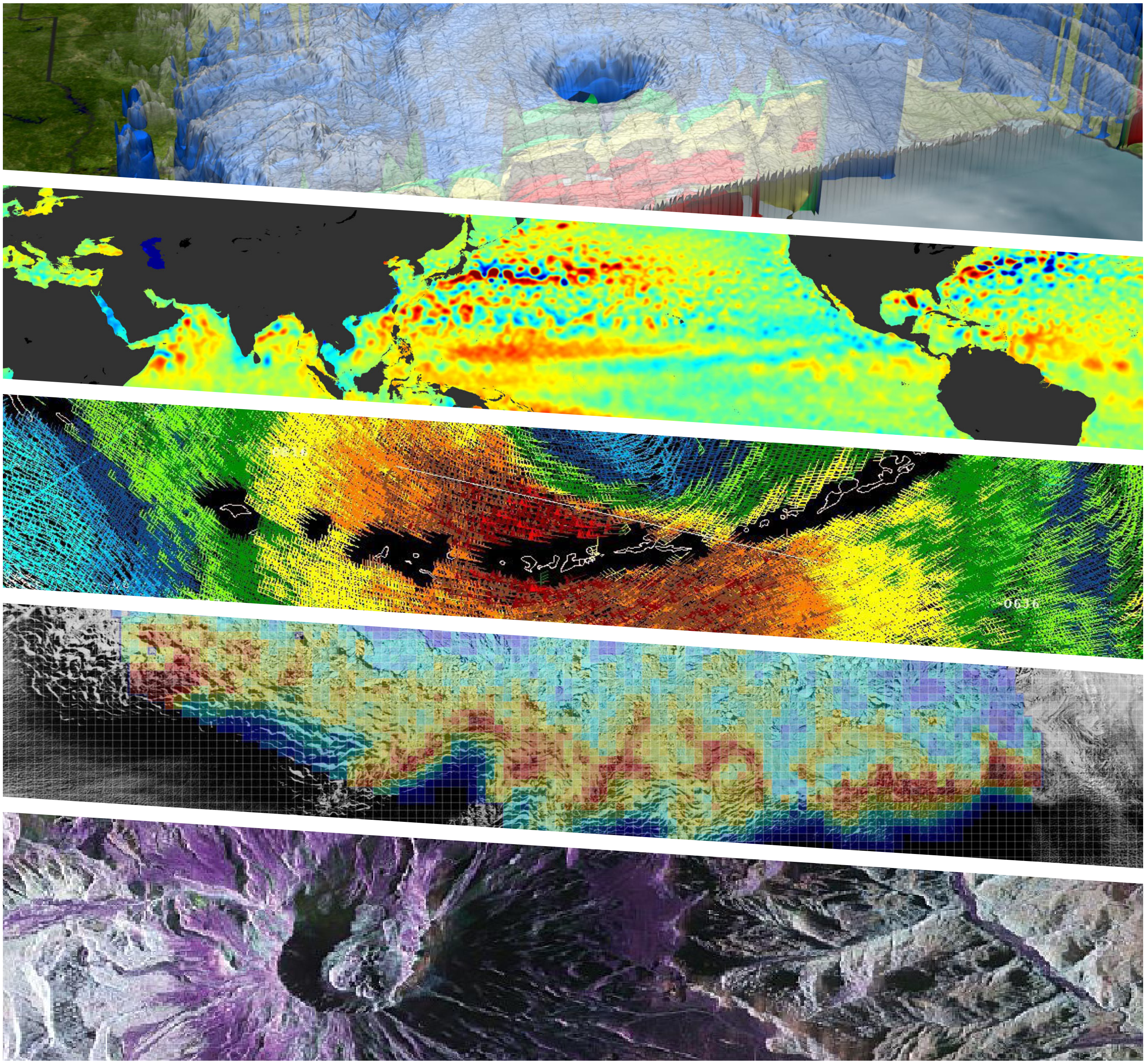
National Aeronautics and Space Administration

2016 Microwave Technologies Review and Strategy



NASA Earth Science Technology Office

2016 Microwave Technologies Review and Strategy
NASA Earth Science Technology Office (ESTO)

Azita Valinia, David Kunkee, and David Mayo (Editors)

Authors

Valinia, Azita (NASA Earth Science Technology Office – Study Lead)
Chandler, Adam (The Aerospace Corporation)
Kantrowitz, Frank (The Aerospace Corporation)
Kunkee, David (The Aerospace Corporation)

Contributors

Bradley, Damon (NASA Goddard Space Flight Center)
Doiron, Terrance (NASA Goddard Space Flight Center)
Gaier, Todd (Jet Propulsion Laboratory)
Hoffman, James (Jet Propulsion Laboratory)
Hyon, Jason (Jet Propulsion Laboratory)
Mayo, David (The Aerospace Corporation)
Piepmeier, Jeffrey (NASA Goddard Space Flight Center)
Spencer, Michael (Jet Propulsion Laboratory)
Tanelli, Simone (Jet Propulsion Laboratory)

Acknowledgements

The authors gratefully acknowledge the many individuals and collective contributions to this report that were made by the NASA center workshop attendees (Appendices A1, A2), virtual community forum participants (Appendix A3) and those that submitted written inputs (Appendix A4). Jessie Kawata of Jet Propulsion Laboratory is greatly appreciated for graphics support.

Table of Contents

Executive Summary 1
1. Introduction 10
2. Scientific Basis for Technology Development 13
  2.1. Atmospheric Composition 13
  2.2. Carbon and Ecosystems 14
  2.3. Climate Variability and Change 15
  2.4. Earth Surface and Interior 16
  2.5. Water and Energy Cycle 17
  2.6. Weather 18
3. Technology Requirements 20
  3.1. Radar Electronics and Antennas Technologies 20
    3.1.1. General Observations from the 2004 ESTO Microwave Technologies Report 21
    3.1.2. Specific Observations on Radar Electronics & Antennas 23
    3.1.3. Technology Challenges 24
    3.1.4. Conclusions and Recommendations 28
  3.2. Radiometer Technology 31
    3.2.1. Technology for Earth science measurements 31
    3.2.2. Technology needs update 34
    3.2.3. Technology Challenges 35
    3.2.4. Conclusions and Recommendations 45
  3.3. Information and Data Processing Technology 48
    3.3.1. Unmet Technology Needs from the Previous Decadal Survey 48
    3.3.2. Workshop Inputs 49
    3.3.3. Technology Development Needs 51
    3.3.4. Summary, Conclusions, and Recommendations 56
4. Emerging Technology 57
  4.1. Radar Technology 60
  4.2. Radiometer Technology 62
  4.3. Information Processing Technology 64
5. Summary and Path Forward 66
6. References 68
A. Workshop/Community Forum Info 72
B. White Papers Submitted 78
C. Acronym List 79
D1. Radar Technology Capability Breakdown Matrix 80
D2. Radiometer Technology Capability Breakdown Matrix 85
D3. Information and Data Processing Capability Breakdown Matrices 90
E. Summary of ESTO Investments in Earth Science (JPL) 101
F. Summary of ESTO Investments in Earth Science (GSFC) 106
G. Emerging Technology Goals for Measurements 107

List of Figures

Figure 1. Microwave remote sensing taxonomy that identifies technology developments required to complete the remaining tiered 2007 NRC decadal survey missions carrying microwave sensors.............. 1
Figure 2. Microwave remote sensing taxonomy that identifies technology developments that will facilitate remaining tiered 2007 NRC decadal survey missions carrying microwave sensors including cost savings opportunities and technologies required to realize new and anticipated Earth science measurements in the 2016 NRC update. 3
Figure 3. Summary of key technologies for active microwave remote sensing.. 4
Figure 4. Key technologies for passive microwave remote sensing 6
Figure 5. Summary of key technologies for information and data processing.. 7
Figure 6. Radar Remote Sensing Techniques and Applications. 11
Figure 7. Radiometer Applications in Earth Science 11
Figure 8. Summary of key technologies across frequency bands. 29
Figure 9. Microwave measurement and technology needs for Earth science summarized within four separate RF frequency ranges. 45
Figure 10. Microwave measurement and technology needs for Earth Science summarized by frequency band 46
Figure 11. Image taken at 2016 JPL Microwave Technology Workshop 72
Figure 12. Image taken at 2016 GSFC Microwave Technology Workshop 74

List of Tables

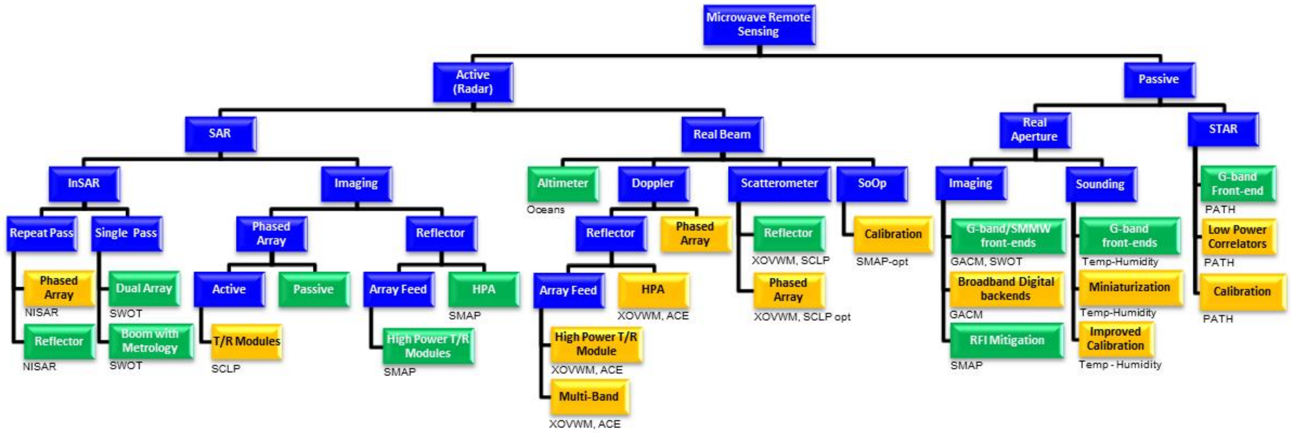
Table 2.1. Spectral bands of the EOS MLS Instrument and scientific measurements 14
Table 2.2. Space-based microwave sensors supporting operational weather missions in the US 19
Table 3.1. Radar technology assessment for the 2007 Tiered Decadal Survey measurements 21
Table 3.2. Technology needs for future measurements 22
Table 3.3. Technology areas for 2016... 23
Table 3.4. Example array Transmit/Receive technology needs. 25
Table 3.5. Example high power amplifier technology needs. 26
Table 3.6. Example antenna related technology development needs. 26
Table 3.7. Example signals-of-opportunity related receiver technology needs. 27
Table 3.8. Example small satellite radar technology needs. 27
Table 3.9. Technology readiness level assessment of greatest challenge technology from 2007 tiered decadal survey missions.. 32
Table 3.10. Technology capability gap associated with new measurements concepts involving passive microwave radiometry (Part I).. 32
Table 3.11. Technology capability gap associated with new measurements concepts involving passive microwave radiometry (Part II). 33
Table 3.12. Summary of technical areas in radiometry for investment in 2016.. 35
Table 3.13. Technology needs for high frequency radiometry 37
Table 3.14. Technology needs for radiometry to achieve multi-sensor multi-frequency sensors (Part I): Combined FPAs for antennas 38
Table 3.15. Technology needs for radiometry to achieve multi-sensor multi-frequency sensors (Part II): Integrated radiometers with radar transmitters and receivers. 38
Table 3.16. Technology needs for RFI mitigation in radiometry... 39
Table 3.17. Technology needs for microwave radiometry with larger aperture reflector antennas 40
Table 3.18. Technology needs in passive microwave polarimetry 41
Table 3.19 Technology needs for Synthetic Thinned Aperture Radiometry (STAR)............................... 41
Table 3.20. Technology needs for microwave radiometer calibration 43
Table 3.21. Cryocooler technology needs... 44
Table 3.22. Small satellite space-based platform improvements to enable next generation radiometric measurements for Earth science.. 44
Table 3.23. Data/information technology assessment for the 2007 Tiered Decadal Survey Measurements 49
Table 3.24. Information technology needs for future measurements... 50
Table 3.25. Onboard data processing needs for microwave Earth science measurements........................ 53
Table 3.26. Spacecraft communication and control technology development needs................................ 54
Table 3.27 Technology development needs related to ground processing.. 57
Table 4.1. Technology availability gaps for future microwave Earth science measurement needs. 59
Table 4.2. Emerging technology roll-up and summary by frequency band. 60
Table 4.3. Emerging technology roll-up for radar 61
Table 4.4. Emerging technology roll-up for microwave radiometers 63
Table 4.5. Emerging technology roll-up for information and data processing... 65

Table G.1. High frequency RF Components and Systems Technology Assessment. 107
Table G.2. Multiple Frequency Integrated Antenna Elements Technology Assessment 108
Table G.3. Technology Assessment to Support Overall Miniaturization of Microwave Sensors (SWaP; Deployables) 108
Table G.4. Technology Assessment for Large Reflectors and Lightweight Materials............................. 109
Table G.5. Sensor Calibration Technology Assessment 109
Table G.6. Technology Assessment of Digital Processing Performance Improvements 110
Table G.7. Assessment of Next Generation Data Processing and Management Needs 110

Executive Summary

This report summarizes the state-of-the-art in microwave technology in support of NASA's Earth science measurement goals and serves as a detailed update to an earlier road mapping activity performed over a decade ago, [*ESTO,* 2004]. The scope of the current activity included two face-to-face working group meetings held at JPL and NASA GSFC, followed by a virtual community forum in which an initial summary of findings for this 2016 update was presented to the teams for critical evaluation. These activities serve as the basis for the current report, which will address technology development needs for active and passive microwave remote sensing for Earth science and associated data and information processing applied to both the space and ground segments.

An overall state-of-the-art assessment of microwave technology needed to support Earth science measurements outlined in the 2007 decadal survey [*NRC,* 2007] can be shown graphically as illustrated in Figure 1.



Key:

Space-Proven (TRL 7-9)
Developmental (TRL 4-6)
Experimental (TRL 1-3)

Notes
1) Missions are identified from Table 2.2 in the 2007 NRC survey document with the exception of NISAR which was formerly DESDnyI.
2) Some technology blocks are identified as options for the named missions (opt).
3) Temperature and humidity measurements are general Earth science measurements.

Each sensor/measurement has its own Command and Data Handling 'shadow', in addition to the cross-cutting IT challenges.

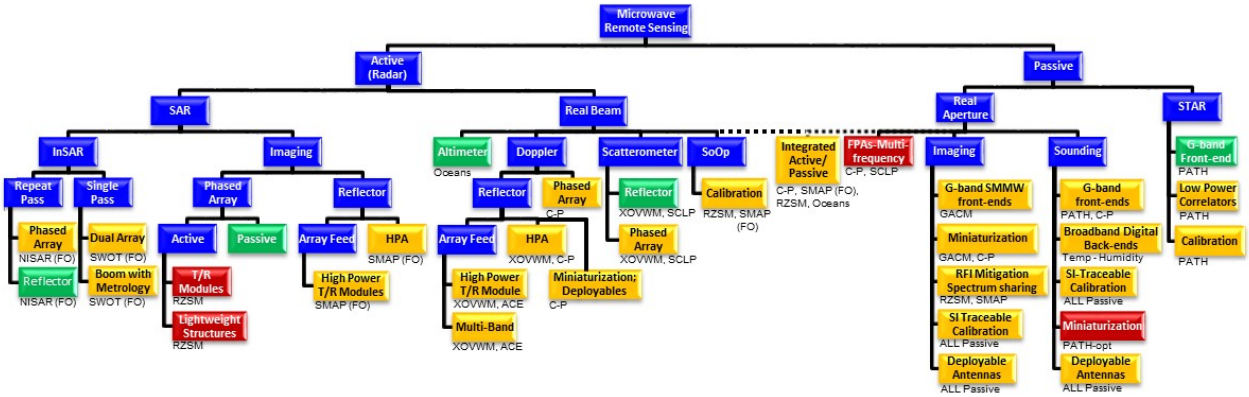
Figure 1. Microwave remote sensing taxonomy that identifies technology developments required to complete the remaining tiered 2007 NRC decadal survey missions carrying microwave sensors.

The above assessment reflects the relatively high maturity of space-based microwave remote sensing which now includes over 50 missions that have carried passive or active microwave instruments capable of measuring characteristics of the Earth's atmosphere and land and ocean surfaces. Technology development areas with high value for supporting the remaining tiered

Earth science missions identified from the 2007 decadal survey [*NRC,* 2007] appear in the yellow boxes in Figure 1. For example, development of phased array technology may enable an alternative or improved approach for the eXtended Ocean Surface Wind Vector Mission (XOVWM). Further development of phased array feed and High Power Amplifier (HPA) technology will support reflector based instrument concepts and improve design of instruments for measuring precipitation and cloud processes. Technology investment opportunities identified for passive microwave sensors may yield similar improvements in Earth science measurements for Precipitation and All-weather Temperature and Humidity (PATH).

Although Figure 1 suggests that microwave technology for recommended Earth science measurements is relatively mature, it is noted that *only one of the ten tiered missions from the 2007 NRC report involving microwave instruments has been launched within the past decade.* This is in sharp contrast with the recommended timeline contained within the report, which suggests that by 2016 all ten missions carrying microwave sensors would be on-orbit or at least in full scale development. One explanation for the delay is significant mission cost growth. For example, the Soil Moisture Active Passive (SMAP) mission, which replaced the NASA ESSP Hydros mission, was launched in January 2015. Costs for SMAP far exceeded the ~$300M ROM estimate reported in the 2007 decadal survey [*NRC,* 2007] Table 2.2. Further, the Global Precipitation Measurement (GPM) mission core satellite was launched in 2014, two years later than the expected date in 2012, and its accompanying constellation microwave imager was de-scoped in part to reduce expenditures. *Therefore, reducing mission cost while maintaining and improving critical Earth science measurements through the use of new technology is of paramount importance for the future of Earth science.*

To achieve this goal, key technology developments designed to facilitate and enhance development of microwave Earth science measurement are expected to play a critical role enabling the successful development of future Earth science missions by reducing payload mass, power, volume and complexity. Examples of anticipated new technology application include 1) integrated multi-frequency feed arrays, front-ends and back-end electroincs allowing a single instrument to replace multiple instruments or subsystems, 2) continuing miniaturization and performance improvements of RF electronics particularly at higher frequencies needed for Earth remote sensing (e.g. LNAs above G-band; SSPAs at Ka-band and above) and 3) technologies to enable lower cost alternative measurement approaches that are increasingly able to take advantage of the explosion in lower cost SmallSat and hosted launch opportunities. It is the conclusion of this report that *successful development of these capabilities will yield significant cost reduction and performance enhancements for the next generation of Earth science measurements compared to use of the current state-of-the-art.* Accordingly, readiness levels for an expanded application of new and necessarily lower maturity technologies to the 2007 recommended missions as well as newly envisioned Earth science measurements are shown in Figure 2.



Key:

Space-Proven (TRL 7-9)
Developmental (TRL 4-6)
Experimental (TRL 1-3)

Notes

1) Missions are identified from Table 2.2 in the 2007 NRC survey document with the exception of NISAR which was formerly DESDnyI.
2) Some technology blocks are identified as options for the named missions (opt).
3) "Temperature and humidity" are general Earth science measurements.
4) "C-P" designates generally applicability to clouds and precipitation measurements.
5) "Oceans" designates general applicability to Ocean surface measurements and characterization.
6) NISAR, SMAP, SWOT (FO): Technology investments may benefit follow-on missions

Each sensor/measurement has its own Command and Data Handling 'shadow', in addition to the cross-cutting IT challenges.

Figure 2. Microwave remote sensing taxonomy that identifies technology developments that will facilitate remaining tiered 2007 NRC decadal survey missions carrying microwave sensors including cost savings opportunities and technologies required to realize new and anticipated Earth science measurements in the 2016 NRC update.

Technology developments supporting radar remote sensing

Within the ten tiered missions presented in the 2007 decadal survey report [*NRC,* 2007] carrying microwave instruments, six involve remote sensing with radar. Additional radar measurements discussed during the working groups include new scenarios to retrieve precision humidity and boundary-layer characterization (G-band), GEO weather radar (Ka-band) and scanning deep (root zone) soil moisture (P-band). An overview of active remote sensing measurements and key technology supporting microwave radar remote sensing is shown in Figure 3.

