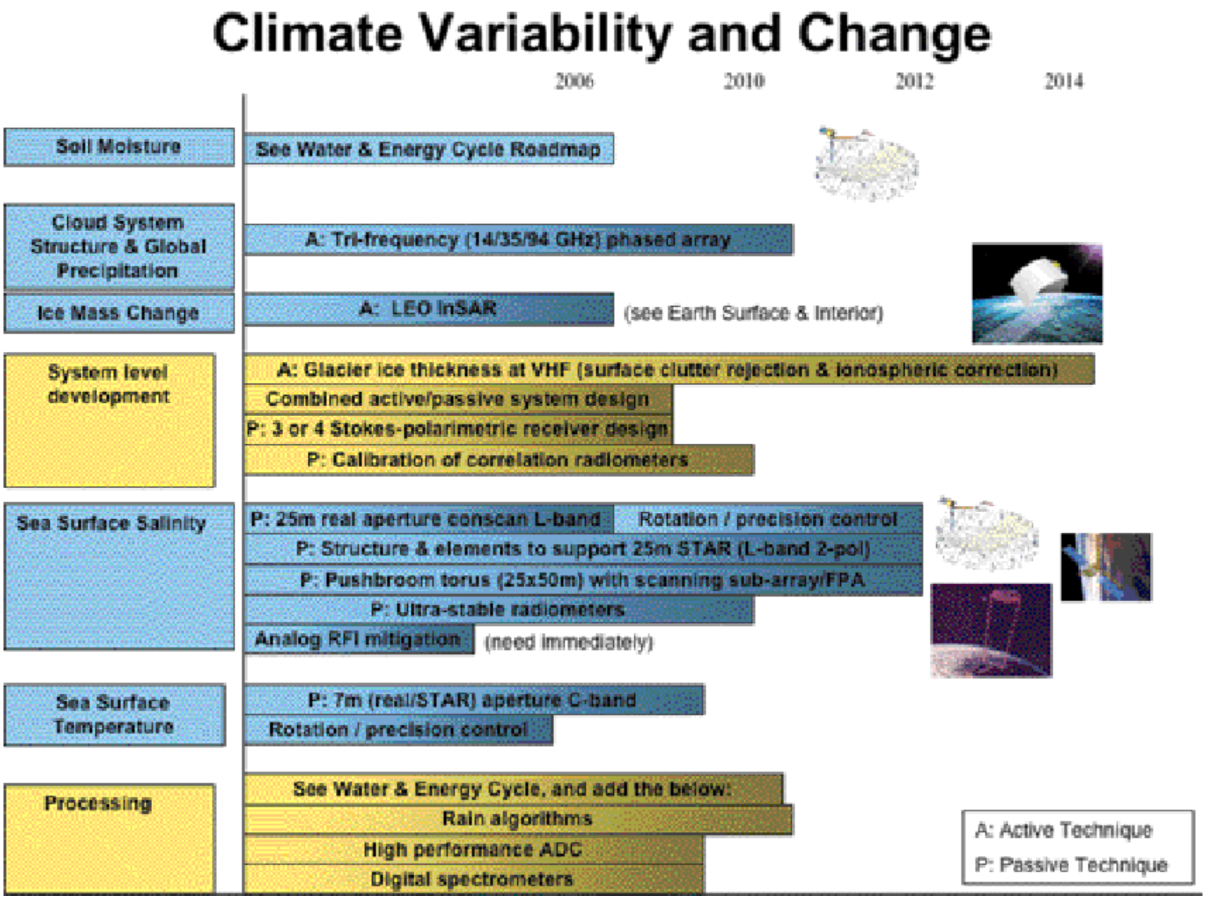

Massively Parallel 1 -Bit Cross Correlators
For STAR
Legend
Products
Capabilities
Technologies
Massively parallel 1 -bit cross correlators
10,000 (threshold) / 90,000(objective) (multiply-accumulate)1 -bit cross - correlations per ASIC; 0.25 mW(threshold) / 0.1 mW(target) correlator cell at 220 MHz clock rate; Fully scalable interconnect architecture
Possible Technologies -ASIC
Not a standard product
TRL 3
Technologies -Under development
Current
Far Term