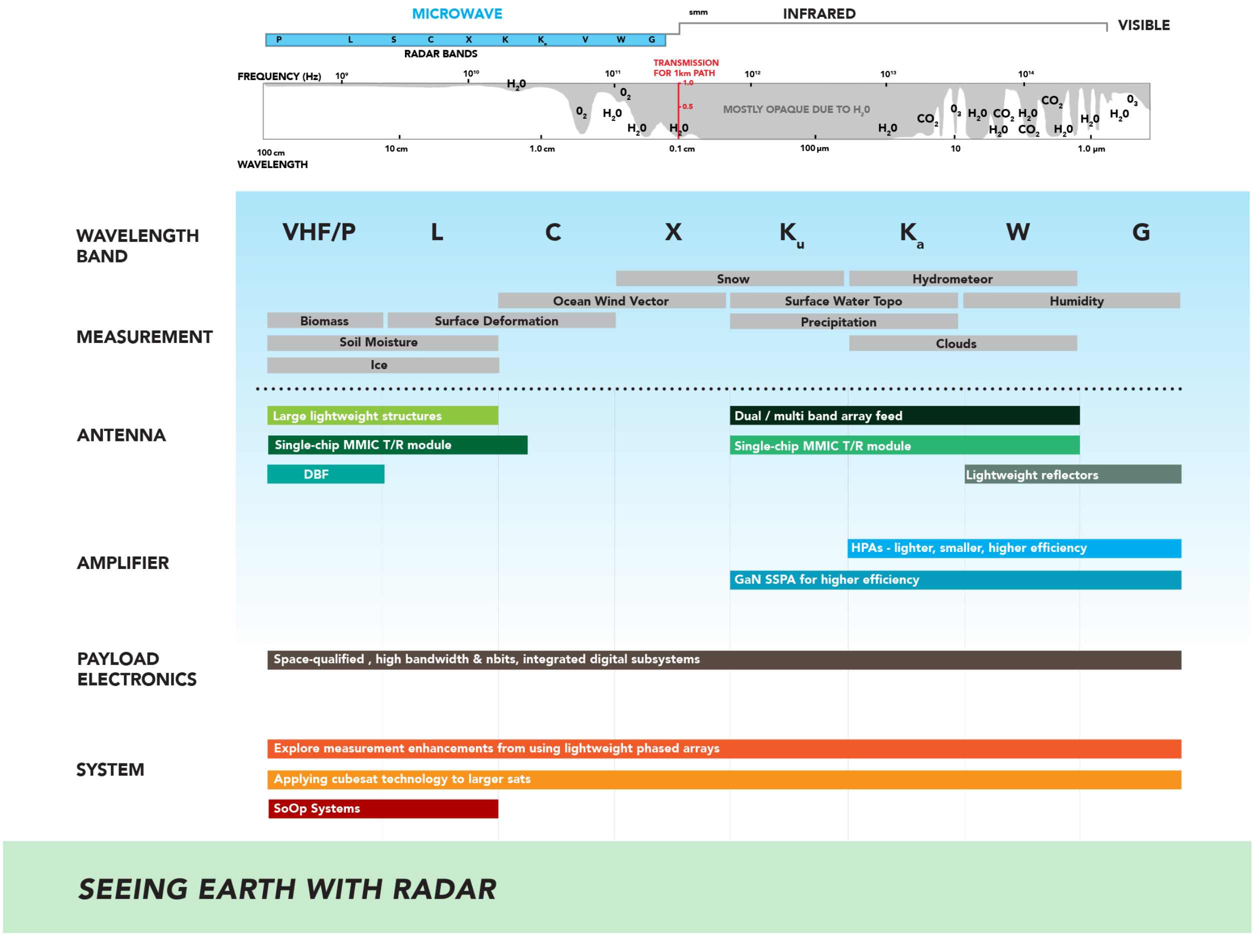


Figure 3. Summary of key technologies for active microwave remote sensing

It can be seen in Figure 3 that many measurements involve dual and multiple bands. Examples include the use of multiple bands to measure hydrometeor size for cloud and precipitation profiles, and the use of dual-bands to enable measurement of volume and density for snow layers. For this reason, technology that reduces size and mass for multi-band radar measurements should be a high priority for investment. The currently flying Global Precipitation Measurement (GPM) Mission employed dual-bands by essentially placing two separate phased array radars side by side. In general this is very expensive. Future use of common antennas and electronics should reduce cost. Examples include the closely spaced linear arrays at Ku-, Ka-, and W-bands feeding a common parabolic cylinder reflector as are being developed for the 2007 decadal mission ACE. Another technology example enabling multi-band radar is the Harris current sheet feed. The 2007 decadal missions SCLP (X-, Ku-bands) and XOVWM (X-, Ku-bands) also utilize multiple bands and can benefit by investment in this technology.

Radar remote sensing satellites are particularly demanding due to the high transmit power (several kW) and large antennas (12m for NISAR, 30m for hurricane wind measurement) that generally are required. For this reason it is important to focus on investments that are aimed at greater efficiency and miniaturization. This includes highly efficient transmit amplifiers, receive amplifiers with low noise figure, and technology that reduces front end losses. Miniaturization can be accomplished through greater use of digital technology for signal generation, beamforming and receivers. In addition, there would be a large benefit to reducing the size and weight of high power vacuum amplifiers. For some measurements (cloud characterization, precipitation), either high power vacuum amplifiers or arrays with solid state amplifiers can be utilized. Systems engineering analysis can inform this decision and avoid the cost of duplicative development.

Signals-of-opportunity (SoOp) based bistatic radar and SmallSats/CubeSats both present new opportunities for Earth science measurements. Specifically, the lower cost of these systems should enable large constellations to be deployed. This will create the opportunity for diurnal and temporal sampling that is not possible with the large satellite missions. Measurement concepts for SoOp and CubeSats should be developed more completely to better understand their value. Examples of SoOp and CubeSat based measurements include using VHF and GNSS signals for root zone soil moisture and snow water equivalent measurement, and RainCube for precipitation measurement.

Technology developments supporting passive microwave remote sensing

An overview of key technologies for Earth science measurements involving passive microwave radiometry is shown in Figure 4. Passive microwave instruments are needed for measurement of temperature and humidity profiles, atmospheric composition, deep soil moisture, as well as support for topography (SWOT) measurements. Passive microwave measurements are also used for snow and cold land processes surface imaging.

Over the past decade RF electronics have continued to achieve greater performance at higher frequencies. Recent developments in low noise amplifiers >200-GHz have provided unprecedented performance from solid state devices requiring lower power and volume. Technology development goals such as MMIC-based superheterodyne integrated receivers exhibiting 300K system noise at 500-GHz (cooled to ~20K) and requiring <0.1 W will allow science goals for atmospheric circulation (GACM) to be met in a robust manner reducing the risk of performance shortfalls and cost overruns. Integrated RF receivers at the above performance levels may also enable ultra-low cost atmospheric temperature and humidity profile measurements from SmallSats. With a sufficient number of SmallSats, adequate spatiotemporal sampling could be achieved to reduce or eventually eliminate the need for a Geosynchonous orbiting microwave sounder as currently envisioned for PATH [*NRC,* 2007].

Stable, consistent, and accurate calibration of microwave radiometers ensures high value and consistency of retrieved geophysical measurements. When many (e.g., N>10) sensors are utilized, the individual observations must have a consistent calibration to enable efficient assimilation of the measurements into higher level models. Achieving standard SI-traceability of microwave radiometer calibration is especially important for measurements supporting climate-based objectives such as global atmospheric temperature and moisture profile.

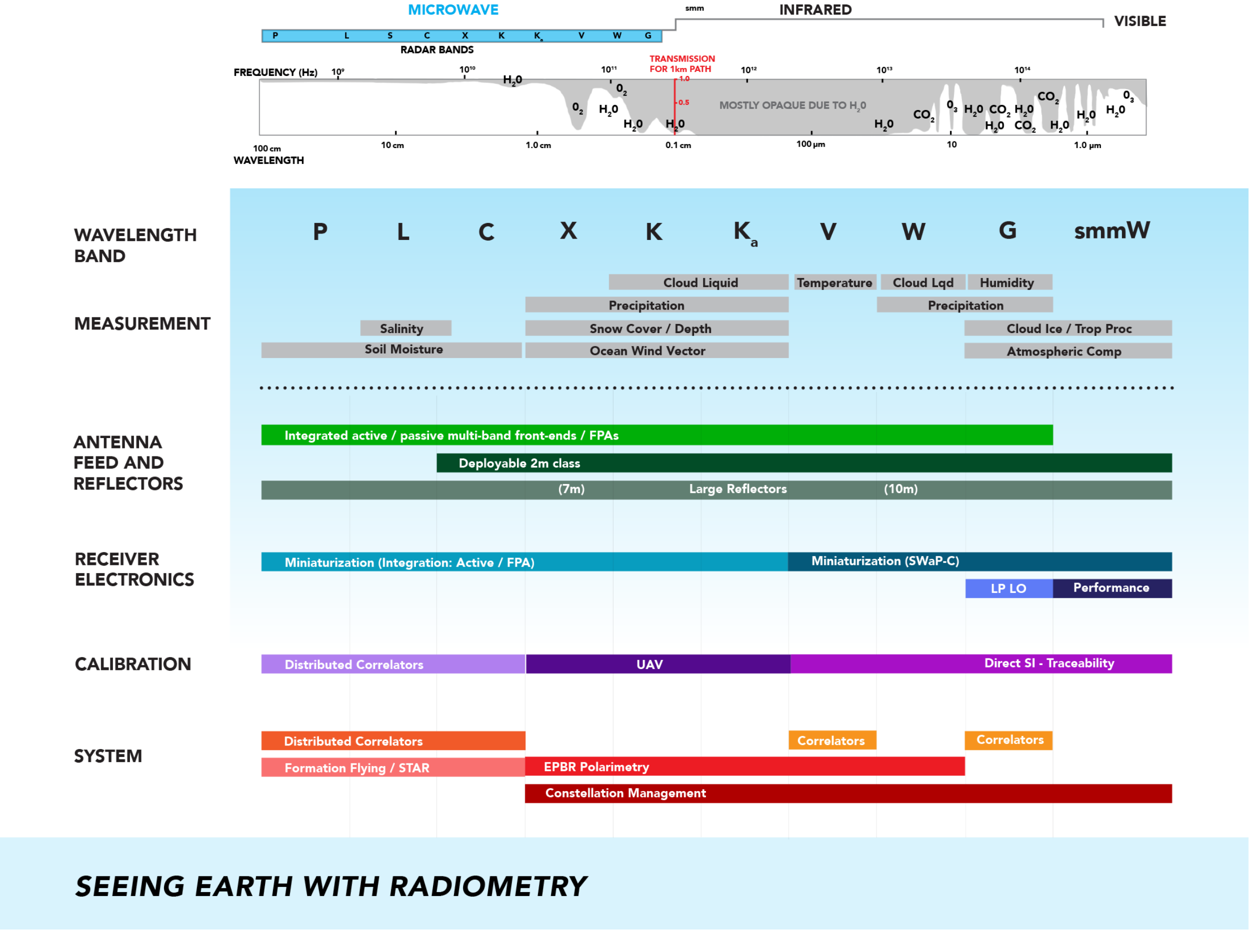


Figure 4. Key technologies for passive microwave remote sensing

To achieve a common goal of reducing SWaP-C for microwave payloads, instrument designers must address Horizontal Spatial Resolution (HSR) as a key characteristic of the sensor data that is driven by diffraction-limited antenna apertures. Accordingly, HSR limitations can be severe when the payload SWaP is limited due to cost constraints host vehicles with limited accommodation capability. In these cases, small scale (up to ~2m) deployable antennas could be used to enable payload SWaP reductions, while maintaining HSR performance. Accordingly, reduction of microwave payload SWaP-C using smaller and lower-power RF electronics with deployable antennas could be applied to many measurement scenarios including atmospheric temperature and humidity profiles, snow and cold land processes, and passive microwave imagers for clouds and precipitation.

And finally, improvement of RFI mitigation performance is recognized to be critical for the future of passive microwave remote sensing due to the trend of increasing impact from RFI over the past decade [*NRC*, 2010]. Future Earth science measurements may also be needed in portions of the radio spectrum that are even more heavily utilized by other radio services, further increasing the impact of RFI. Accordingly, new techniques for RFI detection and mitigation will be needed and are under investigation following the successful implementation of the SMAP RFI mitigation approach. Promising examples include highly selective tunable notches to remove the impact of adjacent high power interferes, improved detection thresholds using complex kurtosis techniques [*Bradley et al.*, 2014] and cooperative spectrum sharing approaches [*NRC,* 2010]. Additional RFI mitigation technology development needs include autonomous (on-board) RFI detection and mitigation algorithms in order to eliminate exponential down link data rate growth that would otherwise be required to enable ground based (post measurement) RFI mitigation.

Data processing technology needs for future microwave Earth science measurements

Every scientific measurement involves the collection and processing of data. Rapidly expanding data volumes and increasing onboard processing needs are expected to present significant challenges in the very near future. Accordingly, it is recommended that investment in information processing capabilities occur alongside sensor hardware system development.

An overview of space-based Earth science data and information processing is shown in Figure 5, along with technology development opportunities associated with each segment in the data handling chain. While there are mature, flying instances of many of the technologies listed in the figure, the 'developmental' designation applies to novel concepts enabling improved or reduced-cost measurements.

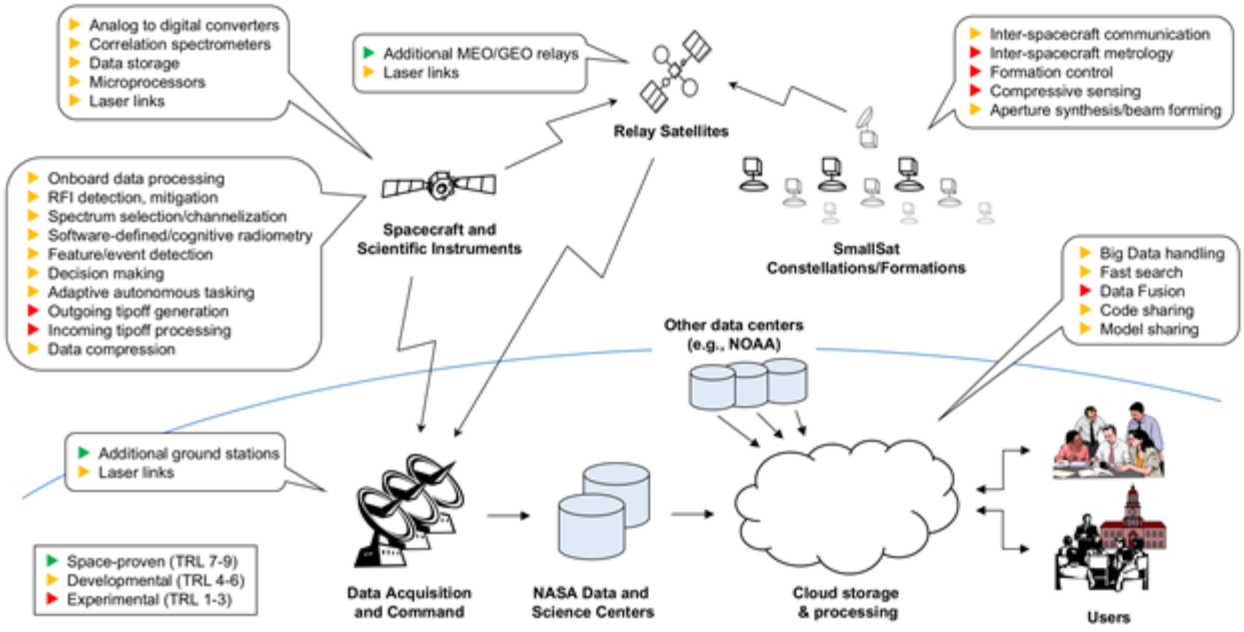


Figure 5. Summary of key technologies for information and data processing

Over the course of the JPL and GSFC workshops, several data and information processing themes emerged: coordination of multiple spacecraft, adaptive processing and tasking, and handling of large amounts of data. While not all-encompassing, these themes subsume the majority of the workshop inputs and serve as a representative summary of information technology needs.

The use of multiple SmallSats to replace or enhance functionality currently resident only in large, expensive, monolithic systems is a topic of keen interest. These constellations or formations may enable simultaneous spatially-extended measurements, cost-effective persistence, and large aperture synthesis (i.e., synthesizing a single large, electronically steerable aperture by coherently combining signals from a sparse array of small individual antennas). Improvements in constellation management and precise station-keeping capabilities will require development of operational concepts and standards, as well as investment in algorithms, onboard processing capabilities, low-SWaP metrology, and communications solutions.

Workshop participants expressed the need to increase instruments' ability to adapt to dynamic measurement environments and autonomously alter collection strategies in response. Adaptive reallocation of resources can improve responsiveness to time-varying events (e.g., storms, earthquakes, etc.), enables targeted interference avoidance or mitigation, and may enable reductions in data volumes and downlink requirements. This will require investment in onboard processing capabilities to enable rapid feature or event detection, decision making, and collection modification. Additionally, development of standards and operational concepts to facilitate inter-spacecraft communication and tasking will be required.

Earth science measurements in the next decade are expected to generate enormous amounts of data. Currently planned microwave systems alone will yield ~petabytes per year, and this amount will only grow as revisit rates, global coverage, and bandwidths increase. Total data processing throughput is expected to top ~100s of terabytes per day. Handling these unprecedented data volumes will require investment in a number of areas. Onboard, radiation-hardened storage and processing hardware will need to advance to allow data reduction and compression prior to downlink. Crosslink and downlink capacity will need to increase (via development and increased use of optical links and/or expansion of relays and ground station facilities), and investments will be needed in intelligent ground data infrastructure for processing, storage, and dissemination.

Model-Based Systems Engineering

In order to fully leverage the availability of new technology it is critical to accurately assess system-level trades involving fundamental aspects of the instrument, measurement scenario and mission-level design. This task requires robust, high-fidelity modeling and simulation capability that accurately represents critical elements of science and engineering within the system. Examples of parameters that impact measurement value include horizontal and vertical spatial resolution; radiometric resolution (sensitivity) and temporal resolution (revisit time). Technology needs can be related to Earth science measurement value by using model-based systems engineering (MBSE) and system engineering principles.

Specifically, the MBSE paradigm offers an approach for independently arbitrating a number of questions prevailing within the microwave community. For example, a rigorous MBSE analysis would determine whether a mission is most efficiently accomplished using a single platform or a distributed architecture involving a SmallSat constellation. These analyses would help to resolve long-running uncertainties, enabling NASA to more effectively utilize available resources. Accordingly, it is the recommendation of this report that *system trades and updates to mission concepts be performed early in the development cycle in order to inform technology development decisions*. Two examples of MBSE in instrument and measurement development include NISAR and SWOT.

The NISAR development has utilized a suite of integrated custom simulation/analysis models to flow science requirements down to the instrument system and subsystems to estimate radar measurement performance for system architecture and design trade-offs and optimization. MBSE is also used to establish current best estimates (CBE) for assessing compliance to system requirements and for requirements development, traceability, linkage and verification. Antenna RF performance and deployment modeling as part of system V&V (GRASP, HFSS, ADAMS, FEM models are used for these) are also managed within the framework of MSE for NISAR. For SWOT, model development and verification is central to the development and assessment of performance requirements at all levels (2-6) of the project. Models are developed of hardware in flight performance (antenna RF performance, structural deformation, thermal environment), and full instrument simulation is used to verify key performance requirements in areas where testing in a flight-like manner is impossible or prohibitively difficult. As a result, the verification and validation program is considered to be highly oriented toward model verification.

In conclusion, addressing cost and risk concerns of a space borne instrument development, there are a few important areas to consider. One is to analyze an instrument signal path in order to understand whether it meets specific instrument performance requirements. When component technologies are integrated, the major risk is often in optimizing the interfaces. Therefore, there should be a testbed established in order to understand how a new technology component behaves in a system before it is claimed ready for infusion. Another important aspect is to capture key characteristics of subsystem behavior such as a large deployable aperture and to validate its behavior because it is usually not feasible to test the actual hardware. The MBSE approach plays an important role in assessing these risks. Furthermore, parts screening, power/mass/volume estimate, and dual string designs could be addressed in an early stage of an instrument development. This will provide an opportunity to optimize the overall instrument design. For example, an instrument was baselined with a 26 volt power supply. Because of an increase of power requirements by the overall system, the input power had to increase by 6 volts. This became a new technology development because there is no such space qualified power supply to provide 32 volts. Therefore, not only technology maturation but also engineering maturation should be considered in order to address risks and to manage the cost of instrument developments.