Figure 4L13

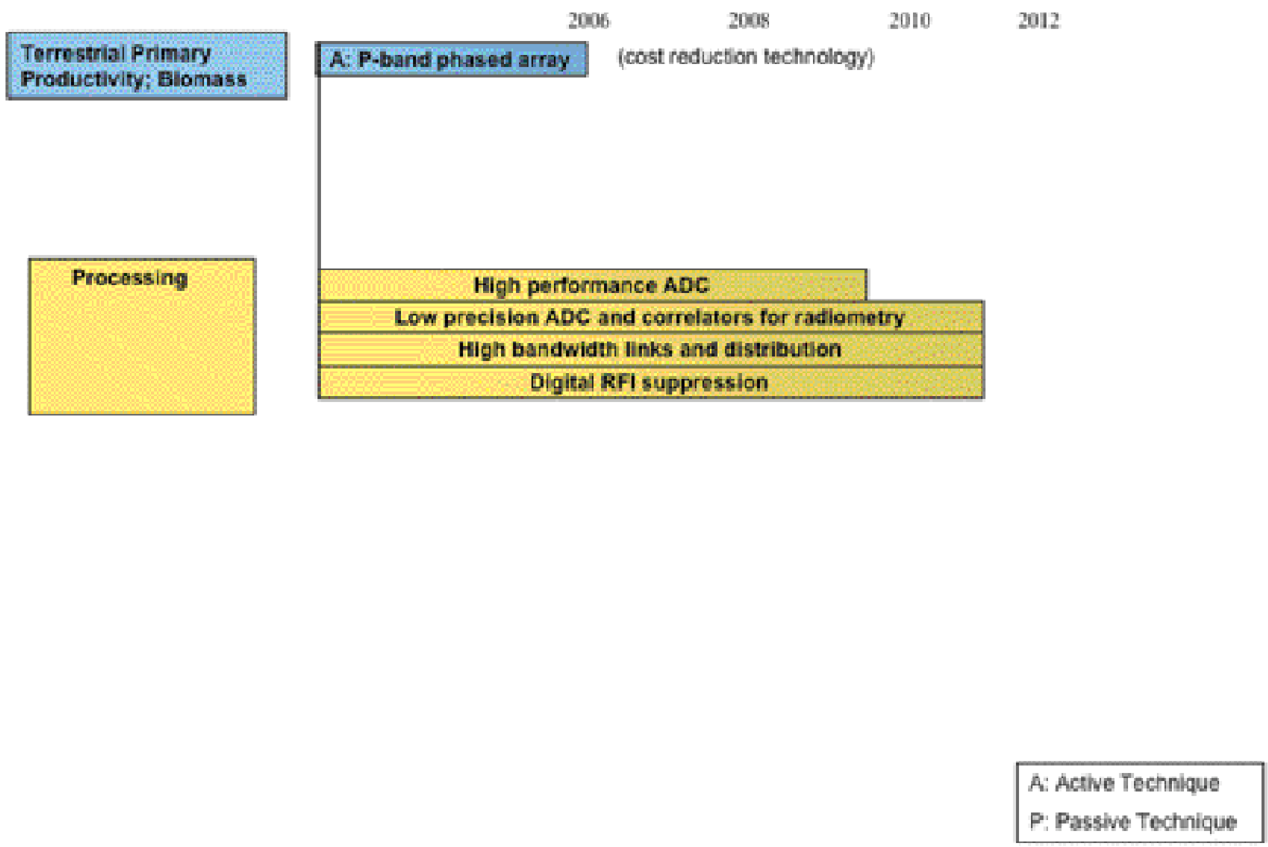
APPENDIX 5: MICROWAVE TECHNOLOGY ROADMAPS FOR SCIENCE FOCUS AREAS

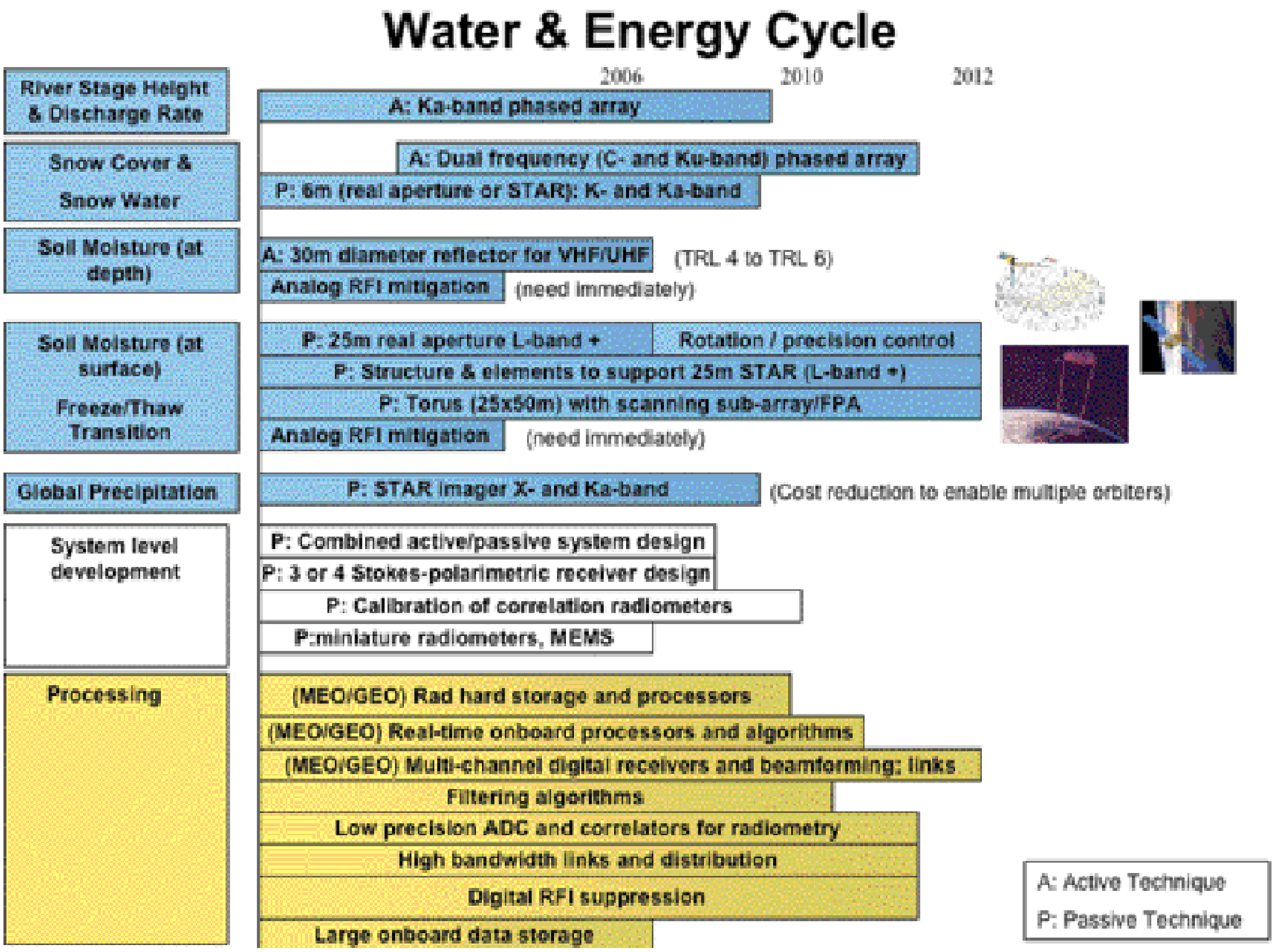



Atmospheric Composition
2006
2008
2012
2014
Upper Troposphere/ Tropopause Ozone & Trace Species
P: Radiometer system noise 100K @ 200 GHz
(adv microwave limb sounder)
P: High-frequency LOs, mixers, detectors 180 GHz to 2.5 THz
P: 2-D scanning mmw antenna; 10μm surface
System level development
P: System design for highly stable mm-wave and sub-mm-wave radiometers
Processing
2008
Real-time onboard processing
High-performance rad-hard processors
High speed & resolution digital spectrometers
A: Active Technique
P: Passive Technique