1. Introduction

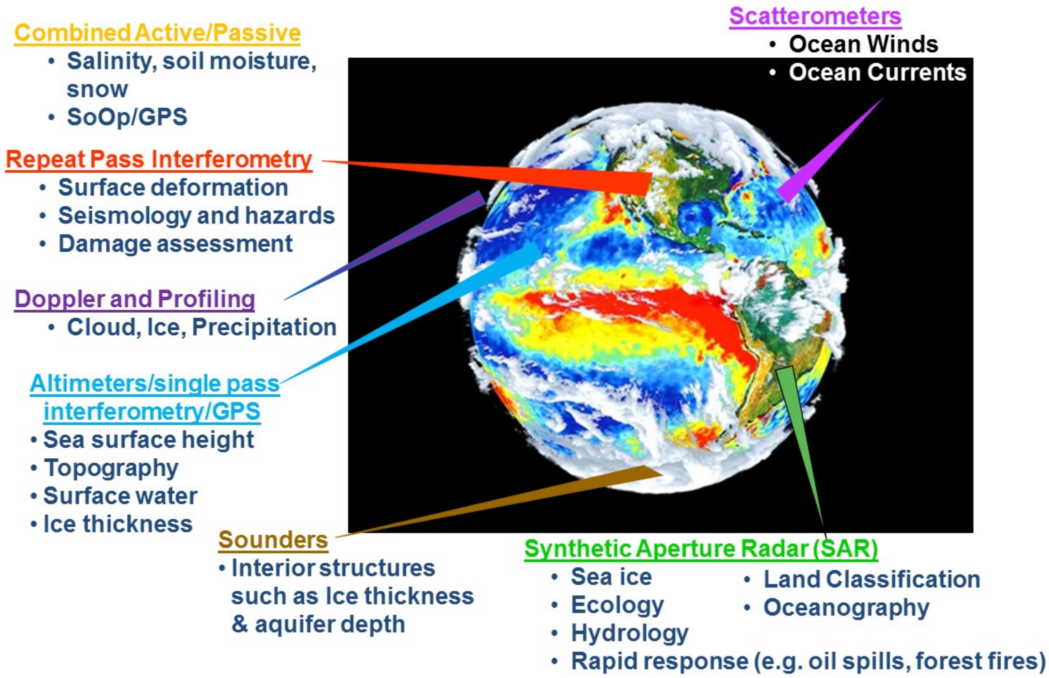
The NASA Earth Science Technology Office (ESTO) published its last microwave technology investment strategy in 2004 [*ESTO*, 2004]. That strategy laid out a decadal active and passive microwave technology implementation plan, investment strategy, and related technology roadmaps to enable NASA's Earth Science measurement goals.

This current (2016) report assesses the state-of-the-art in microwave technologies more than a decade later. Microwave technology maturation in the past decade has been evaluated, and the ESTO investment strategy is updated and laid out in this report according to the current NASA Earth science measurement needs and new emerging technologies.

Azita Valinia (NASA/ESTO) served as the study lead for the ESTO microwave technology investment strategy team that assembled this report. The core study team consisted of The Aerospace Corporation's independent subject matter experts: David Kunkee, Frank Kantrowitz, and Adam Chandler. David Mayo from The Aerospace Corp. served as the coordinator. Terence Doiron (NASA/GSFC) and Jason Hyon (NASA/JPL) served as lead representatives for their respective NASA Centers.

For the purpose of gathering community input, the team conducted two microwave technology workshops at NASA Centers. These workshops were held on January 21, 2016 at NASA JPL, and January 28, 2016 at NASA GSFC. A list of attendees at the workshops is provided in Appendix A. Additionally, a white paper input site was created and a request for information was issued by ESTO for the community to submit their input. The list of submitted white papers is available in Appendix 2. A large amount of input was received during the workshops, which is summarized in spreadsheet format in Appendix C. On March 17, 2016, the ESTO microwave strategy team convened a virtual microwave technology Community Forum to brief the community on the status of inputs gathered thus far. Members of the core study team gave presentations on how they have integrated the community input received to date, and the emerging technology requirements and trends. Additional input and feedback was requested from the community before finalizing the ESTO microwave technology investment strategy for the next decade. The Community Forum briefing package is available at: https://esto.nasa.gov/MicrowaveStrategies/MicrowaveCommunityForumCharts.pdf

This report is the culmination of the community inputs and the integration and analysis of the inputs leading to an investment strategy and path forward for enabling NASA's Earth Science Measurement goals. The technology requirements discussed in this report address three major scientific measurement areas: Atmospheric Composition; Earth Surface and Interior; Carbon Cycle and Ecosystems; Climate Variability; Water and Energy Cycle; and Weather. Active and Passive techniques along with the applicable scientific measurements are summarized in Figure 6 and Figure 7, respectively.



Combined Active/Passive
- Salinity, soil moisture, snow
- SoOp/GPS

Repeat Pass Interferometry
- Surface deformation
- Seismology and hazards
- Damage assessment

Doppler and Profiling
- Cloud, Ice, Precipitation

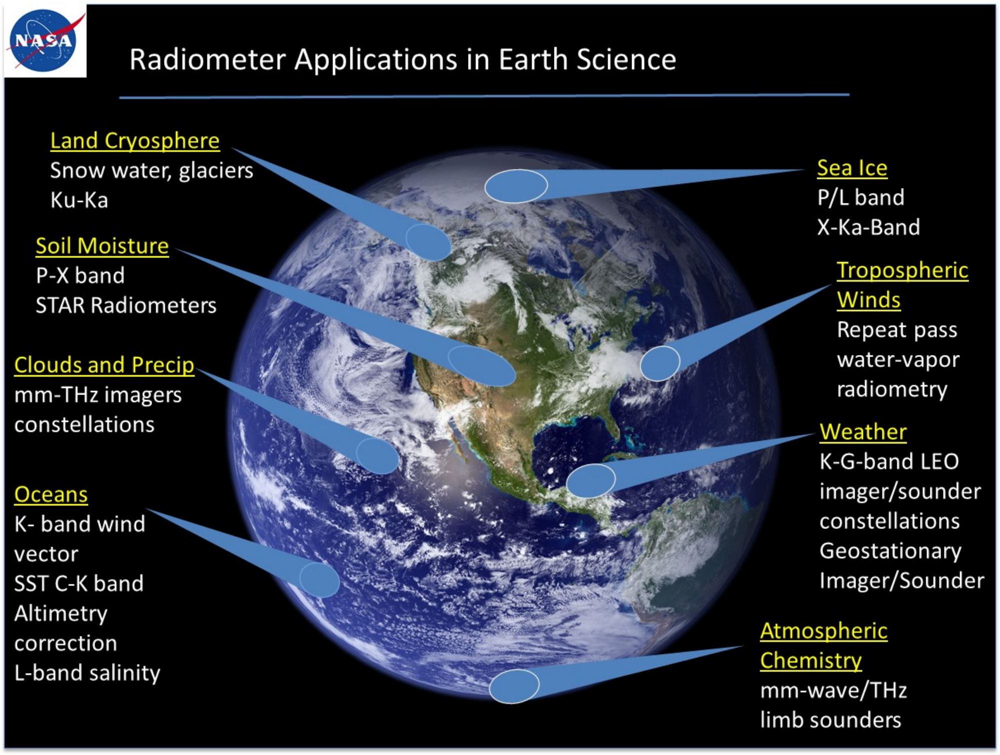
Altimeters/single pass interferometry/GPS
- Sea surface height
- Topography
- Surface water
- Ice thickness

Sounders
- Interior structures such as Ice thickness & aquifer depth

Scatterometers
- Ocean Winds
- Ocean Currents

Synthetic Aperture Radar (SAR)
- Sea ice
- Ecology
- Hydrology
- Rapid response (e.g. oil spills, forest fires)
- Land Classification
- Oceanography

Figure 6. Radar Remote Sensing Techniques and Applications.



Radiometer Applications in Earth Science

Land Cryosphere
Snow water, glaciers
Ku-Ka

Soil Moisture
P-X band
STAR Radiometers

Clouds and Precip
mm-THz imagers
constellations

Oceans
K- band wind vector
SST C-K band
Altimetry correction
L-band salinity

Sea Ice
P/L band
X-Ka-Band

Tropospheric Winds
Repeat pass water-vapor radiometry

Weather
K-G-band LEO imager/sounder constellations
Geostationary Imager/Sounder

Atmospheric Chemistry
mm-wave/THz limb sounders

Figure 7. Radiometer Applications in Earth Science

Technology requirements are organized in three focused areas: radar electronics and antennas; radiometer; and information and data processing. Chapter 2 of this report summarizes the scientific basis for microwave technology development. Chapter 3 outlines the technology requirements in the three technology subgroup areas mentioned above. Chapter 4 discusses emerging technology trends since publication of the last ESTO microwave technology investment strategy [*ESTO*, 2004]. Finally, Chapter 5 lays out the plan forward regarding current investment strategy needs.

2. Scientific Basis for Technology Development

The NASA Earth sciences program is structured around 6 principal focus areas:

- Atmospheric Composition
- Carbon and Ecosystems
- Climate Variability and Change
- Earth Surface and Interior Structure
- Water and Energy Cycle
- Weather

Within these areas active and passive microwave (radar and radiometer) observations provide direct measurements of atmospheric, oceanographic, terrestrial and cryospheric parameters that are directly relevant to meeting the goals of the six focus areas [*ESTO,* 2004; *NRC,* 2007]. Measurements applicable to each focus area are addressed in the following sub-sections.

A particular advantage of microwave over Electro-Optics techniques is the relative insensitivity of microwave observations to cloud cover and weather conditions, especially at the lower microwave frequencies. Microwave remote sensing is also particularly responsive to water in all phases and represents and effective means for measuring water and its spatiotemporal distribution over the planet.

2.1. Atmospheric Composition

The Atmospheric Composition science focus area addresses the gaseous molecular species and aerosols that comprise the Earth's atmosphere. A variety of molecular species can be detected and quantified through microwave remote sensing, limb measurements are usually employed to measure elements in small quantities. Microwave limb sounding instruments observe the atmosphere using near horizontal incidence and vertically scan the limb from near the surface (h~5 km), to the mesosphere (h~90 km). This approach enables good vertical resolution of atmospheric constituents dependent on antenna size (antenna main beam width), molecular quantity and absorption line strength. The observing geometry allows for a long path length allowing detection of trace species in general. For constituents in the upper troposphere and stratosphere, ground contamination, normally an issue for resolving weak interactions in the atmosphere, is not a problem for the limb sounding observing geometry.

Although microwave remote sensing is capable of measuring many constituents, water and chlorine and its compounds in the upper troposphere have been of the greatest interest. While it is accepted that high levels of atmospheric chlorine continue to destroy stratospheric ozone [*Manney et al.,* 2011], another important aspect of the upper troposphere and stratospheric measurements is to provide insight on global transport of greenhouse gasses (GHG) [*Jiang et al.,* 2012]. Improving the representation of these and other constituent quantities within global circulation models would lead to greatly improved understanding of upper troposphere and stratospheric dynamics.

Space based microwave measurements of atmospheric composition include the Microwave Limb Sounder (MLS) on the Upper Atmosphere Research Satellite (UARS) launched in September 1991 [*Barath et al.,* 1993]. The MLS was a microwave radiometer that provided global measurements of chlorine monoxide, hydrogen peroxide, water vapor, and ozone. The MLS consisted of three-channels utilizing a heterodyne receiving system in a limb sounding configuration with the following measurement center frequencies: 63 GHz (1 band), 183 GHz (2 bands) and 205 GHz. The last data were obtained on 25 August 2001.

The Earth Observing System (EOS) Microwave Limb Sounder on EOS-Aura followed the UARS MLS and was launched in July 2004. The EOS MLS measures thermal emission from Earth's 'limb' (the edge of the atmosphere) viewing forward along the Aura spacecraft flight direction, scanning its view from the ground to ~90 km every ~25 seconds in the submillimeter and millimeter wavelength spectral bands listed in Table 2.1

Table 2.1. Spectral bands of the EOS MLS Instrument and scientific measurements

Band Center	Measurement Objective
118 GHz	Primarily for temperature and pressure
190 GHz	Primarily for H_2O, HNO_3, and continuity with UARS MLS measurements
240 GHz	Primarily for O3 and CO
640 GHz	Primarily for N_2O, HCl, ClO, HOCl, BrO, HO_2, and SO_2
2.5 THz	Primarily for OH

The MLS makes measurements of atmospheric composition, temperature, humidity and cloud ice that are needed to (1) track stability of the stratospheric ozone layer, (2) help improve predictions of climate change and variability, and (3) help improve understanding of global air quality.

A second area where microwave instruments can contribute to the priorities of Atmospheric Composition science focus is that of convection and circulation. These have been identified as two of the outstanding questions in atmospheric composition [*NASA,* 2014a] because they lay at the core of how trace constituents interact with cloud and precipitation processes and how they are transformed and transported (vertically and horizontally) by weather systems. In this sense, besides the indirect role of microwave (active and passive) instruments addressing specifically weather, three types of microwave based measurements provide a unique view of motion inside clouds or precipitation by using the hydrometeors as tracers: Doppler radar, rapid revisit (i.e., minutes) profiling radar, and rapid revisit microwave imagery. This is primarily because wind Lidar or passive optical or IR feature tracking (of water vapor or cloud edges) do not have the capability to provide estimates of motion inside a storm or cloud system.

2.2. 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. A number of microwave remote sensing measurements have key roles in making the observations needed for development, fine-tuning, and validation of carbon/climate models. Radar measurements at multiple frequencies can provide reliable, repeatable, above-ground biomass estimates at local to global scales. 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 microwave measurements (f < ~1GHz). Both passive and active microwave measurements are used to improve the accuracy of soil moisture measurements, and maybe the only feasible means for estimating soil moisture on a global scale. Passive microwave radiometers operating at L-band are also used to determine ocean salinity, another variable required in carbon cycle and ocean circulation models.

The Soil Moisture Active Passive (SMAP) instrument launched on January 31, 2015 is a combined Radar and Passive Radiometer sensor with a 6m diameter main reflector antenna operating at L-band (1.26- and 1.4-GHz respectively) [*NASA,* 2015a]. The SMAP radar and radiometer were designed to provide volumetric estimates of soil moisture to a sufficient accuracy to improve climate and weather models. The sensor utilizes the accuracy of passive measurements to measure the average soil moisture within antenna main beam footprint and then applies SAR processing techniques to estimate variability within the antenna footprint [*Entehkabi et al.,* 2010]. The combined use of passive and active radar was conceived to effectively produce a better Soil Moisture product than either instrument by itself. Combined sensor measurements, including active, passive and signal of opportunities, are a strong theme in future measurement scenarios.

The Airborne Microwave Observatory for Subcanopy and Subsurface (AirMOSS), is a UHF (~400 MHz) Synthetic Aperture Radar (SAR) flown on an uninhabited aeronautical vehicle (UAV) to measure Root-Zone Soil Moisture (RZSM) in some cases to 1.2 m below the surface [*Chapin et al., 2012*]. Extensive ground and in-situ measurements are used to validate the soil measurements and carbon flux model estimates which are particularly important in forested regions where they are linked to evaporation and transpiration from the root zone [*Moghaddam et al.,* 2007]. AirMOSS surveys are anticipated to provide measurements at 100m spatial resolution and at sub-weekly, seasonal, and annual time scales.

The next generation low frequency radar includes NASA-ISRO Synthetic Aperture Radar (NISAR), a combined L- and S-band radar that is being built in a collaboration between NASA and ISRO (Indian Space Research Organisation) and is anticipated to launch in 2020 [*NASA,* 2015]. With its low radio frequencies of operation and large (12m) aperture, NISAR is expected to retrieve surface Soil Moisture and help determine the contribution of Earth's biomass to the global carbon budget as well as characterize ecosystem disturbance impacts.

2.3. 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. Important remote sensing measurements made by active and passive microwave instruments include global sea surface salinity, sea ice characterization, ocean circulation, ocean altimetry and clouds among others. These measurements are accomplished using passive microwave imagers and microwave radar scatterometers for surface currents and winds. In some cases where finer resolution is required, for example, to characterize ice structure and its extent SAR may be used. Measurements from microwave (in contrast to electro-optic measurements) are required when necessary to observe thorough persistent cloudiness such as commonly experienced in arctic regions. And finally, a key consideration for use of remotely sensed data over decadal timeframes is the need for precision inter-calibration between sensors, many of which exhibit lifetimes < 5 years on orbit.

Changes in sea ice, snow extent, perma-frost and surface melting, cloud and precipitation patterns and occurrence of severe weather events (including droughts and floods, tropical storms and tornadoes and others) are all important observations that can elucidate climate trends as well as interrelate them to other indicators in the arctic and Antarctic such as sea ice extent. Global ocean circulation is also an important aspect of understanding climate change and is aided by global observations of Sea Surface Salinity (SSS) obtained using low frequency microwave radiometric measurements coupled with radar scatterometry [*Le Vine et al.,* 2010].

Ocean surface wind speed and direction measurements using microwave scatterometry are another important resource for global climate studies. The QuickScat, a K_U-band radar scatterometer was launched in 1999 and provided a continuous data record until 2009 [*NASA,* 2015b]. For climate-quality ocean winds it is noted that the eXtended Ocean Vector Wind Measurement (XOVWM), a tiered mission included in the 2007 decadal survey [NRC, 2007], is not yet planned. Connections between surface currents and retrieved winds have also been observed [*Plagge et al.,* 2012].

Cloud vertical structure and occurrence of patterns with radically different radiative properties (feedback of various cloud types range from negative to positive) has been observed by the NASA/CSA CloudSat Cloud Profiling Radar as part of the A-Train since 2006, and has provided key elements to the ice sheet mass balance assessments over Antarctica and other parts of the globe. CloudSat is well beyond its mission design life and its natural continuation within NASA was captured by the ACE mission concept in Tier 2 of the 2007 decadal survey, which is still in pre-formulation phase.

In general there is a broad suite of observations required to meet the goals associated with climate variability and change that are associated with microwave techniques. These include systematic measurements of certain greenhouse gases, atmospheric temperature and moisture, sea surface topography, sea surface salinity, sea ice characterization, ocean wind vector, clouds, aerosols, precipitation, surface temperatures, ice cover, snow cover, and both surface and deep (root zone) soil moisture.

2.4. Earth Surface and Interior

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. 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 microwave interferometric SAR and the ability to detect surface deformations on a centimeter level. 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 surface deformation measurements are used to help determine the likelihood of earthquakes. Longer-term deformation measurements are used 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.

One of the first high resolution elevation data sets originated from the Shuttle Radar Topographic Mission (SRTM) data flight in 2000. SRTM was an interferometric SAR using two antennas with a boom separating them. The SRTM data flight occurred Feb. 11-22, 2000 on STS-99 (Endeavour). The highest resolution data from SRTM were released in 2015 [*NASA,* 2015c]. The Japan Aerospace eXploration Agency (JAXA) launched the Advance Land Observing System (ALOS), Jan 24, 2006, carrying the P- and L-band Synthetic Aperture Radar (PALSAR). The PALSAR instrument was designed with range resolution to up to 7m [*JAXA,* 2006] but with limited swath 40 – 70 km at the finest range resolution. More recently a combination of TerraSAR-X and TANDEM-X built by the German Aerospace Center, DLR, and launched in 2007 and 2010 respectively [*DLR,* 2010] allow generation of a three-dimensional elevation model of the entire earth surface. Lastly, as described above, NISAR [*NASA,* 2015] is expected to make significant contributions in the science focus area of Earth surface characterization.

2.5. 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 key to observing and measuring water in the Earth's atmosphere or on land is through the use of microwave remote sensing. 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.

In general, 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.

Some recent examples of water and energy cycle microwave missions include Global Precipitation Measurement (GPM), a NASA-JAXA collaboration [*NASA,* 2014]. The GPM core observatory was launched on February 27, 2014 and includes a Dual-frequency Precipitation Radar (DPR) [*Iguchi et al.,* 2003] and multi-frequency dual-polarized microwave radiometer [*Draper et al.,* 2014]. Other significant contributions from microwave sensors include SMAP

[*NASA,* 2015], and ocean surface topology from space utilizing microwave radar altimetry and radiometry [*NASA 2016*].

New capabilities information includes Surface Water Ocean Topography (SWOT) [*NASA,* 2015c], and extension of ocean altimetry measurements to be acquired over a swath to enable global altimetry data. Like SRTM, SWOT will be an interferometric SAR with two antennas separated by booms. Inter-calibration activities associated with calibration of the GPM constellation [Wilheit et al., 2015] are providing good insights into potential issues with inter-calibration of even larger constellations [*Blackwell et al.,* 2015] that may be necessary to improve spatiotemporal measurements of cloud properties. And finally, measurement of RZSM is enabled using airborne VHF/UHF SAR.

2.6. Weather

Weather can be called the state of the atmosphere and its variability on time scales of minutes to months. Several measurements drive the state of the atmosphere as shown by numerical weather prediction models, but among the most influential model inputs are the vertical temperature and moisture profiles measured by microwave and thermal infrared sounders placed in a polar-orbit such as the Advanced Technology Microwave Sounder (ATMS) [*NOAA,* 2016] and the Cross-track Infrared sounder (CrIS) [*NOAA,* 2016a]. These instruments are part of the operational fleet of satellites fielded by NOAA Environmental Satellite Data Information Service (NESIDS). Ultraviolet through infrared imagers placed into geostationary orbit are also very important for developing accurate weather forecasts due to their ability to image the entire Earth's disk in a fraction of the time required from low Earth orbit. To date, no microwave weather sensors have been place in geosynchronous orbit due in part to significant limitation on horizontal spatial resolution as a result of the diffraction limited apertures. However, technology developments are taking place in an effort to overcome this limitation while remaining economically feasible to develop the sensor. Another key advantage is that microwave instruments are essentially 'all-weather', that is not limited by clouds and light precipitation and therefore form an effective complement to thermal infrared imagers that may exhibit better vertical resolution but can't make measurements in cloud cover.

A complete characterization includes not only the state of the atmosphere, but also the temperature and moisture characteristics of the atmosphere-Earth surface interface, because these parameters are also drivers of the weather. Therefore ocean surface winds and volumetric soil moisture are also important microwave measurements supporting weather forecasting. Recently there has been increased attention on improving measurements and understanding of boundary layer dynamics due both because of the importance in coupling atmosphere and surface states, but also due to the relatively poor characterization of these regions close to the surface due to the challenges of the remote sensing problem where surface and atmosphere meet.

In the most recent NASA Weather focus area workshop [*NASA,* 2015] it was identified that one key role of observations from space is that of establishing global 'reference' datasets to strengthen the definition and the application of statistical methods and metrics to improve weather prediction models. One of the most important areas where new observations are needed relates to the quantitative improvement of our understanding of the microphysical and dynamical processes that drive the genesis and evolution of severe weather events, including convection, intense precipitation, hailstorms and others. Therefore, in addition to the established need to continue and improve the observations required to initialize and guide numerical weather prediction models through data assimilation, there is a well-documented need to improve the representation of the physical processes within the same models (be they parametrized or explicitly resolved). Microwave observations have been clearly identified as the primary means to obtain such observations. In this context, the role of Doppler radar measurements and of 4-dimensional observations of storms resolved at the spatial and temporal scales that are relevant to convective evolution, have been presented in several entries to the Decadal Survey 2017 and in workshop reports.

Here it is noted that repeated observations of storms at the scales of minutes to tens of minutes from LEO has been enabled by the advent of CubeSats and SmallSats, and technological advances in digital and microwave RF. It has resulted in the selection by the Earth Venture program and ESTO's InVEST program of missions such as TEMPEST-D, RainCube and TROPICS. This new paradigm addresses the need of the science community to evolve from isolated snapshots to temporally resolved sequences of measurements and it fills a gap between the capabilities of GEO platforms and large single LEO platforms.

In summary, key to improving weather forecasts are more accurate and timely atmospheric temperature and moisture profiles, improved cloud characterization and improved understanding/modeling of boundary layer dynamics. Microwave remote sensing is essential to observe and characterize water in all phases within the atmosphere and Earth surface. Within the past ~10 years there has been a significant investment in microwave weather sensors as shown by the entries in Table 2.2.

Table 2.2. Space-based microwave sensors supporting operational weather missions in the US

Sensor Series	Launch Span	Key Parameters	# in series
MSU+SSU (TOVS)	1978 - 94	AVTP	10
SSM/I (DMSP)	1987 – 99	SSW, Clouds, Surface Winds, Imagery	7
SSM/T1,2 (DMSP	1987 – 99	AVTP, AVMP	4, 4
AMSU-A,B (TOVS)	1998 – 05	AVTP, AVMP	4, 4
AMSR, AMSR-E	2002	Surface Winds, Clouds Imagery	2
SSMIS (DMSP)	2003 - 14	SSW, AVTP, AVMP, Clouds	5(4)
ATMS (JPSS)	2011 -	AVTP, AVMP	1

*WindSat, launched January 6, 2003 as a technology demonstration mission, is also used to supporting operational forecasting

3. Technology Requirements

3.1. Radar Electronics and Antennas Technologies

Radar electronics and antenna technology has evolved along with radar based earth science measurement concepts since the 2004 ESTO Microwave Technologies Report [*ESTO,* 2004] and the 2007 Earth Sciences Decadal Report [*NRC,* 2007]. In this section, the technology status and development needs for this subject area are discussed. This is followed by conclusions and recommendations.

Technology needs for radar systems in space include efficient transmit amplifiers (both HPAs and SSAs for arrays), LNAs with low noise figure and power consumption, tightly spaced multi-band feeds, large lightweight antenna structures, and digital technology including beamforming, signal generation and receiver technology. Transmit / receive isolation and phase stability are important performance parameters. Space qualification for components that currently operate in airborne systems is a key challenge. Several earth science measurements are enhanced by simultaneous collection of active radar and passive radiometer data from the same platform. Technology topics related to simultaneous collection are discussed in Section 3.2.

In the 2007 Decadal Survey, six missions were described that included radar instruments. These missions along with the frequency bands they use are:

- Extended Ocean Vector Winds Mission (XOVWM) – C, Ku-bands
- Surface Water and Ocean Topography (SWOT) – Ka-band (formerly Ku)
- Aerosol Cloud Ecosystem (ACE) – W, Ka-bands
- Snow and Cold Land Processes (SCLP) – X, Ku-bands
- NASA ISRO SAR (NISAR) (formerly DESDynI Radar) – L-band
- Soil Moisture Active Passive (SMAP) – L-band

Of the six missions listed in 2007, only SMAP has flown in space. NISAR and SWOT (in Phase B and Phase C respectively as of this report) are planned to be launched in the 2020 timeframe. It is noteworthy that all six missions utilize or envision utilizing reflector antennas, most with array feeds. The most significant variation is SWOT, which uses dual reflect-array antennas.

Over the course of the past decade, many other radar-based Earth science measurement concepts have been developed. These include:

- GEO weather radar – prior technology development at Ka band
- Cloud + precipitation processes – Ku, Ka, W-bands, Doppler, scanning
- Deep (root zone) soil moisture – dual L-, P-band
- SoOp systems – ocean wind vector, RFI detection
- Humidity, temperature and pressure active profilers – V- and G-bands
- GEO based systems – earthquake, hazard warning
- Surface winds and currents – Doppler scatterometer, Along Track Interferometer
- Compact cloud and precipitation radars for cubesats and smallsats
- Subsurface (ice, aquifers, etc.) – UHF to P-band "radar sounders"
- Biomass structure – 3D SAR & InSAR architectures, tomography.

Technology for the radar measurements for the 2007 missions has continued to develop. An assessment of the current status of this technology is summarized in Table 3.1. Likewise, technology for other radar measurements has continued to develop and the current status in these topics is summarized in Table 3.2

Table 3.1. Radar technology assessment for the 2007 Tiered Decadal Survey measurements

Capability Gap	Measurement	TRL	"Greatest Challenge" TRL
Ka-band phased array	Water surface topography (SWOT)	6	High phase stability Ka-band electronics
Ka, W-band scanning	Aerosol, cloud (ACE)	4	Closely spaced multi-band active feed array
X-, Ku-band feed array	Snow Cover (SCLP)	5	Multi-band feed
None	Soil Moisture (SMAP)	9	N/A
None	Surface deformation, ice (NISAR, formerly DESDynI radar)	6	System integration & test
High efficiency solid state amplifiers	Ocean wind vector (XOVWM)	5	Dual-band single instrument

3.1.1. General Observations from the 2004 ESTO Microwave Technologies Report

In the 2004 ESTO Microwave Technologies Report, radar electronics & antennas technology areas were:

- Antenna structure and electronics
    - High efficiency T/R modules
    - Light weight phased arrays
    - Multiple frequency antennas / multiple feeds
    - Phased array feeds for reflector antennas
    - High efficiency reflectarrays
    - Large deployable rotating reflectors
    - Adaptive waveform sensing and correction technology
    - RF power, control, signal distribution
- Radar Electronics
    - High power amplifiers
    - Waveform generators
    - A/D converters

Table 3.2. Technology needs for future measurements

Capability Gap	Measurement	TRL	“Greatest Challenge” TRL
Large rigid antennas	Cloud characterization	5-9	Mass, deployment at highest frequency bands
Very large non-rigid antenna surfaces	Weather radar, hazard monitoring	2-4	Adaptive wavefront sensing and compensation
G-band technology	Humidity profiles	2-4	Transmit power generation
SoOp technology	Ocean wind vector, soil moisture, RFI detection for radiometers	3	Wideband tunable receiver
CubeSat / SmallSat radar technology (Ku-, Ka-, W Band)	Precipitation, Sea, Ice, and snow topography	2-5	Antenna size, thermal. Power and data rate
Fully integrated single-chip MMIC T/R modules	All	3-5	Efficiency, T/R isolation
Improved High Power Amplifiers for high frequencies (Ka-,W-, G-bands)	Cloud profiles, rain droplet size, humidity profiles, atmospheric gases	2-6	Power supply reduced mass and size; improved efficiency; improved maximum RF power
Space-qualified, high bandwidth & nbits, integrated digital subsystems	All	4-9	Reduce risk and perception of risk going from non-space to space applications.
Multi-frequency antenna and feed arrays with multi-channel	P/L-Band soil hydrology and ocean, X through W-Band for snow, altimetry, and cloud and precipitation applications.	3-6	Ability to efficiently accommodate multiple channels for variable penetration through soil, biomass, and cloud volumes; as well as combined Active/Passive capability.

An evaluation of the present status of these technology areas in 2016 has found that RF power, control, and signal distribution for phased arrays and large deployable rotating reflectors can be dropped as technologies requiring further development to enable future radar measurements. New measurement concepts and technology development have led to new topics being added for 2016. These are G-band technology, signal-of-opportunity (SoOp) technology, CubeSat and SmallSat technology and digital signal generation, beamforming and receiver electronics. These changes are summarized in Table 3.3.

Smaller, lighter T/R modules can be advantageous for multi-band array feeds, where it is best that the feed array elements at the different frequency bands be as close to the reflector focus as possible. An example of this is multiple line feeds for parabolic cylinder reflectors, which enables 1D electronic scanning for cloud and precipitation measurements at Ku-, Ka- and W-bands. In all cases, T/R module transmit efficiency, noise figure, and T/R isolation are important parameters strongly impacting system cost and performance.

Table 3.3. Technology areas for 2016

Technical Area	**2004 Report**	**2016 Report**	**Rationale**
T/R modules	X	X	Key component for virtually all measurements
MMIC Devices	X	X	Mass and size reduction
High Power Amplifiers	X	X	Enabling for high frequency measurements
RF power, control, signal distribution	X	Drop	Mature
Waveform generators	X	X	Space qualify advanced waveform generators
Rotating Reflectors	X	Drop	Mature
ADCs for DBF	X	X	Reduce mass & power
Membrane antennas	X	X	Potential for array mass reduction
Adaptive waveform sensing	X	X	Potential for array mass reduction
SoOp		X	New measurement area
CubeSats / SmallSats		X	New measurement area
G-band technology		X	New measurement area
Digital signal generation, beamforming & receiver		X	Mass & power reduction

3.1.2. Specific Observations on Radar Electronics & Antennas

There have been several radar missions flown in space, both by NASA and by foreign civil agencies (SMAP, RadarSat II, TerraSAR-X), that demonstrate that single-frequency L-, C- and X-band space technology is more mature than lower or higher frequency bands. All of the radar missions in the 2007 Decadal Survey are relatively expensive, estimated to cost $500 million or more. This is a major reason why only one has flown to date. For this reason, future development should focus on technologies that will reduce cost for future systems.

Many technology needs are related to phased array antennas or array feeds for reflectors. T/R modules under development can be separated into low power versions intended for phased arrays, and high power versions intended for array feeds for reflectors. Much development at all frequency bands is focused on single-chip MMIC-based T/R modules, which are smaller, lighter and potentially less expensive to manufacture in large number. The advantages for single-chip MMICS are most important for phased array antennas where very large numbers of T/R modules are required.

Array-fed reflectors do not necessarily benefit from the smaller, lighter T/R modules enabled by single-chip MMICs. The number of modules is smaller and heat dissipation can be better for larger modules. Smaller, lighter modules can be advantageous for multi-band array feeds, where it is best that the feed array elements at the different frequency bands be as close to the reflector focus as possible. An example of this is multiple line feeds for parabolic cylinder reflectors, which enables 1D electronic scanning for cloud and precipitation measurements at Ku-, Ka- and W-bands. In all cases, T/R module transmit efficiency, noise figure, and T/R isolation are important parameters strongly impacting system cost and performance.

The use of large phased array antennas in space has been limited by the high structure mass required to maintain surface tolerance of 1/20 of a wavelength over the full array. Lightweight, small T/R modules do not solve this problem for rigid structures. For this reason, use of phased arrays can be enabled by development of lightweight structures such as membranes and shape memory polymers. This in turn will necessitate development of adaptive wavefront sensing to compensate for non-rigid structures. For array structures of this type, thermal control and power distribution, as well as small lightweight T/R modules to enable roll or fold up are key technologies. This technology also applies to reflectors at W- and G-band, where it is difficult to maintain the very tight surface tolerance required. For all large phased array antennas, it is important to develop deployment mechanisms that are lightweight and reliable.

The on-board processing required to compensate for non-rigid structures can be computationally intensive for high frequencies. At the opposite end of the spectrum, it is difficult to envision array-fed reflectors or single feed reflectors with high power amplifiers at P-band. This is due to the size of the array feed, and size and mass of high power amplifiers at this frequency. For this reason, phased arrays with digital beam forming are key technologies for measurements requiring P-band. Digital beam forming is a candidate technology at P-band because of the size of analog beamforming components at this frequency and the relatively small number of elements which reduces the computational load.

Dual/multi-band technology enables many radar measurements. This was accomplished for the Global Precipitation Measurement (GPM) Mission by essentially placing two separate phased array radars side by side. In general, this is very expensive. Future use of common antennas and electronics may reduce cost.

Historically, it has been difficult for NASA to leverage DoD radar technology due to security classification issues. There may be some potential to leverage DARPA radar technology, which is somewhat more open. An example is the Innovative Space-based radar Antenna Technology (ISAT) Program, which had the goal of developing a 300 meter long electronically steerable antenna for MEO based X-band Ground Moving Target Indication (GMTI) radar. Most work on this project, which was funded from 2002 through 2007, was focused on development of large deployable structures [*Guerci,* 2003]. Another project with potential synergy is the Arrays at Commercial Timescale (ACT) Program [*Olsson,* 2016].

3.1.3. Technology Challenges

The challenge looking forward for radar-based Earth science measurements is to develop technologies that either enable improvements in the quality of measurements, enable new measurements that can't be done with present technology, or that reduce the cost of measurements that are very expensive with present technology.

It is essential to perform system trades and update mission concepts early in the development cycle in order to inform radar technology development decisions. It is difficult to determine quantitative technology goals for future measurements without an associated mission concept and design point. For example, variation in altitude and antenna size will impact goals for amplifier output power and efficiency. There also is uncertainty in many parameters for state-of-the-art technology due to various research group and commercial developments being closely held for competitive advantage. For this reason, the following assessments of state-of-the-art and performance goals for radar technologies are not precise in nature. The information can be used as a guide to determine whether derived technology needs for a specific system concept are within the state-of-the-art or require additional development.

T/R performance for phased arrays and array feeds is central to radar technology. Important qualities include transmit power and efficiency, LNAs with low noise figure and power consumption, small size to enable tight spacing, T/R isolation and phase stability. A summary of the state-of-the-art for this technology is shown in

Table 3.4.

Table 3.4. Example array Transmit/Receive technology needs.

Measurement	Technology	State-of-the-Art	Goals	Development Needs
Ice, surface deformation, biomass	Smaller, more efficient SSAs, MMIC modules	100W @ L-band	200W @ L-band η = 40%, 2dB NF, BW=80 MHz	Thermal capacity
Snow cover, ocean topography	Ku-, Ka-band T/R modules, improved phase stability	10W @ Ka-band η = 20%	20W @ Ka-band η = 40%	GaN device development
Precipitation, cloud characterization, Ku-, Ka-, W-, G-bands	Multi-band array feeds	1W @ W-band	1W @ G-band η = 40% W-band	GaN device development

Among the greatest challenges for new measurements is producing sufficient transmit power and amplifier efficiency at Ka-band frequencies and above. Miniaturization of these devices is also a great challenge. For phased arrays and array feeds, improving Solid State Power Amplifier (SSPA) efficiency will both reduce spacecraft prime power and mitigate thermal control problems. For systems that utilize individual high power amplifiers such as Extended Interaction Klystron Amplifiers (EIKAs), it is important to reduce the mass of high voltage power supplies and improve efficiency. This is especially important for W- and G-band measurements. A selection of needs identified is provided in Table 3.5.

Table 3.5. Example high power amplifier technology needs.

Measurement	Technology	State-of-the-Art	Goals	Development Needs
Precipitation, snow cover, ocean topography	Space qual TWT	200W @ Ku-band	500W @ Ku-band η =40%	Small reliable high voltage power supply
Cloud characterization	EIKA	2 kW	10 kW @ W-band G-band HPA	Precision machining

Dual/multi-band feeds/antennas that enable the same area coverage at different bands is another challenge with high potential impact for several measurements. Common antenna electronics covering dual bands can simplify system designs. Examples of this are the Harris current sheet array feed and the tightly spaced line-feeds for parabolic cylinder reflectors under development for the ACE mission. A summary of needs, in the area of antennas and feeds to support identified earth science measurements is provided in Table 3.6.

Table 3.6. Example antenna related technology development needs.

Measurement	Technology	SoA	Goals	Development Needs
Biomass, Soil Moisture, Ice, Snow	large active P-band arrays	Single band feeds	2-D array, multifrequency L/P band.	Digital beam forming
Surface deformation and topography weather	Membrane high-efficiency T/R modules, thermal management for membranes	10m class rigid	30m class non-rigid T/R modules for roll / fold up	What approach needs to be supported with funding
Cloud profiling	Lightweight, deployable reflector for W- and G-band	D=1.85m rigid	D=3m deployable F_{max}=200 GHz	Surface tolerance for deployable

It is important to understand radar technologies that enable new measurements along with measurement limitations for emerging radar technologies. New measurements that utilize multiple look angles and tomographic techniques should have their requirements flowed down to electronics and antenna technology needs. Emerging radar technologies include SoOp based bistatics, G-band radar systems, and CubeSat and SmallSat based systems. A challenge with great potential benefit is the application of technology used in CubeSats, such as digital signal generation and receiver electronics, to large satellite concepts in order to realize SWaP-C savings, while retaining most of the functionality of the larger system. Technology needs identified for SoOp and small satellite based measurements are summarized in Table 3.7 and Table 3.8, respectively.

Table 3.7. Example signals-of-opportunity related receiver technology needs.

Measurement	Technology	State-of-the-Art	Goals	Development Needs
Root Zone Soil Moisture	SoOp bistatics	GNSS signals	Narrowband VHF, UHF	Space qual of narrowband low freq measurements
Snow	SoOp bistatics	GNSS signals	Narrowband VHF, UHF	Space qual of narrowband low freq measurements
Ocean Surface Winds	Integrated front end and back-end processors, direction algorithms	Multi-frequency/mode front-ends	GNSS-R signals	Multi-mode front-ends

Table 3.8. Example small satellite radar technology needs.

Measurement	Technology	State-of-the-Art	Goals	Development Needs
RZSM; Biomass, Cloud Characterization, Precipitation	Lightweight phased arrays	X- and C-band are more mature	VHF/P-band; W- and G-band	Application of material science and engineering to extend the size of arrays
RZSM; Biomass; Cloud characterization	Improved small satellite platforms	CubeSat limited lifetimes; SWaP accommodation	Reliable 5-year lifetimes, increased power and data rate	SE; QA, system quality standard
RZSM; Ocean Winds, Precipitation; Clouds	Multi-mode sensor (Active/Passive/SoOp) integration;	Separate sensors and data processing	Integrated front-ends; isolation; sensor block-level sharing	Techniques and applications of RF isolation and miniaturization
Precipitation, Altimetry	Larger reflectors for 2U stowed	0.7m	1.5m	Reduce stowed volume

Many planned system concepts are high SWaP and very expensive. Most planned technology development will result in small, incremental improvements and is unlikely to significantly reduce cost. A possible exception is CubeSat- and SmallSat- inspired new architectures that have the potential to significantly reduce mass and number of parts, subsystems and interfaces. In this area, at the mission design level, novel architectures can be envisioned where multiple small radars are designed to operate in a coordinated or even synchronized way to achieve similar performance as significantly larger single-platform counterparts. In this context it is essential that the performance of the instrument is defined in the context of a specific platform performance (in terms of navigation control and knowledge, data rates etc.) and accounts for the demonstrated progress in autonomous formation flying (e.g., *Bonin et al.,* 2015). Likewise, insertion of CubeSat and SmallSat technology into larger satellite concepts to produce smaller satellites has significant potential and risk. An example of this is increased use of integrated digital subsystems with high bandwidth and larger number-of-bits. Finally, insertion of any new technology requires understanding the benefit to the associated measurement. Technology needs, across all frequency bands, is summarized by Figure 8.

3.1.4. Conclusions and Recommendations

The following discussion contains conclusions and recommendations related to the major technology areas and needs for radar in earth science. No attempt has been made to prioritize the technology areas within this report. However, the previous discussion has identified many cross-cutting technology investment areas that are summarized in the text below and in the Capability Breakdown Structure (CBS) Tables in Appendix D. Lower TRL items will be brought forward for additional discussion within the emerging technologies section in Chapter 4.

Up-front system design trades are essential for determining technology needs. It is important to develop a clear understanding of the benefit of specific technology needs and focus on technology development that will lead to significant earth science measurement enhancement or cost reduction. Where technology development will enhance system performance, it is important to quantify the Earth science measurement improvement.