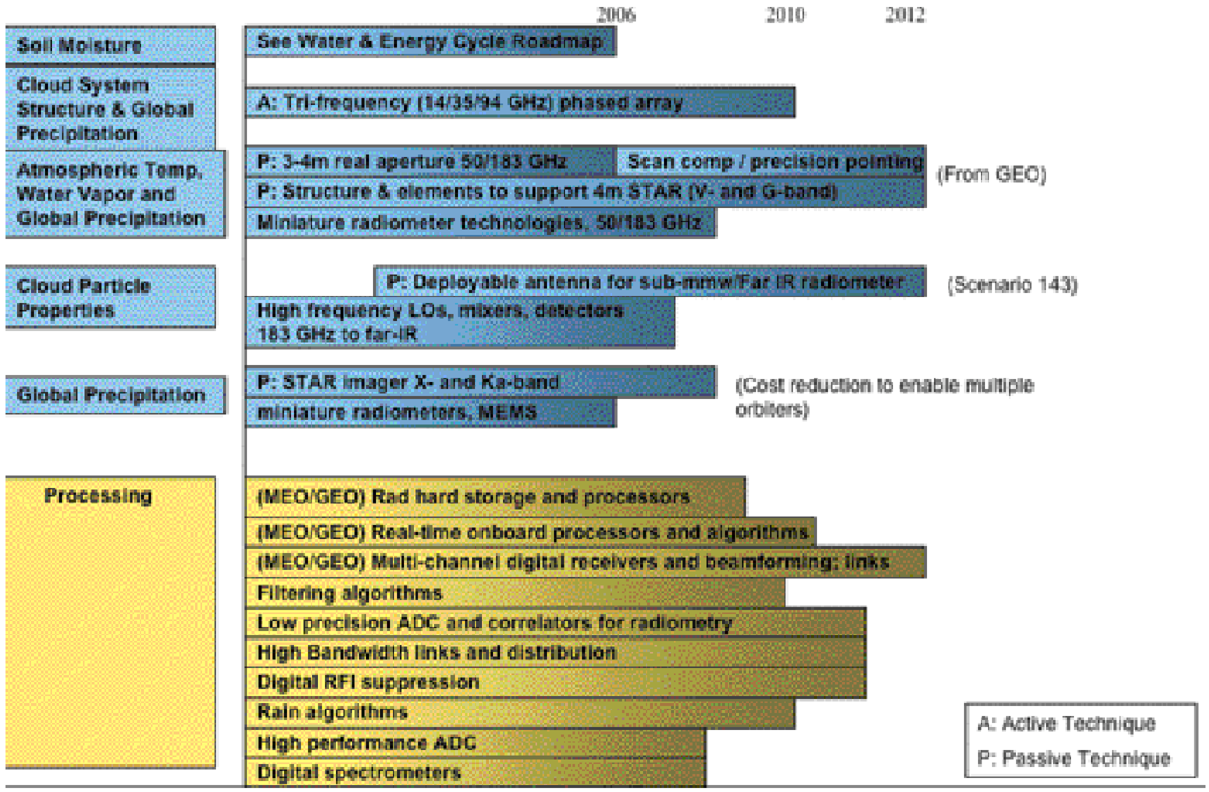

Climate Variability and Change
2006
2010
2012
2014
Soil Moisture
See Water & Energy Cycle Roadmap
Cloud System Structure & Global Precipitation
A: Tri-frequency (14/35/94 GHz) phased array
Ice Mass Change
A: LEO InSAR
(see Earth Surface & Interior)
System level development
A: Glacier ice thickness at VHF (surface clutter rejection & ionospheric correction)
Combined active/passive system design
P: 3 or 4 Stokes-polarimetric receiver design
P: Calibration of correlation radiometers
Sea Surface Salinity
P: 25m real aperture conscan L-band
Rotation / precision control
P: Structure & elements to support 25m STAR (L-band 2-pol)
P: Pushbroom torus (25x50m) with scanning sub-array/FPA
P: Ultra-stable radiometers
Analog RFI mitigation
(need immediately)
Sea Surface Temperature
P: 7m (real/STAR) aperture C-band
Rotation / precision control
Processing
See Water & Energy Cycle, and add the below:
Rain algorithms
High performance ADC
Digital spectrometers
A: Active Technique
P: Passive Technique

Carbon and Ecosystems




Water & Energy Cycle
2006
2010
2012
River Stage Height & Discharge Rate
A: Ka-band phased array
Snow Cover & Snow Water
A: Dual frequency (C- and Ku-band) phased array
P: 6m (real aperture or STAR): K- and Ka-band
Soil Moisture (at depth)
A: 30m diameter reflector for VHF/UHF
(TRL 4 to TRL 6)
Analog RFI mitigation
(need immediately)
Soil Moisture (at surface)
Freeze/Thaw Transition
P: 25m real aperture L-band +
Rotation / precision control
P: Structure & elements to support 25m STAR (L-band +)
P: Torus (25x50m) with scanning sub-array/FPA
Analog RFI mitigation
(need immediately)
Global Precipitation
P: STAR imager X- and Ka-band
(Cost reduction to enable multiple orbiters)
System level development