Dual/multi-band technology enables several measurement scenarios, particularly for precipitation and cloud characterization and the combined retrieval of salinity, RZSM. This area should receive greater focus, including integrated dual/multi-band technology which potentially can reduce cost. Many technology needs are related to array feeds for reflectors. This should also be a future focus area. It also is important to develop higher power, space qualified HPAs along with T/R module transmit amplifiers. This is most important at higher frequencies (Ka-, W-, G-bands). Along with investment in these technologies, it is important to perform the system level design trades that will inform the choice between HPAs and array feeds.

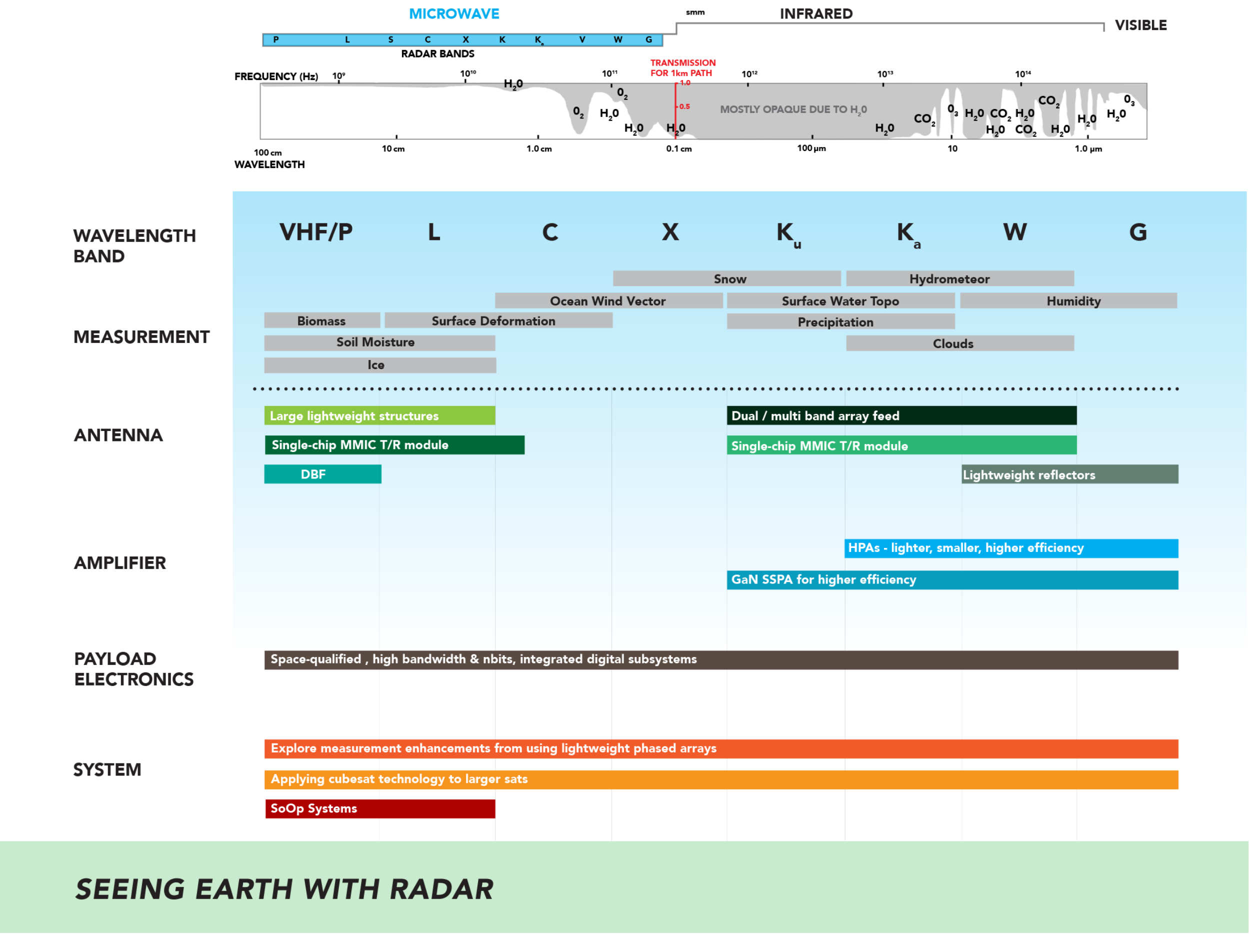


Figure 8. Summary of key technologies across frequency bands.

There are several additional technology areas that offer potential for cost reduction or measurement enhancement in future systems. MMIC based T/R modules have most value when there is a need for smaller and lighter, or, a large quantity of modules. Development of digital technology has the potential to enable mass and power reduction.

Several measurement concepts have evolved over the past decade. For example, SWOT changed its frequency from Ku- to Ka-band. Future cloud characterization is envisioned to utilize both Ka- and W-bands, whereas CloudSat utilized only W-band. As a result, Ka-band now has the largest number of measurements and therefore should perhaps receive more focus.

Signal-of-opportunity (SoOp) based bistatic radar and CubeSats both present new opportunities for Earth science measurements. Specifically, the lower cost of these systems should enable large constellations to be deployed. This will create the opportunity for diurnal and temporal sampling that is not possible with the large satellite missions. Measurement concepts for SoOp and CubeSats should be developed more completely to better understand their value, considering system architecture, mission design, and earth science measurement parameters. Examples of

SoOp- and CubeSat-based measurements include using VHF and GNSS signals for root zone soil moisture and snow water equivalent measurement and RainCube for precipitation measurement.

3.2. Radiometer Technology

3.2.1. Technology for Earth science measurements

This assessment of technology required for Earth science measurements using radiometry begins with a review of the unmet technology needs of measurements identified as part of the 2007 decadal survey tiered missions [*NRC,* 2007]. The associated missions listed in the survey include: Soil Moisture Active / Passive (SMAP), Surface Water / Ocean Topology (SWOT), Precipitation and All-weather Temperature and Humidity (PATH), Snow and Cold Lands Processes (SCLP) and the Global Atmospheric Composition Mission (GACM). Technology needs associated with new measurement concepts were then added to the needs remaining from the 2007 decadal report. The new measurement concepts include: The use of multi-frequency radiometry at P-band and higher to retrieve deep (root zone) soil moisture (RZSM), low Size Weight and Power (SWaP) and Cost (SWaP-C) G-band (and higher) radiometers to measure clouds and precipitation processes on improved spatial and temporal scales, G-band and higher radiometers with back-end spectrometers to infer atmospheric composition, improved calibration techniques for temperature and humidity sounding, improved spatial resolution for imaging radiometers, improved RFI mitigation techniques to enable more effective measurements in portions of the electromagnetic spectrum that are heavily utilized, and finally, recognition of the value of multi-frequency and multi sensor feed and antenna designs that allow larger scale integration with active microwave sensors (radar).

Tiered missions from the 2007 decadal survey carrying microwave radiometers

- Soil Moisture Active/Passive (SMAP)
- Surface Water / Ocean Topography (SWOT)
- Precipitation and All-weather Temperature and Humidity (PATH)
- Snow and Cold Land Processes (SCLP)
- Global Atmospheric Composition Mission (GACM)

New measurement concepts for microwave radiometers identified as part of the current microwave working group study

- Root Zone Soil Moisture – P-band; multi-frequency feeds/FPA; integration w/radar
- Clouds and Precipitation Processes – G-band and above performance with low SWaP-C
- Atmospheric Composition – G-band and higher radiometers with spectroscopy
- Calibration techniques for multiple small radiometers – V/G-band
- Higher Spatial Resolution Imaging in traditional bands – C-band through W-band
- RFI Mitigation – broadband radiometers with improved general RFI detection levels
- Ocean Altimetry – Multi-frequency feeds; integration with radar

A summary assessment of the current Technology Readiness Level (TRL) of the greatest challenge associated with each tiered 2007 decadal survey missions is shown in Table 3.9 below. Of note are: 1) SMAP [*Entekhabi et al.,* 2010] launched January 31, 2015 and assessed to remain TRL 9, and 2) the passive microwave radiometry component of SCLP, also considered to be mature (TRL 9).

Table 3.9. Technology readiness level assessment of greatest challenge technology from 2007 tiered decadal survey missions

Capability Gap	Measurements	TRL	"Greatest Challenge" TRL
High-frequency low power Radiometers	Wet Path (SWOT)	6	High performance low SWaP radiometers to ~250-GHz
Broadband Spectrometer	Upper Atmosphere Chemistry (GACM)	5	High performance, low SWaP RF Front-ends at 500 – 600 GHz
None	Snow Cover (SCLP)	7-9	N/A
None	Soil Moisture (SMAP)	7-9	N/A
High spatial and temporal resolution sounding - GEO	Precipitation and All-weather Temperature/ Humidity (PATH)	6	V-/G-band GeoSTAR system
High spatial and temporal resolution sounding - LEO	PATH	5	Low Cost Microwave spectrometers on CubeSats

A similar TRL assessment was then conducted for technologies needed to carry out more recently identified measurement concepts that were central topics at the two NASA ESTO-sponsored workshops: 1) at JPL on January 21, 2016 and 2) near GSFC on January 28, 2016. The following two tables summarize the TRL assessments for electronics and antenna subsystems of radiometers needed to meet these new measurement needs.

Table 3.10. Technology capability gap associated with new measurements concepts involving passive microwave radiometry (Part I).

Capability Gap	Measurements	TRL	"Greatest Challenge" TRL
Concurrent Radar and Radiometer measurements; wide range of radio frequencies	Precipitation, Root Zone SM, SSS, Air-Sea Flux/Sea Ice and Ocean Altimetry measurements	4	Integrated Radiometer & Radar transmitter (P- L- S-band; K-Ka-band; Ka-G-band)
Polarimetric Radiometry from L- to SMMW	Ocean Surface Winds; high spatial resolution phenomena	3-7	Microwave polarimetry at W-band and above (lower TRL for higher frequencies)
Low SWaP-C G-band heterodyne receivers	High repeat atmospheric water vapor and temperature profiling	6	Low Power: <50mW; Low Mass: 100g; low power LOs
P-band radar/radiometry with additional bands	Root-Zone Soil Moisture	4	Wide bands at low frequencies (P-band); spectrum sharing technology
Super-heterodyne receivers; 500 – 600 GHz + G-band (SWaP-C)	Trace gasses; atmospheric water and temperature profile	3	100mW; 200g; 300 K T_{sys} at ~80 K
SWaP-C of G-band WV profiling radiometers	Tropospheric winds from repeat pass WV radiometry	5	Technique needs to be proven; requirements for low-cost sensor still TBD (Technology TRL is high)

Table 3.11. Technology capability gap associated with new measurements concepts involving passive microwave radiometry (Part II).

Capability Gap	Measurement Concept	TRL	"Greatest Challenge" TRL
Dual-polarized radiometers operating at 89 - 650 GHz;	Cloud Ice, tropospheric water characterization	2-5	Low power, 0.5W / size to fit in a focal plane/feed array; low BW (2%) filters; Lower TRL for higher frequencies
Low cost atmospheric sounding for 'high volume' use in small platforms	Clouds and precipitation processes – high temporal	4	300K T_{rec}; up to 183-GHz; <50mW; <100g
2m class deployable antenna	Improved HSR for traditional measurements from low cost/ small platforms	3	Performance to ~600 GHz; stowed volume ~ 2.5U
Broadband well-calibrated frequency agile radiometer	Imaging radiometer coverage in environments with increasing RFI	4	25 kHz band segments from 1 – 50 GHz
P- to K-band feed array for large reflector	Root Zone Soil Moisture	5	Radiometer front-ends to fit within a specialized feed array
Direct SI traceability; Distributed Cal for STAR; Calibration of UAV radiometers	Radiometer Calibration	4	Blackbody standards & analysis; Stability of distributed Cal; (SM) System-based approach to Cal;
Broadband/Multiband FPA feed technologies to support ~7m aperture antennas	Spatial Resolution Improvements to OSW, Cloud Liquid, Precipitation, Integrated Water, Snow Cover etc.	4	10-1 band feeds with high beam efficiency and surface factor to W-band;
Large deployable antenna (e.g. D >= 10m and f =< 40 GHz)	Ultra-high spatial resolution for imaging below 40 GHz	3-5	>90% beam efficiency; mods to existing commercial antennas
SMMW Receiver Technology: Instrument front-ends (including LNAs); filters; detectors; calibration noise sources and switches; isolators	Cost effective high temporal sampling of precipitation, clouds, and ice	2-5	5dB NF from 200 – 1000 GHz (High TRL); filters to allow SSB operation at 10% BW (Low TRL); Direct detection at <100K added noise temperature (Mid TRL)

3.2.2. Technology needs update

The 2004 MWG report identified 8 areas for technology development in order to facilitate measurement scenarios identified by the report that were connected with microwave radiometer electronics. These technology areas were the following:

- High Frequency Electronics
- Miniaturized Radiometer Technologies
- Analog RFI Mitigation
- Correlation Radiometer Calibration Sub-system
- On-board RF Signal distribution
- 3 or 4 Stokes' Polarimetric Receiver Design
- Ultra-stable Low-Loss Radiometers
- Combined Passive / Active System Design

Technologies identified for current development, based on Earth science measurements needs anticipated for the next ten years include the following changes with respect to the 2004 areas. This report:

- Expands role of combined passive / active designs and calibration
- Includes several aspects of combined technologies covering a broad range of frequencies
- Expands RFI mitigation to include use of digital technologies
- Adds spectrum sharing and greatly improved performance of digital spectroscopy and Kurtosis
- Adds broad-band radiometer capability with adjustable band segments and tunable notches
- Considers RFI mitigation capability to become increasing important for future measurements
- Adds compact, low power cryocooler technology for improved SMMW receiver performance

The 2004 MWG report identified antenna-related technology developments required for then-future passive measurements and then combined the required technology developments into assessment tables (Combined Breakdown Structure) for 1) passive and 2) active (radar) instruments. Accordingly, the 2004 MWG report identifies 7 technology investment areas related to antennas utilized by passive radiometers:

- Low Profile Lightweight Array Feeds
- Millimeter Wave Scanning Antenna
- Mechanically Scanning Aperture for Millimeter Wave
- Rotating Large Aperture for Low Frequency
- Torus with Electronically Scanning Feed Array
- 2-D STAR with Receiver Elements
- 2-D STAR with Membrane WG Technology

Included with the technology area list, were key performance thresholds required in order to enable the needed measurements:

- 10 km L-band; 5 km K-band measurements from LEO

The 2016 report combines technology developments identified to enable future Earth science measurements using microwave radiometers into a single focused assessment containing antenna, RF analog and digital electronics technology development needs. Some general observations and changes to the focus of areas identified in 2004 for the current report include:

- 2-D STAR developments focused on calibration and low power correlators
- No discussion of membrane WG technology
- Larger antennas for traditional frequency bands
- Desire for improved Horizontal Spatial Resolution
- Additional focus on multi-frequency and active/passive sensor integration

For 2016 the performance threshold quantitative requirements remain TBD pending further refinement of the current NRC decadal review.

3.2.3. Technology Challenges

A summary of technology areas moved forward from 2004 along with the current associated focus area for each technology is provided in Table 3.12 below. The table also identifies cross-cutting technologies that may benefit multiple measurements and instruments.

Table 3.12. Summary of technical areas in radiometry for investment in 2016

Technical Area	2004 Report	2016 Report	Rationale
High Frequency Radiometers	X	X	Enables clouds and precipitation measurements from lower SWaP platforms
Miniaturized and multi-frequency radiometers	X	X	Enables measurements requiring multiple frequencies or combination with Radar using a single instrument
RFI Mitigation (S/W & H/W)	X	X	Increasingly important for measurements requiring K-band and lower frequencies
Radiometer Calibration	X	X	SI-traceability and improved calibration for UAV-based sensors for climate
Polarimeters (L- W-band)	X	X	Ocean wind vector and cloud ice
Combined Active/Passive FEs	X	X	Enables increased integration of active and passive sensors for lower SWaP
2m deployable (<350 GHz)	-	X	Crosscutting – for lower SWaP-C; and improved HSR performance
6m class antennas (<100 GHz)	X	X	Crosscutting – enables improvements to HSR
10m class antennas (<40 GHz)	X	X	Crosscutting – enables improvements to HSR
Cryocoolers	-	X	Enables scanning SMMW radiometers for atmospheric composition measurements

Expanding on the descriptions contained within the above table, several points are expanded to more completely describe the value of each area and how technology developments may be leveraged for Earth science.

High Frequency Radiometers

Recent developments in low noise amplifiers have enabled unprecedented performance at frequencies above 200-GHz using room temperature InP-based solid state devices [*Mei et al.,* 2007]. Radiometric system noise temperatures <400 K at 183-GHz have been established using 35nm gate technology leveraged from commercial production of InP devices [*Kangaslahti et al.,* 2010, *Deal,* 2016]. Similar devices are envisioned to enable high spatiotemporal temperature and humidity sounding (e.g. PATH) using a GEO-based Synthetic Thinned Aperture Radiometer (STAR) [*Lambigtsen et al.,* 2010a] concept. Further performance improvements may yield ultra-low SWaP radiometers covering bands well into the SMMW region. This has the potential to enable a range of low cost measurement opportunities from LEO including temperature and humidity sounding from CubeSats [*Blackwell et al*., 2014], low cost high spatiotemporal monitoring of clouds and precipitation and scanning limb sounder concepts to support GACM.

Enabling technology to achieve lower power and cost measurements above 180-GHz includes local oscillators (LOs) with greatly improved RF generation efficiency. Currently, RF power generation efficiency remains below 1% at 180-GHz and above [*Deal,* 2016]. As a result, several watts of DC power are generally required to produce LO signals at sufficient power levels to drive MMW and SMMW mixers. Continued development of InP HEMTs as signal multipliers, has shown some promise showing improvement to ~4.2% power generation efficiency in the laboratory. Improving efficiency of generating RF to levels suitable for mixers operating up to and beyond 640-GHz will provide a valuable and fundamental capability to fly SMMW radiometers on a variety of power and volume-limited space-based platforms.

Direct detection receivers may also be used to reduce SWaP as a result of eliminating the need for the LO and frequency conversion. However, performance limitations related to passband selectivity, detector sensitivity, and stability, currently limit applications of direct detection radiometers in Earth science to lower frequency (e.g. below W-band) and generally broadband imaging applications. Heterodyne receivers are utilized in applications involving high frequencies or high selectivity such as sounding applications and measurements above W-band. As noted above, heterodyne receivers generally require more SWaP accommodation due to the relatively low efficiency of high frequency power generation required by the Local Oscillator (LO) for frequency conversion.

Future improvement of RF filter technology may also enable adequate receiver front-end selectivity to allow direct detection radiometers to be utilized for measurement of atmospheric temperature or moisture profiles. If this is realized, microwave sounding of the atmosphere could be performed from significantly smaller space based platforms with limited SWaP accommodation and with lower development cost greatly improving spatiotemporal resolution.

Technology development as envisioned for future Earth science measurements utilizing high frequency microwave radiometers is summarized in Table 3.13.

Table 3.13. Technology needs for high frequency radiometry

Measurement	Technology	State of the Art	Requirements	Development Need
Cloud Ice; Precipitation	High frequency receiver front-ends operating from 89-GHz up to >800-GHz	183-GHz LNAs @ 500 K noise temperature; frequency; down conversion; DSB configuration with filtering to achieve 3-5 separate offsets from 183-GHz line. Passive front-ends above ~200-GHz and noise temperature >>500 K operating at room temperature	300K noise temperature at room temp @183 GHz; Power <0.05W; Mass<100g	Reduce mass, volume and power requirements for high frequency radiometers Low power LO Filtering at primary frequency of operation Wideband receivers (multi-band back-ends) Sufficiently small enough to fit within a single focal plan
Atmospheric Chemistry	High frequency receiver front-ends operating from 500- to 600-GHz	Passive front-ends above ~200-GHz and noise temperature >>500 K operating at room temperature	MMIC-based super-heterodyne integrated receivers: 300K @ 20K, 500 GHz Power: <0.1W; Mass<200g	Continued improvement of performance and f_{MAX} for high frequency InP LNAs Performance under cryo-cooling may be an option Low NF and noise stability are primary metrics

Multi-frequency and Multi-sensor integration

Several past remote sensing missions have utilized both active and passive microwave sensors. One example is the Global Precipitation Measurement (GPM) mission which includes the GPM Microwave Imager (GMI) and the Dual-frequency Precipitation Radar (DPR). In general, active and passive microwave instruments designed as separate sensors and sharing a common space-based platform is considered standard practice and current state-of-the-art. However, larger scale integration of instrument functions or, equivalently, active and passive microwave instruments combined into a single instrument with a common aperture, may yield significant cost and performance advantages. Advantages of this approach include reduced SWaP, and reduced systems integration complexity and compatibility testing at the spacecraft or observatory level. It is noted that examples of missions carrying multiple sensors that have experienced cost increases due to unexpected electromagnetic compatibility issues identified late in the system integration and test cycle are not uncommon. Accordingly, larger scale integration of instrument functions, with a goal of multiple instrument types combined into a single instrument may enable important Earth science measurements to be carried out with lower overall costs.

Technology investments include improved packaging of multi-frequency feed structures including focal-plane arrays as well as receiver RF front-ends. Another aspect of this approach may be to utilize *broadband* instrument designs that could be built at reduced cost compared with multi-band sensors and require smaller volume. And finally, high performance, lower cost internal MMIC switches may also provide a path to broader-band instrument performance and multi-function microwave instruments (active + passive + SoOp).

Table 3.14. Technology needs for radiometry to achieve multi-sensor multi-frequency sensors (Part I): Combined FPAs for antennas

Measurement	Technology	Sate of the Art	Requirements	Development Need
Root Zone Soil Moisture/ SSS/ Air-Sea Flux/ Sea Ice	Broadband/ Multi-band Focal Plane Array feed for Large (e.g. >7m) Antennas	Single band and/or multiple feedhorns	10-1 band feeds; non moving conical scan; P/ L/ S/ C-band; Multi-angle may also be useful	Combined Radar/ Radiometer/ SoOp; Multi-purpose SDR; Reconfigurable frequency agile systems
High resolution imagery to support Snow/OSWV/ Precipitation & cloud amounts	6-/10-GHz through 90-GHz, spatial resolution substantially better than AMSR-2 (e.g. 6m deployable)	2m class apertures for multi-frequency space-based radiometers	~6m reflector antenna; array receivers to accommodate Nyquist sampling at improved spatial resolution	6m deployable reflector with surface figure to support W-band imaging

Table 3.15. Technology needs for radiometry to achieve multi-sensor multi-frequency sensors (Part II): Integrated radiometers with radar transmitters and receivers.

Measurements	Technology	State of the Art	Requirements	Development Need
Precipitation	Internal low loss high isolation switches	High power switching; frequency multiplexers with individual receiver chains	Instrument Front-end (low SWaP); Power: 10 – 30W; efficiency 40%	Single unit on a small platform
Root Zone Soil Moisture/ SSS/ Air-Sea-Flux/ Sea Ice	Internal low loss high isolation switches	High power switching; frequency multiplexers with individual receiver chains	Instrument Front-end; stable internal calibration	Coexistence with Radar unit; single instrument front-end .
Ocean Surface Winds/ Altimetry	Internal low loss high isolation switches	High power switching; frequency multiplexers with individual receiver chains	~2m single aperture, multi-frequency, integrated active/passive, C- to Ka-band	Integrated polarimeter and radar receivers

RFI Mitigation

Technology investment in RFI mitigation is driven by its increasing impact to microwave Earth science measurements caused in part by increasing utilization of the RF spectrum. Improvement of RFI detection and mitigation performance is required not only to offset the impacts of this trend but also to enable high quality measurements in regions of the spectrum that are heavily utilized by other radio services. For example, frequency agile notch filters with sufficient frequency selectivity to reject unwanted adjacent signals and enable radiometric measurements in isolated spectral regions are needed to enable radiometric measurements near P-band for deep soil moisture. Improved algorithms are needed to achieve better detection thresholds for demanding ocean retrieval algorithms. Other RFI mitigation technology development needs include autonomous (on-board) RFI detection and mitigation to eliminate exponential down link data rate growth that would otherwise be required to perform ground based (post measurement) RFI mitigation.

Table 3.16. Technology needs for RFI mitigation in radiometry

Measurements	Technology	State of the Art	Requirements	Development Need
Root Zone Soil Moisture	Broadband tunable notch filter; spectrum sharing technology	Relatively low selectivity tunable notch filters	Tunable from ~400-MHz to 2-GHz; Low loss; high selectivity	Autonomous detection and tuning of RF band notching
Imagery products over and near populated areas	Ultra-Broadband Digital Spectrometer	3 GHz BW with CMOS 65-nm technology;	20- to 50-GHz BW; Improvements in spectral resolution; mitigation techniques	On-board real time RFI detection and mitigation

Larger and lower cost antennas

It is expected that advances in Earth science phenomenology and modelling will drive increased requirements for spatial and radiometric resolution (sensitivity) for future Earth science measurements. For passive microwave measurements, horizontal spatial resolution is typically determined by the diffraction limit of the main antenna aperture. Therefore, to meet this need, larger antennas with extended frequency range will be required and may in turn drive mission costs due to increased accommodation requirements. One path to limit growth in SWaP is the use of deployable antennas. Deployable antennas up to 2m operating up to 300-GHz may enable greatly improved horizontal spatial resolution measurements from systems having ~2.5U cube-sat sized stowed volumes. Larger size antenna developments include 6m-class antennas operating up to ~100-GHz and 10m-class apertures operating up to 40-GHz that could be deployed from smaller rocket fairings enabling missions at greatly reduced costs.

Table 3.17. Technology needs for microwave radiometry with larger aperture reflector antennas

Measurements	Technology	State of the Art	Requirements	Development Need
Precipitation; clouds: L-band through 350 GHz (lower cost alternatives)	2m deployable antenna and feeds	1.5U stowed; 0.7m aperture deployed	Surface figure: W-band: full aperture; f < 350-GHz: 1m diameter Stowed volume: 2.5U	Develop and demonstrate 2m deployable reflector;
Root Zone Soil Moisture/ SSS/ Air-Sea Flux/ Sea Ice	Broadband/ Multiband Focal Plane Array Feed Technologies for Large (e.g. >7m) Antennas	Single band and/or multiple feedhorns	10-1 band feeds (options); non-moving conical scan; P/ L/ S/ C-band; 40° ONA; Multi-angle may also be useful	Combined Radar/ Radiometer/ SoOp; Multi-purpose SDR; reconfigurable frequency agile systems
High resolution imagery to support Snow/OSWV/ Precipitation & cloud amount	6-/10-GHz through 90 GHz, spatial resolution substantially better than AMSR-2. (e.g., 6-meter deployable)	2m class apertures for multi-frequency space-based radiometers	~6-m reflector radiometer antenna; spatial resolution substantially better than AMSR-2. (e.g., 6-meter deployable); array receivers to accommodate Nyquist sampling	6m deployable reflector with surface figure to support W-band

Polarimetry

Passive microwave polarimetry is used to measure ocean surface wind direction from space [*Gaiser et al.,* 2004; *Meissner and Wentz,* 2006]. Other potential applications of polarimetric microwave brightness temperature measurements for Earth science include land surface structure (e.g. Antarctic) and clouds (hydrometeor shape and orientation). Passive polarimetry can also be used as an integral part of the microwave radiometer instrument design in order to simplify the scanning mechanism of conical-scanning radiometers by enabling the sensor RF electronics to remain stationary while only the antenna rotates to perform the conical scan [*Brown et al.,* 2014]. Conical-scanning radiometers are used to make dual orthogonally polarized measurements over the Earth's surface and currently require the space-based platform to accommodate significant spinning mass. This results in increased cost and complexity to accommodate the payload with other sensors, particularly when demanding stability and pointing requirements are placed on the satellite. As a result, polarimetric radiometers operating at C-band and higher could utilize the Electronic Polarization Basis Rotation (EPBR) technique to significantly reduce SWaP of multi-frequency, dual-polarized and polarimetric, conical-scanning radiometers.

Table 3.18. Technology needs in passive microwave polarimetry

Measurements	Technology	State of the Art	Requirements	Development Need
OSWV, Imaging (W-band), Cloud characteristics	High performance stable polarimetric receivers W-band and above	Ka-band (WindSat)	Polarimetric radiometers with channel-to-channel calibration; matching dual-pol radiometers	High frequency polarimetric back-ends (analog) or wideband digital back-ends
Dual-polarized microwave atmospheric and surface imagery to support PATH and improved Weather	Electronic Polarization Basis Rotation (EPBR)	Ka-band (TRL 6)	Enable Electronic Polarization Basis Rotation for Conical scanners	Stable noise diodes at W-band to G-band and above; polarimetric calibration

Thinned Aperture Radiometers

The need for high spatiotemporal sampling of precipitation and atmospheric temperature and humidity profiles are supported by both Geostationary (STAR) and LEO (many small sensors) instrument and mission concepts. The Geostationary-based instrument concept, GeoSTAR has been prototyped [*Tanner et al.,* 2007]. Enabling technology for the Geo-based STAR instrument includes high performance correlators currently assessed at TRL 6. Further maturation of correlator technology (lower power; space qualification) may make a significant contribution by lowering the overall risk to flight for this sensor. Other concepts for STARs include formation flying using discrete small satellites in order to provide a path to several advanced measurements in Earth Science including atmospheric composition, deep (root zone) soil moisture and high spatial resolution Sea Surface Salinity (SSS).

Table 3.19. Technology needs for Synthetic Thinned Aperture Radiometry (STAR)

Measurement	Technology	State of the Art	Requirements	Development Need
Atmospheric Sounding;	Analog/Digital Cross Correlator	TRL 6	1-GHz IF band; 250 uW/correlation; 256x256 inputs; 500 MHz BW	Space qualification
Root Zone Soil Moisture and Sea Ice	Distributed Correlators for P/ L/ S/ and C-band	TRL 3	<100 MHz BW; limited baselines in distributed STAR systems	Signal processing (correlator function) as part of inter-satellite links

Improved Calibration for Microwave Radiometers

Absolute calibration of microwave radiometers is critically important for the most challenging applications such as atmospheric temperature and moisture sounding. To achieve the required calibration performance and direct SI traceability of the sensor calibration, detailed accounting of the antenna pattern interaction with an external blackbody standard is necessary. It is noted that calibration and inter-calibration of measurements from LEO, which by their nature utilize many individual sensors, presents a significant challenge related to ensuring uniformity and spatiotemporal 'continuity' of the observations to support higher level data products [*Ruan et al.,* 2015]. Observations from UAV-based platforms may also present unique challenges for achieving absolute calibration due to the impact of the ambient environment on the accuracy of radiometric observations. Therefore, application of a systematic approach for calibration in order to identify and correctly categorize transient calibration phenomena and anomalies are also of interest in order to improve the effectiveness of all radiometric observations within the constellation.

Also connected with increased number of observations from smaller platforms is the need for improved internal calibration of radiometers, especially those operating at 183-GHz and higher. To this end, miniaturization, an important enabling aspect of high frequency space-based radiometry for higher spatiotemporal sampling of transient phenomena such as clouds and precipitation, drives new requirements on internal calibration and components. One path to improve internal calibration relies on improved, low loss, high speed internal RF switching. Currently RF switch insertion loss ranges from ~1.5 to > 4 dB over the frequency range 183- to 640-GHz [*Deal*, 2016]. Excessive and undesirable calibration path-loss results in variable ambient conditions impacting the radiometer calibration. An alternate path to improve internal calibration is to use pseudo-correlation radiometer designs, although this approach generally doubles the required number of components [*Gaier et al.,* 2013].

And finally, calibration of 2D STAR radiometers continues to be an important topic in the assessment and acceptance of the overall performance of this approach for high performance temperature and moisture sounding. Calibration technology development needs for microwave radiometry are summarized in Table 3.20.

Table 3.20. Technology needs for microwave radiometer calibration

Measurement	Technology	State of the Art	Requirements	Development Need
Imagery; Atmospheric Temperature Sounding;	SI Traceability (through the antenna)	SI-traceable blackbody temperature sensors – misses largest uncertainty	Techniques developed	Black body standards, traceability techniques
Atmospheric Temperature and Humidity Profiles	Distributed calibration techniques for STAR	Pre-launch characterization	Instrument front-end; stable internal calibration	Space-based verification; model development
Imagery; high revisit/ regional measurements	Calibration of UAV radiometers	Sensor and platform unique artifacts / biases requiring reprocessing before integration/assimilation	Level 3 calibrated data with minimal or no unique application-specific / platform-specific reprocessing	Combine information about ambient environment to improve unattended airborne (vs. space-based) instrument calibration
Atmospheric Sounding; Cloud Ice	183-GHz and higher noise sources for internal calibration	W-band internal noise sources are beginning to be established	Calibration stability (TBD) ENR (TBD) Low loss RF switches	Stable noise sources and low loss switches

Cryocoolers

Although cryocoolers provide an additional path to improved performance particularly at SMMW frequencies, their impact compared to SWaP requirements for the sensor payload may be determined by the size of the host space-based platform. In general, it is noted that the quality and efficiency of single and two-stage coolers has continued to improve, achieving perhaps 18% Carnot efficiency with smaller packaging [reference TBS]. Currently, cryocoolers capable of operation at 50 K are available and helpful but generally require mass and power accommodations that drive the instrument and platform design SWaP-C especially when considering coolers to achieve operating temperatures below 50 K [reference TBS]. Improvements to obtain high efficiency coolers operating at ~20K and capable of ~1.5 W lift capacity could provide an efficient path to important performance enhancements of microwave limb sounding instruments operating in the MMW and SMMW spectral region. When coupled with improved SMMW low noise amplifier technology, efficient cryocooling allows the sensor to achieve markedly improved signal to noise ratios of key trace species such as stratospheric CO against a relatively cool high altitude background. As a result, two dimensional scanning can be carried out providing greatly increased coverage and scientific insight to the distribution and tracking of CO and other important trace species.

It is noted that although several organizations are continuing to develop high efficiency cry-cooling technology, availability of units specifically adapted for these Earth science and limb sounding instrument applications may be significantly limited. Cryocooler technology needs are summarized in Table 3.21.

Table 3.21. Cryocooler technology needs

Measurements	Technology	State-of-the-Art	Requirements	Development Need
Microwave Limb Sounding	Low SWaP Cyrocoolers	20 K; η~0.2% (2-Stage)	20K; 1.5 W lift; η >15% (TBR)	Low SWaP-C Cryo-coolers to improve limb sounder performance

Improvements in small space-based platforms and reliability

It is recognized that small satellite platforms such as CubeSats present many possibilities for the realization of alternate methods for several high priority Earth science measurements at potentially less cost. However, there is also strong feedback suggesting that these opportunities would be greatly enhanced with the availability of small space-based platforms with greater payload accommodation capability (e.g. volume and power) with improved reliability. Therefore, in order to ensure continued growth in use of small space-based platforms and to enhance their utility to support low-cost alternatives for Earth science measurements, improvements in reliability, power availability, and communication links are considered ‘enabling’. For example, goals may initially be set to achieve lifetimes of ~3 years on-orbit operations. Additional development options may include improved miniaturized subsystems, and system engineering and modelling to support high precision formation flying.

Table 3.22. Small satellite space-based platform improvements to enable next generation radiometric measurements for Earth science

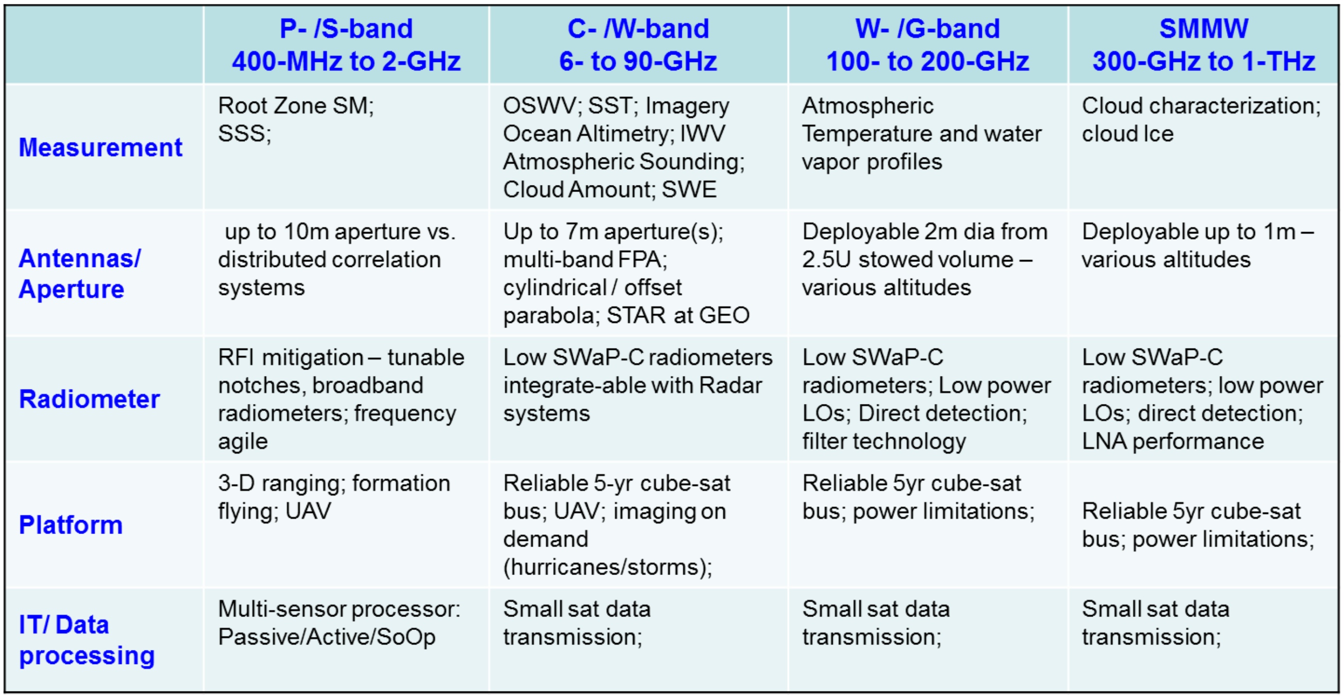
Measurements	Technology	State-of-the-Art	Requirements	Development Need
PATH	Reliable more capable small satellite bus	6 mos – LEO	3+ years life – improved accommodation	subsystems
RZSM, sea ice	3-D ranging and data transmission	N/A for Small-Sats (TRL 3)	500m separation 1 cm precision	Models, miniaturization of subsystems

System Engineering applied at the science measurement level

Of note currently is the potential increased role of commercial and small satellite interests in realizing new measurements and improving existing measurements. As a result, alternative options exist to realize measurements that have been traditionally involved large dedicated space-based platforms. For example, PATH-related atmospheric measurements envisioned to originate from a dedicated geostationary platform may also be achieved using a large number of LEO-based SmallSats. In order to determine the optimal path forward, informed system-level trades will need to be carried out supported by disciplined application of science models flow of technical performance requirements to lower levels of the system.

Summary of Technology Needs

The following figures summarize key areas of the above discussion by frequency range and by individual frequency bands. Although quantitative aspects and associated details of the technology needs are not included, Figure 9 and Figure 10 illustrate the connection between measurement and technology needs for Earth science over a significant portion of the RF spectrum.



	P- /S-band 400-MHz to 2-GHz	**C- /W-band 6- to 90-GHz**	**W- /G-band 100- to 200-GHz**	**SMMW 300-GHz to 1-THz**
Measurement	Root Zone SM; SSS;	OSWV; SST; Imagery Ocean Altimetry; IWV Atmospheric Sounding; Cloud Amount; SWE	Atmospheric Temperature and water vapor profiles	Cloud characterization; cloud Ice
Antennas/ Aperture	up to 10m aperture vs. distributed correlation systems	Up to 7m aperture(s); multi-band FPA; cylindrical / offset parabola; STAR at GEO	Deployable 2m dia from 2.5U stowed volume – various altitudes	Deployable up to 1m – various altitudes
Radiometer	RFI mitigation – tunable notches, broadband radiometers; frequency agile	Low SWaP-C radiometers integrate-able with Radar systems	Low SWaP-C radiometers; Low power LOs; Direct detection; filter technology	Low SWaP-C radiometers; low power LOs; direct detection; LNA performance
Platform	3-D ranging; formation flying; UAV	Reliable 5-yr cube-sat bus; UAV; imaging on demand (hurricanes/storms);	Reliable 5yr cube-sat bus; power limitations;	Reliable 5yr cube-sat bus; power limitations;
IT/ Data processing	Multi-sensor processor: Passive/Active/SoOp	Small sat data transmission;	Small sat data transmission;	Small sat data transmission;

Figure 9. Microwave measurement and technology needs for Earth science summarized within four separate RF frequency ranges.

3.2.4. Conclusions and Recommendations

This section contains conclusions and recommendations related to the major technology areas and needs for microwave radiometry in Earth science. It is important to note that no attempt has been made to prioritize the technology areas within this draft report, however, the previous discussion has identified many cross-cutting technology investment areas that are summarized in the text below and in the Capability Breakdown Structure (CBS) Tables in Appendix D. Lower TRL items will be brought forward for additional discussion within the emerging technologies chapter.