P: Combined active/passive system design
P: 3 or 4 Stokes-polarimetric receiver design
P: Calibration of correlation radiometers
P:miniature radiometers, MEMS
Processing
(MEO/GEO) Rad hard storage and processors
(MEO/GEO) Real-time onboard processors and algorithms
(MEO/GEO) Multi-channel digital receivers and beamforming; links
Filtering algorithms
Low precision ADC and correlators for radiometry
High bandwidth links and distribution
Digital RFI suppression
Large onboard data storage
A: Active Technique
P: Passive Technique

Weather


2006
2010
2012
Soil Moisture
See Water & Energy Cycle Roadmap
Cloud System Structure & Global Precipitation
A: Tri-frequency (14/35/94 GHz) phased array
Atmospheric Temp, Water Vapor and Global Precipitation
P: 3-4m real aperture 50/183 GHz
Scan comp / precision pointing
(From GEO)
P: Structure & elements to support 4m STAR (V- and G-band)
Miniature radiometer technologies, 50/183 GHz
Cloud Particle Properties
P: Deployable antenna for sub-mmw/Far IR radiometer
(Scenario 143)
High frequency LOs, mixers, detectors
183 GHz to far-IR
Global Precipitation
P: STAR imager X- and Ka-band
miniature radiometers, MEMS
(Cost reduction to enable multiple orbiters)
Processing
(MEO/GEO) Rad hard storage and processors
(MEO/GEO) Real-time onboard processors and algorithms
(MEO/GEO) Multi-channel digital receivers and beamforming; links
Filtering algorithms
Low precision ADC and correlators for radiometry
High Bandwidth links and distribution
Digital RFI suppression
Rain algorithms
High performance ADC
Digital spectrometers
A: Active Technique
P: Passive Technique

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Space Administration

Earth Science Technology Office

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