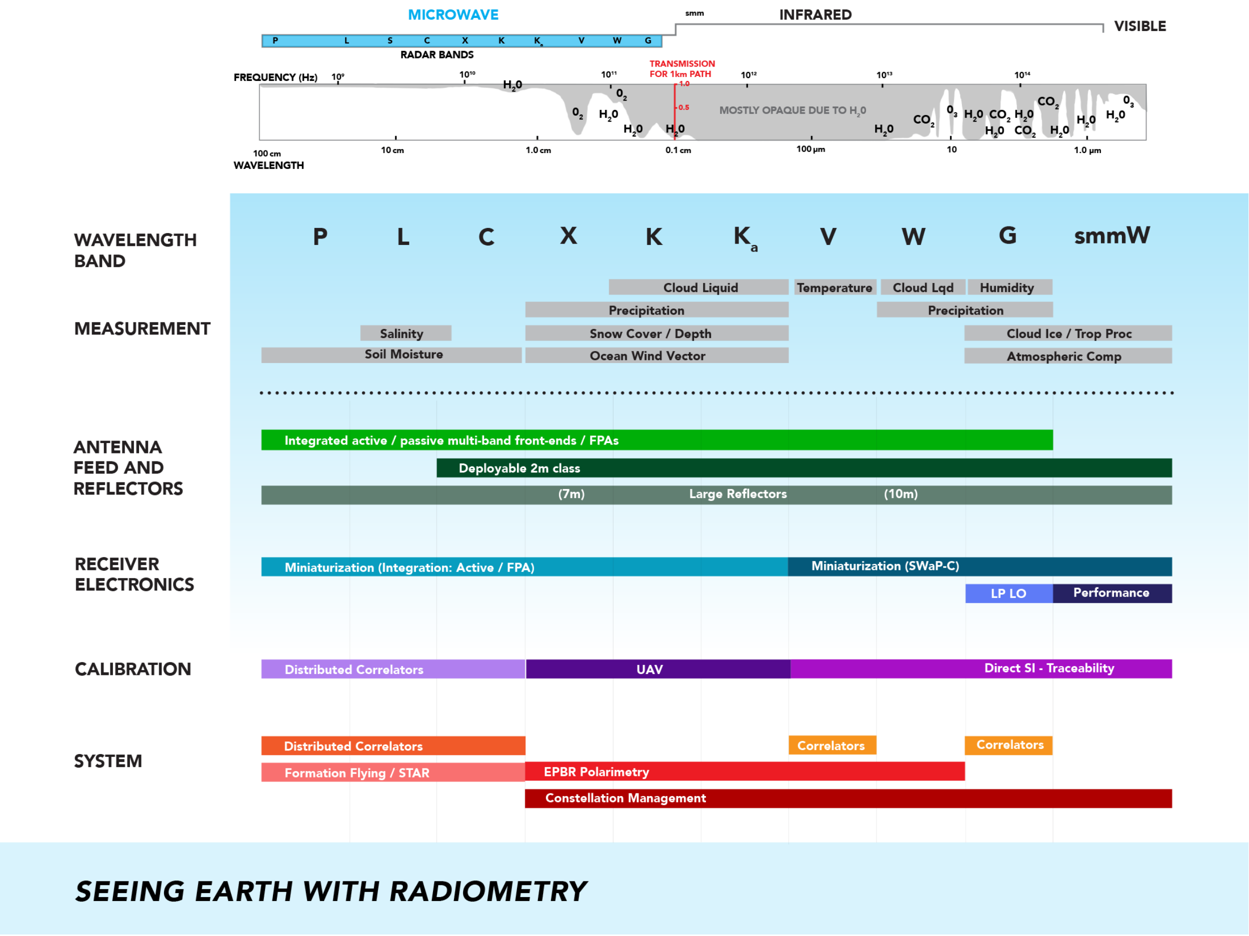


Figure 10. Microwave measurement and technology needs for Earth Science summarized by frequency band

As shown in Figure 9 and Figure 10, technology development for the next generation of microwave radiometers for Earth science measurement needs include high frequency receiver components such LNAs, filter, detectors, high efficiency RF sources, and isolators. Use of high performance components in radiometers must also consider additional requirements common to commercial communications and signal electronics, such as gain and phase stability and in some cases, larger working bandwidths. Low cost, high efficiency, compact cryocoolers may also facilitate achievements of greater performance, however, it is not clear that their use with small satellites can be achieved considering the current accommodation limitations, especially for CubeSats. High frequency RF performance is cross-cutting to several measurement scenarios and can be leveraged in multiple approaches as outlined in Table 3.1.

Integrated multi-frequency and multi-sensors utilizing a common shared aperture have potential to enable cost effective measurements that currently require discrete sensors either flying on the same or multiple platforms. Future sensor concepts include multi-frequency Focal Plane Array (FPA) antenna feeds to enable new and cost-effective system trades for Root Zone Soil Moisture (RZSM). Multi-band measurement concepts for clouds and atmospheric processes currently utilizing multi-band linear array covering Ku- to W-band may also benefit from technology advancements in this area [*NRC,* 2007a; *Durden et al.,* 2016].

Further progress in Radio Frequency Interference (RFI) mitigation techniques for microwave radiometry is needed to enable measurements in portions of the RF spectrum that contain strong emitters. Regardless of whether the immediate band is clear, the presence of strong emitters can impact radiometric performance due to limitations of the receiver front-end selectivity. In this circumstance, tunable high selectivity notch filters can greatly enhance the value of radiometer measurements especially in portions of the spectrum that are highly utilized by active radio services. Increasing utilization of RF spectrum by radio services has also had an increasing deleterious impact on scientific measurements. At the same time, increasing requirements on accuracy and long term stability of measurements utilized for scientific inquiry have resulted in ever increasing requirements for RFI detection and mitigation. Two important implications of these requirements are the need for better detection of contaminated spectrum overall such as the development of complex Kurtosis methods [*Bradley et al.,* 2014], and on-board / real time RFI mitigation in order to limit bandwidth requirements for downlinks [*Misra et al.,* 2014].

In order to more effectively utilize new launch opportunities for small satellites, and at the same time be able to make useful measurements with diffraction limited apertures, a new class of cost-effective small deployable antennas will need to be available for investigators. Current examples include the RainCube satellite [*Peral et al.,* 2015]. Needed technology developments include improvement in stowed and deployed volumes, surface figure, and higher maximum frequency of operation will enhance opportunities for new measurements requiring high temporal and spatial resolution such as clouds and precipitation as well as atmospheric temperature and moisture measurements. Cost and performance improvements to larger deployable aperture antennas [*Focardi et al.,* 2011] will also benefit high spatial resolution measurement, or allow traditional measurements from higher altitudes to improve global coverage or revisit characteristics.

It is noted that many new measurement concepts under consideration utilize small satellite platforms as potential low-cost alternatives for existing approaches or fundamentally may be enabled by the ready availability of low-cost small satellites. Viability of these new approaches will likely depend on significant improvements to small satellite reliability and improved payload accommodations such as power availability and data rates. Still other measurement concepts will require development of new constellation management and data processing techniques [*Ruan, et al.,* 2015] for large numbers of small satellites.

3.3. Information and Data Processing Technology

All scientific measurement requires the collection and processing of data. Indeed, processed data products are the ultimate purpose of any measurement system, providing inputs for operational or scientific analysis. System modeling and simulation are also crucial to the development of new measurements and instruments, and information technology must therefore be considered at every stage of mission development – from measurement concept to development to flight to scientific exploitation. Investments in information and data processing technology are vital and must be made alongside investments in transmitter, receiver, and antenna hardware.

Earth science measurements will continue to generate increasing amounts of data, which must be stored, processed, and disseminated. Data handling needs include on-board storage and processing, communication to ground terminals, storage and processing on the ground, and distribution to scientific users. The 2004 MWG report [*ESTO,* 2004] focused solely on on-board processing development needs. In the present study, a more holistic approach was followed, additionally considering multi-spacecraft systems-of-systems, crosslink and downlink needs, and ground system capabilities.

Any particular instrument will have its own particular modeling, simulation, data handling, and data processing needs. It is recommended that technology investments not concentrate on instrument-specific applications (e.g., specific retrieval algorithms), but rather on more general, measurement-enabling technologies or technologies that cut across multiple measurement scenarios. Determining specific, quantitative requirements for instrument-agnostic information technology development presents some difficulty. As much specificity as possible has been included in this report, given this limitation.

In the subsections below, information technology needs remaining from the 2007 decadal survey [*NRC,* 2007] missions are discussed, as well as new needs identified at the 2016 JPL and GSFC workshops. The various information and data handling concepts that emerged from these meetings can be divided into just a few broad themes. Similarly, the actual technology development required to realize these concepts can be broken down into a handful of categories, each of which is discussed below. This section ends with a summary and our conclusions and recommendations.

3.3.1. Unmet Technology Needs from the Previous Decadal Survey

Table 3.23 summarizes the remaining information and data processing technology needs for the microwave missions recommended in the 2007 decadal survey. Missions not explicitly mentioned in the table reported no unmet information technology needs (XOVWM, SWOT, PATH, NISAR/DESDynI).

Table 3.23. Data/information technology assessment for the 2007 Tiered Decadal Survey Measurements

Capability Gap	Measurements	TRL
Waveform generation/ultra-low-range-sidelobe pulse compression	Clouds (ACE - radar)	5
OSSE; mission configuration and performance studies	Aerosols, Clouds (ACE)	2-5
Information-aware compression algorithms for downlink and RFI mitigation	Atmospheric composition (GACM)	3
Advanced 3D tomographic retrieval algorithms	Atmospheric composition (GACM)	3
Retrieval algorithms	Snow water equivalent, depth, wetness (SCLP)	3

There were also several technology needs from the 2004 microwave study that are still relevant for the current assessment. These holdovers include fast analog-to-digital converters (ADCs), correlators, onboard storage, and onboard processors. There are, of course, examples of each of these technologies with high maturity (TRL 9). But while these technologies have indeed progressed since 2004, so have measurement needs. For example, ultra-wide-band (tens of gigahertz) ADCs and correlators are now desirable for digital RFI mitigation, and improvements in onboard storage and processing will enable adaptive resource allocation and reduced downlink rates. As user needs in these areas can be expected to continue to grow into the foreseeable future, development of these technologies will continue to be beneficial for decades to come.

3.3.2. Workshop Inputs

Information technology needs for a wide variety of new measurement concepts were discussed at the workshops held at JPL and GSFC in early 2016. Table 3.24 contains a summary of new technology concepts distilled from these workshops. Note that while this list includes many of the inputs from these meetings, it is not exhaustive. Appendix 0 contains a more complete list.

Over the course of the workshops, several concept themes emerged. Many, but not all, of the inputs collected are relevant to one of these three broad areas: coordination of multiple spacecraft, adaptive processing and tasking, and handling of large amounts of data.

Coordination of multiple spacecraft

Advances in SmallSat technology open up the possibility of replacing large, expensive systems with collections of smaller, cheaper systems. Distributed SmallSat concepts can enable measurements that might otherwise be cost-prohibitive. A specific application brought up at the workshops is persistence – a LEO constellation of SmallSats, for example, could provide near-continuous, global environmental monitoring, eliminating the need for or allowing more efficient utilization of more expensive GEO systems. Other applications include simultaneous, spatially extended measurements (in situ magnetospheric sampling, for example) or replacing monolithic large-aperture instruments with sparse arrays of SmallSats flying in formation. These concepts require information processing technology development to enable inter-spacecraft communication, coordination, metrology, and control.

Adaptive processing and tasking

Workshop participants expressed a need to increase instruments' ability to adapt to dynamic measurement environments and alter collection strategies accordingly. Adaptive reallocation of resources can improve responsiveness to time-varying events (e.g., storms, earthquakes, etc.), enables targeted interference avoidance or mitigation, and may enable reductions in data volumes and downlink requirements. Adaptive tasking requires rapid data processing for feature or event detection, decision making, and resource reallocation. Ideally, this processing and decision making occur autonomously onboard, but also may occur on the ground, with or without a human in the loop. Retasking may involve only a single instrument, other instruments on a single spacecraft, or instruments onboard other spacecraft.

Handling large data sets

Earth science measurements in the next decade are expected to generate increasing amounts of data. Currently planned microwave systems alone will downlink ~petabytes per year, and this amount will only grow as revisit rates, global coverage, and bandwidths increase. Including end-user processing and exploitation activities on the ground, data throughput is expected to approach or exceed 500 TB per day. Handling these unprecedented data volumes will require investment in flight storage and processing technology, crosslink and downlink capabilities, and ground infrastructure.

Table 3.24. Information technology needs for future measurements

Capability	**Measurement Concept**	**TRL**	**Challenge**
Onboard storage	Synoptic, multi-sensor, and/or data-intensive measurements (e.g. land deformation, topography, vegetation height/density,…)	4-5	Capacity, speed, SWAP
Onboard processors	Rad Hard By Design, 3D ICs (applicable to wide variety of measurements; e.g., tasking for storm observation, range compression for profiling)	3-5	Performance, SWAP, reusability
Onboard algorithms	Adaptive beam forming, adaptive tasking, formation control, RFI detection and mitigation, compressive sensing, data reduction, data compression (applicable to wide variety of measurements)	2-4	Development, implementation
Fast ADCs	Wide-bandwidth radiometry – digitize 20+ GHz, adaptively channelize to mitigate RFI (RFI mitigation, atmospheric composition)	4	Power, performance for radiometry

Capability	Measurement Concept	TRL	Challenge
High-speed, high-res digital correlators / spectrometers	RFI mitigation over up to 20+ GHz bands (applicable to wide variety of measurements)	4-5	Large BW, # of channels, SWAP
Advanced radar waveform generation	Frequency and/or phase diversity for multiple, simultaneous independent looks (e.g. clouds, precipitation, storms)	5	Implementation, space qualification
Affordable continuous coverage/high revisit rates	Constellations of SmallSats (e.g. temperature, moisture, precipitation, wind vector in dynamic environments)	2-3	Coordination, calibration
Automated event-driven operation, low-latency retasking	Hierarchical collection methodologies, dynamic reallocation of resources based on detected events/features (e.g. temperature, moisture, precipitation, wind vector in dynamic environments)	2-3	Robust event detection; rapid coordination
Inter-spacecraft metrology for ~cm-level formation control	Increased use of small-sats; synthesize larger apertures using formation flying (e.g. root zone soil moisture, sea surface salinity, air-sea flux measurements)	2-4	Low-SWAP-C metrology solution
Fast external data links	Data sharing among satellites in formation (e.g. root zone soil moisture, sea surface salinity, air-sea flux measurements)	3	Low-SWAP-C
Fast, reliable downlink	Increased data production – multiple payloads, small-sat constellations, data-intensive SARs, … (e.g. precipitation, root zone soil moisture, cloud processes, deformation, topography)	3-5	Space and ground infrastructure, laser COMMs, SWAP-C/specialization for SmallSats
Ground data management	Big Data – petabyte storage, persistent teraflops processing, data fusion, distribution (applicable to wide variety of measurements)	2-3	Interoperability, tool development, efficiency, cost
Modeling, simulation, processing algorithm development	Enable new instrument/constellation concepts, new measurements/products, new CONOPS (applicable to wide variety of measurements)	2-3	Standards, interfaces, reusability

3.3.3. Technology Development Needs

The general themes outlined above encompass many of the information technology concepts discussed at the JPL and GSFC workshops. Realization of these concepts will require investment in and development of a number of specific technologies. The majority of required technology development can be broadly placed into the following three categories: onboard processing, spacecraft control & communication, and ground processing.

Modeling, simulation, and algorithm development can be crucial to instrument design, mission planning, and data handling applications, and may be worthy of a technology development category of their own. Instead, algorithm development needs are distributed among the three categories mentioned. Algorithms and models that are instrument-specific are generally not recommended for investment in this report, since they would typically be developed under specific instrument programs. Those that are measurement-enabling or that transcend multiple measurement scenarios are more likely to merit investment. Examples are cited explicitly in the subsections below.

Onboard Processing

The ability to process collected radar or radiometer data onboard a spacecraft enables a number of key capabilities. For example, in the presence of RFI, adaptive beam forming and spectrum utilization can be employed to optimize data collection. Performing these functions on the ground would likely require prohibitively large numbers of antenna/spatial channels and prohibitively large bandwidths to be downlinked. Autonomous adaptive tasking also requires onboard processing to reduce data, detect features or events of interest, and generate tip-offs and/or retasking parameters. Formation flying requires local processing of metrology inputs to determine station-keeping maneuvers. As a final example, onboard data processing and compression may significantly reduce downlink requirements and enable direct downlink to users.

Some specific technology development needs for onboard data storage, processor hardware, and ADC/correlator systems are shown in Table 3.25. The specific quantitative goals indicated in the table are somewhat notional, since exact requirements will generally be instrument-specific.

Investments in hardware technology should be accompanied by investments in algorithm and software development. RFI mitigation techniques, software-defined/cognitive radiometry, compressive sensing (e.g., for aperture synthesis with sparse SmallSat formations), and data compression techniques may have wide applicability and therefore large impact.

Table 3.25. Onboard data processing needs for microwave Earth science measurements.

Measurements	Technology	State of the Art	Development needed	Desired State
Solid Earth (next gen NISAR)	On-board storage	~10 Tb, ~9 Gbps flash memory (Solid State Recorder)	3D ultra-high-density packaging, additive manufacturing	Increased capacity and speed, decreased SWaP-C
Atmospheric Composition; RFI mitigation; RZSM/Sea Ice; weather	On board processors	50 MHz 32-bit ARM microprocessor	Rad-hard-by-design tools; 3D IC technology	Increased performance, decreased SWaP-C
Atmospheric Composition; RFI mitigation	ADCs and correlators	~3-GHz	Faster ADCs, ASIC polyphase spectrometers	ADC: BW >20 GHz (10 GHz I/Q), ENOB > 4, < 2W; Spectrometers: BW>20 GHz, 1 MHz resolution; BW 2-3 GHz, 128 channels, <2 W for RFI mitigation

Spacecraft Control & Communication

This category includes technology development needs for coordination of multiple spacecraft, adaptive tasking, and increased downlink capacity. These are summarized in

Table 3.26.

SmallSat constellations and formations

As noted above, constellations or formations of SmallSats have the potential to enable cost-effective global persistence, simultaneous spatially-extended measurements, and aperture synthesis. Multi-SmallSat concepts existed prior to the 2004 study and 2007 decadal survey and technological progress over the last decade has led to the successful deployment of several small-scale measurement and technology demonstration systems. A recent literature survey [*Bandyopadhyay et al.,* 2015] indicated that a large number of current multi-SmallSat mission concepts pertain to earth science applications, and that most concepts currently in development are constellations, not formations. Large-scale constellation coordination is still an area of active development, and formation flying, particularly with moderate to large numbers of satellites, is an emerging technology where investment may yield big payoffs.

Persistent global coverage will require development of constellation management capabilities including concept of operations (CONOPS) development for coordination, communication, and control of large numbers of satellites (potentially 100s or 1000s), along with onboard and ground processing capabilities to manage resources efficiently. Formation flying will require investments in onboard processing hardware and algorithms to allow real-time autonomous control, as well as development of hardware systems including low-SWaP position sensors, communication technology, and thrusters.

Table 3.26. Spacecraft communication and control technology development needs

Measurements	Technology	State of the Art	Development needed	Desired State
RZSM; global storm monitoring; hazard monitoring	SmallSat formation flying and constellation management	Constellations of ~tens of CubeSats with limited coordination; small (~2-3) CubeSat formations with ~1 m position control	System modeling; onboard processors and algorithms for real-time autonomous control; low SWaP-C position sensors/ metrology and COMM technology; long-life thrusters	Coordinate constellations of ~100s to ~1000s of sats; 3D attitude and formation control to ~cm level; ~year+ mission life
Precipitation / arctic monitoring; storms; hazard monitoring	Adaptive tasking	Latency ~ hours to days	Onboard processing, inter s/c links, CONOPS development	Rapid (~minutes) response to dynamic measurement environments
Surface deformation/high resolution SAR	Downlinks	~3-4 Gb/s	Investment in onboard processing HW, compression algorithms; RF and/or optical infrastructure	Measurements not limited by downlink

Adaptive tasking

The Autonomous Science Experiment on NASA's Earth Observing-1 satellite demonstrated that a space system could adaptively task itself based on a list of requested targets, and cloud cover prediction data. Some of the 2016 workshop participants expressed keen interest in expanding autonomous tasking capabilities – for single-instrument self-retasking and multi-spacecraft tipping and cueing – based not only on pre-provided data or rules, but in response to real-time collected data. Improved capabilities in this area will require investment in onboard processing hardware, inter-spacecraft communication, and CONOPS development.

To retask most efficiently, data processing, feature detection, decision making, and collection re-planning should occur without ground contact. While many data reduction algorithmic details would be instrument-specific, investment in versatile onboard processing hardware would benefit many potential adaptive measurement systems. Once an event has been detected and a response determined, that information may need to be communicated directly to other spacecraft, requiring efficient inter-spacecraft communication. Operational concepts must be developed to enable rapid information sharing (space-to-space or space-to-ground-to-space) and low-latency rescheduling. Standards, interfaces, and requirements can be developed without reference to specific instruments.

Downlink

Remote sensing instruments are expected to produce ever-increasing amounts of data. NISAR alone will downlink 3-4 Gbps, and is in fact downlink-limited (i.e., more science data could be collected if additional downlink capacity were available). Other planned high-rate systems (ICESat-2, LIST, etc.) may also approach ~Gbps levels. In some cases, onboard processing of raw data may be able to reduce downlink requirements (potentially at the cost of lost information). It seems clear, however, that downlink infrastructure capacity will need to increase to satisfy future measurement requirements.

Increased onboard data processing capability may help alleviate some downlink bottlenecks. Processed data products may be smaller than raw data. Onboard data compression may also reduce the size of data sets prior to downlink. Again, processing algorithms will generally be instrument-specific, but processing hardware development may have more general applicability. Research into compression algorithms (lossless and lossy) would also be of broader benefit.

Downlink infrastructure can be expanded with additional radio frequency (RF) channels, increased use of laser links, and increased numbers of ground stations. Laser communication systems have matured significantly in recent years. Since clouds are a fundamental issue with direct-to-ground links, MEO or GEO relays, along with a proliferation of ground stations would be required to take full advantage of the faster data rates optical communications allow. Partnering with commercial ventures may be a cost-effective avenue to explore.

Ground Processing

Once on the ground, data need to be stored, processed, and disseminated to users. None of these functions can be taken for granted in view of the rapid expansion in data volumes expected over the coming decade. Specific missions with known throughput will probably continue to require dedicated ground systems sized appropriately for the needs of that particular mission. NISAR, for example, will require ~petabyte/year storage and consistent ~TeraFLOPs processing capability. This constant, predictable level of processing is best accomplished on purpose-acquired servers, consistent with current paradigms.

Workshop participants however expressed a need for easy access to current and archival data from multiple missions for scientific study and exploitation, as well as a need for convenient code sharing and other collaborative activities. These capabilities will require investment in Big Data infrastructure. This may involve dedicated hardware or cloud storage and processing. Systems and protocols to store and access data from multiple sources (e.g., space-based instrument data, airborne data, buoy data, etc.) will need to be developed, as well as standards and interfaces to facilitate code/library sharing, data set identification and retrieval, and efficient data fusion. These ground enterprise needs are summarized in Table 3.27.

Table 3.27. Technology development needs related to ground processing

Measurements	Technology	State of the Art	Development needed	Desired State
All	Big Data storage and processing infrastructure	~Petabyte storage; ~TeraFLOPs processing	Architecture and interface to manage/access large data sets from multiple sources	Easy, user-friendly access to multi-source data
All	Standards and interfaces for code sharing and other collaboration	www sharing; local processing	Standards and interfaces for code sharing and other collaboration	Convenient algorithm/ software dissemination and sharing
All	Data fusion	Mission-dependent data formats, data locations, analysis tools	Interface to search and integrate multi-source data	Convenient data identification, access, and integration

3.3.4. Summary, Conclusions, and Recommendations

Numerous information technology and data handling needs were identified at the 2016 JPL and GSFC microwave workshops. Based on community inputs from these workshops, it appears that large scientific payoffs may result from advances in empirical, event-driven adaptive tasking and processing, constellation/formation control and exploitation, and the ability to handle large data sets. Advances in these areas will require investments in concept development, algorithm development, and hardware maturation as described in the preceding subsections.

Exact quantitative data handling requirements cannot be determined without reference to specific instruments. The imminent reevaluation of NASA's science goals for the next decade and the concomitant definition of instrument concepts should allow specific information technology requirements to be defined.

But in many cases, even without specific quantitative requirements and without specific, focused investment, technological development can still occur. However, R&D programs leading to data handling advances that may be generalized for wider benefit may be most beneficial. Funding projects that push the limits of current capabilities in the areas of onboard processing hardware and algorithms, tasking CONOPS, compressive sensing, formation modeling, inter-spacecraft metrology and communication, data compression, and RFI mitigation, for example, may have synergistic, transcendent effects. Additionally, planning for infrastructure upgrades to increase crosslink/downlink capacity, and ground storage, processing, and dissemination capabilities can begin ahead of the upcoming decadal survey. This may allow more capable mission designs with fewer downlink and ground data management limitations.

4. Emerging Technology

For the purpose of applying the concept of emerging technologies to Earth science measurement requirements, emerging technologies are defined as being at a maturity level TRL 3 or lower. It is further noted that TRL 2[1] is the entry point for ESTO's ACT (Advanced Component Technology) and AIST (Advanced Information Systems Technology) programs.

One of the most significant developments since the 2004 MWG report [*ESTO,* 2004] is the revolution of small satellite and hosted payload opportunities for Earth remote sensing, a trend strengthened by increasingly cost-constrained satellite development environments. As a result of both realities, reduced payload and mission SWaP-C are important for essentially all measurement proposals while at the same time it is necessary to demonstrate high science value. Reduction in SWaP can enable use of numerous new low-cost launch opportunities and thereby facilitate realization of new measurement scenarios that were not envisioned in 2004.

New capabilities created by small space-based platforms present many opportunities to facilitate missions and new measurement concepts. These opportunities are actively addressed as an emerging technology in the updated 2016 report. It is noted that increased access to space by universities and commercial interests may result in radically different approaches achieve new measurements and to extend existing measurements. As a result, trades between aperture size, transmit power, altitude, integration of multiple sensor operating bands and/or active/passive sensors sharing a single aperture will be needed in order to demonstrate 'best value' to achieve a measurement. These analyses will also require robust, high-fidelity modeling and simulation capabilities that accurately represent the critical elements in science and engineering, of trade e.g. horizontal and vertical spatial resolution; radiometric resolution or sensitivity, temporal resolution or revisit time as well as SWaP-C. The goal will be to closely couple technology needs to measurement needs and flow requirements using model-based engineering and system engineering principles.

Computational simulation tools for systems engineering can act as effective arbitrators of evolving technology options by enabling quantitative trades between measurement system parameters such as aperture size, receiver sensitivity and bandwidth, transmit power, and waveform generation that could mitigate technological hurdles. To be successful, this approach requires robust, high fidelity models and high performance computational algorithms in both the environmental and sensor performance domains.

An important consideration for microwave remote sensing is the impact of diffraction limited apertures on microwave instrument SWaP. Accordingly, one consequence of maintaining horizontal spatial resolution performance while reducing microwave payload size commensurate SmallSats is that a new class and smaller size (up to ~2m) deployable antennas may be required. However, for severely limited SWaP scenarios, stowed volume constraints may remain inconsistent with science measurement performance goals targeted for relevant microwave measurements. As a result, a best value goal for some microwave sensors and their respective

---

[1] Technology Readiness Levels (TRL) (http://esto.nasa.gov/technologists_trl.html)

deployed antenna size may be to pursue ESPA-class volumes as well as cube-sat 1 – 3U stowed volumes.

A summary of mapping of emerging technologies and their application to enable measurement scenarios for 2016 and beyond appears in Table 4.1.

Table 4.1. Technology availability gaps for future microwave Earth science measurement needs.

Capability Gap	**Measurements**	**TRL**
MMW and SMMW technology at ultra-low SWaP/ G-band transmitter technology (Radar)	GACM, PATH, Cloud Characterization, and Humidity profiles	2
SMMW technology at ultra-low SWaP	Cloud Ice and Atmospheric Processes	2
RFI Mitigation improvements	Wideband spectrometer/algorithms	2-3
Integrated Radar/Radiometer or multi-frequency Front-ends	Root Zone/Sea Surface Salinity/Air Sea Flux	2-3
Very large antennas	Weather radar, hazard warning surface deformation, volcanic activity, ice	2
Inter-spacecraft metrology for formation control (aperture synthesis in formation flying)	Root zone soil moisture	2
High-speed, high-resolution correlators /spectrometers	Atmospheric composition; RFI mitigation	2-5
Constellation management for small satellites: platform reliability, data routing and management, system engineering tools	Root Zone Soil Moisture, Precipitation, Atmospheric Humidity	2

A summary of emerging technologies as they relate to three separate aspects of microwave sensors supporting Earth science measurements is shown in

Table 4.2.

Table 4.2. Emerging technology roll-up and summary by frequency band.

	P- /S-band 400-MHz to 2-GHz	C- /W-band 6- to 90-GHz	W- /G-band 100- to 200-GHz	SMMW 300-GHz to 1-THz
Measurement	Root Zone SM; SSS;	OSWV; SST; Imagery Ocean Altimetry; IWV, Atmospheric Sounding; Cloud Amount; SWE	Atmospheric Temperature and water vapor profiles	Cloud characterization; cloud Ice
Antenna/ Aperture	Up to 10m aperture vs. distributed correlation systems; Larger antennas for radar	Up to 7m aperture(s); multi-band FPA; cylindrical / offset parabola; STAR at GEO	Deployable 2m dia from 2.5U stowed volume – various altitudes	Deployable up to 1m – various altitudes
Radiometer	RFI mitigation – tunable notches, broadband radiometers; frequency agile	Low SWaP-C radiometers integrate-able with Radar systems	Low SWaP-C radiometers; Low power LOs; Direct detection; filter technology	Low SWaP-C radiometers; low power LOs; direct detection; LNA performance
Radar	T/R modules – extend down to P-band	C-/X-band Mature; Ka and higher band GaN T/R Modules	GaN T/R modules for higher efficiency; HPAs, very small SSPAs	N/A
Platform	3-D ranging; formation flying; UAV	Reliable 5yr cube-sat bus; UAV; imaging on demand (hurricanes/ storms);	Reliable 5yr cube-sat bus; higher power;	Reliable 5yr cube-sat bus; higher power;
IT/ Data Processing	Multi-sensor processor: Passive/Active/ SoOp	Small sat data transmission;	Small sat data transmission;	Small sat data transmission;

4.1. Radar Technology

Emerging technologies to support radar measurements through the next decade focus on continuing improve performance vs. reductions in size, weight, power and cost. Many technology needs are related to phased array antennas or array feeds for reflectors. Much development at all frequency bands is focused on single-chip MMIC based T/R modules, which are smaller, lighter and potentially less expensive to manufacture in large number. Another key technology area is space-qualified, high bandwidth integrated digital subsystems.

T/R modules under development can be separated into low power versions intended for phased arrays, and high power versions intended for array feeds for reflectors. Important properties of T/R modules include phase stability and T/R isolation, along with transmit efficiency and LNA noise figure. The advantages for single-chip MMICS are most important for phased array antennas where very large numbers of T/R modules are required, and for multi-band feeds, where small size enables tight spacing.

The use of large phased array antennas in space has been limited by the high structure mass required to maintain surface tolerance of 1/20 of a wavelength over the full array. Lightweight, small T/R modules do not solve this problem for rigid structures. For this reason, use of phased arrays can be enabled by development of lightweight structures such as membranes and shape memory polymers. This in turn will necessitate development of adaptive wavefront sensing to compensate for non-rigid structures. For array structures of this type, thermal control and power distribution, as well as small lightweight T/R modules to enable roll or fold up are key technologies. Non-rigid, lightweight structure technology also applies to reflectors at W- and G-band, where it is difficult to maintain the very tight surface tolerance required.

Among the greatest challenges for new measurements is producing sufficient transmit power and amplifier efficiency at frequencies at and above Ka-band. For phased arrays and array feeds, improving SSPA efficiency will both reduce spacecraft prime power and mitigate thermal control problems. For systems that utilize individual high power amplifiers such as EIKAs, it is important to reduce the mass of high voltage power supplies and improve efficiency. This is especially important for W- and G-band measurements.

Table 4.3. Emerging technology roll-up for radar

Technology Area	Measurement	State-of-the-Art	Notional Requirements
T/R modules	All	100 W @ L-band 1 W @ W-band	200 W @ L-band 1 W @ G-band η=70% @ L-band
Large non-rigid antenna structures	RZSM; surface deformation, land topography	10 m class rigid	30 m class non-rigid
Transmit power generation	Cloud characterization, river discharge	2 kW EIKA @ W-band	500 TWT @ Ku-band 10 kW @ W-band
CubeSat / SmallSat, SoOp	Precipitation, water vapor, ocean surface wind vector	0.7 m antenna from 2U	1.5 m antenna from 2U
Digital Backend-Transmit & Receive	All, mainly high data rate instruments such as SAR	NISAR digital calibration; single NCO-based Tx waveform generation	Combined digital Tx/Rx: multiple, agile AWGs mated with multiple digitally calibrated Rx

It is important to understand measurement limitations for emerging radar technologies such as signal-of-opportunity (SoOp) based bistatics, G-band radar systems, and CubeSat and SmallSat based systems. New measurements that utilize multiple look angles and tomographic techniques should have their requirements flowed down to electronics and antenna technology needs.

4.2. Radiometer Technology

Emerging technologies to facilitate radiometric measurements for Earth science through the next decade involve improving performance vs. size, weight, power, and cost of high frequency solid-state devices including Monolithic Microwave Integrated Circuits MMICs (Table G.1). A variety of devices including Low Noise Amplifiers (LNAs), low power Local Oscillators (LOs) for heterodyne receivers, detectors with improved sensitivity and stability at frequencies above W-band, higher Q filters to support improved selectivity using direct detection receiver schemes, and efficient isolators above W-band are examples. Lower TRLs are driven by the need for significant improvements are required in order to fully realize the potential the recent explosion of low-cost launch opportunities for SmallSats. Performance goals can be found in Table G.1 and include LNA performance at frequencies >200-GHz, LO sources >100-GHz, detectors operating >100-GHz and Micro-Electro Mechanical Systems (MEMS) aided filter and isolation technology.

New technologies and instrument system design to enable combined active/passive systems with a goal to utilize common apertures and electronics with significantly reduced SWaP (Size Weight and Power) could greatly benefit and enable Earth science measurements that require combined instruments and multiple RF bands. Lightweight structures and structural elements to accommodate active and passive multi-frequency feed systems technologies may also be high pay-off items if project goals can accommodate the necessary period for maturing the technology (Tables G.2 – Table G.4). Deployable antennas with up to ~2m apertures and stow-able to dimensions of CubeSats (~1.5) may also have high value after establishing maturity, performance and reliability. Other aspects of emerging antenna technology directed at achieving performance goals outlined in Table G.4 include additive manufacturing techniques (in-space construction), and improved antenna metrology.

The ready availability of small satellite platforms and launch opportunities has enabled new and competing concepts, including many that are still nascent, to address some of the more challenging Earth science measurements identified in the 2007 decadal survey [*ESTO,* 2007] as well as the current 2016 report. As a result, there is a new and substantial need for understanding costs, benefits, and liabilities of adopting a ‘traditional’ vs. ‘newly enabled’ path for these measurements at the systems and mission level. Considering the cost constrained development environment common for remote sensing, this a critical step for gaining required consensus view. This realization, places a new emphasis on end-to-end system engineering and trade study analysis.

Improvement of radiometer calibration and inter-calibration is an important aspect to enable future Earth science measurements supporting a wide range of applications including climate and weather. Partial traceability to an SI-standard, usually through calibrated temperature sensors on a blackbody target is the current state-of-the-art. Complete traceability to an SI standard has so far eluded the microwave radiometry community. Although calibration and radiometric stability has continued to improve to support more demanding applications, new applications involving constellations of radiometers to achieve new levels of spatiotemporal sounding will also require further improvements in calibration consistency and inter-calibration stability. Future concepts involving N>100 or perhaps N>1000 will reasonably need to exhibit new standards of predictable and reliable calibration. Therefore, a highly systematic approach to pre-launch and post-launch calibration will need to be developed, greatly extending the current best practice approach. One path to address new calibration requirements is to continue to develop a direct SI-traceable calibration for microwave radiometers [*Houtz et al.,* 2014]. New and end-to-end calibration techniques could also be extended to consider UAV and STAR radiometers which provide additional and unique calibration challenges. The above points are also summarized in Table G.5 in the Appendix.

New technology applicable to microwave radiometers designed for future Earth science measurements assessed with TRL~3 or higher, also includes techniques to extend polarimetric measurements to W-band and higher frequencies, improvements implementing digital receiver back-end electronics including realization of ultra-wideband radiometers with RFI mitigation technology. A summary of emerging technology generally assessed at TRL~3 and below, for microwave radiometry is summarized in Table 4.4 below.

Table 4.4. Emerging technology roll-up for microwave radiometers

Technology Area	Measurement	State-of-the-Art	Notional Requirements
High frequency Microwave Component technology	Clouds and precipitation, Atmospheric Composition, Humidity and Temperature	183-GHz 500K Tsys; 100mW LO; η=10% W-band detectors	900-GHz 500K Tsys; 100mW LO; η=40% >G-band detectors WG Filters >300 GHz
Integrated Systems	RZSM; Precipitation; Air-Sea-Flux; Altimetry	Separate instrument systems	Combined higher level of integration, aperture sharing, common FPAs
Large Aperture	RZSM; Precipitation; Land Surface	6m+ class deployable from rocket faring; 0.7m deployable from 1.5U f > 40-GHz for comm.	Performance to ~600 GHz at 2m diameter deployable from 2.5U; 10m class to W-band;
Uniform and stable calibration for small radiometers; SI-traceable calibration	Temperature profile; Precipitation; Water vapor Ocean surface Clouds	Individual radiometer calibration assessments; cross calibration analysis required with other radiometers	Uniform calibration between fleet sensors; N>>10 radiometers all traced to SI-standard

4.3. Information Processing Technology

As described in Section 3.3, a number of information technology development areas were identified in the present study. The least mature, but most promising emerging technologies relate to SmallSat formation flying and constellation management, adaptive resource allocation, and next-generation ground infrastructure development.

Constellations or precise formations of SmallSats can replace larger, more expensive systems, enabling affordable global persistence, simultaneous spatially distributed measurements, and sparse aperture synthesis. Constellations of as many as 28 CubeSats have flown, but these systems have involved little to no active coordination between constellation members. Formation flying of 2-3 CubeSats has been demonstrated with ~1 m station-keeping. Technology development to enable coordination between constellations of ~100s to ~1000s of SmallSats and formation control with ~cm-level precision will be necessary for persistence and aperture synthesis applications. A number of hardware challenges exist, including low-SWaP position sensors, long-life thrusters, and miniaturization of communications technology. These systems will also require data handling technology development to enable real-time autonomous formation control (onboard processing of metrology inputs, calculation of positioning maneuvers, inter-spacecraft communication, etc.).

Adaptive tasking is another emerging information processing concept, involving real-time reallocation of sensor resources in response to empirical detections of features or events in collected data. A system might alter its spectrum usage in response to detected RFI, for example, or tip off other observation systems in response to detected volcanic activity. Limited autonomous tasking has been demonstrated, but technology development in onboard processing and inter-spacecraft communication is needed to expand this capability. Standards, interfaces, and operational concepts must also be developed to enable rapid information exchange, target prioritization, and low-latency rescheduling.

These technologies are readily combined – SmallSat constellations are well suited to adaptive tasking scenarios. For example, an inexpensive LEO CubeSat constellation with high revisit rates might be used to make an initial coarse detection of a time-sensitive event (e.g., storm formation) and trigger collection by a more capable GEO system. This paradigm takes the burden of wide-area search off of the more expensive GEO asset, freeing it up for longer or more frequent dwells on areas of interest.

Future earth science measurement systems are expected to produce very large amounts of data. Managing these large data sets and making them easily available to scientific users will require next-generation Big Data ground infrastructure. Whether this involves dedicated hardware or cloud storage and processing, standards and interfaces must be developed to facilitate code sharing, data mining, and fusion of data from multiple sources.

Table 4.5. Emerging technology roll-up for information and data processing

Technology Area	Measurement	State-of-the-Art	Notional Requirements
SmallSat formation flying and constellation management	Clouds / precipitation; Atmospheric Composition; RZSM; global storm monitoring; hazard monitoring	Constellations of ~tens of CubeSats with limited coordination; small (~2-3) CubeSat formations with ~1 m position control	Coordinate constellations of ~100s to ~1000s of sats; 3D attitude and formation control to ~cm level; ~year+ mission life
Adaptive tasking	Precipitation / arctic monitoring; storms; hazard monitoring	Latency ~ hours to days	Rapid (~minutes) response to dynamic measurement environments
Big Data ground enterprise	All	Mission-specific storage, processing, dissemination, archiving	Integrated access to multi-source data; facilitated collaboration

5. Summary and Path Forward

The previous chapters have reviewed the state-of-the art in the areas of active and passive microwave Earth remote sensing along with their supporting information and data processing systems. An overview of current technology challenges and needs for NASA's Earth science measurement goals has also been provided. It is noted that given the limited resources of the technology program there is a need for prioritization. In the 2004 microwave working group report [*ESTO*, 2004], technology investment prioritization was based on the following criteria (the science value has the highest ranking of all prioritization criteria).

1. *Scientific Value*:
    a. *Measurement Importance* – The importance is rated only within a science focus area by NASA HQ program managers and as it appears on the NASA Earth science roadmaps [reference].
    b. *Measurement timeline* – The timeline is determined by Earth science roadmaps and other relevant documents [reference]
2. *Candidate Scenario Value:*
    a. *Scenario Uniqueness* – Unique capabilities that a particular scenario offers to meet science requirements
    b. *Scenario relevance* – Whether the scenario meets or exceeds the threshold and goal science needs as discussed in Chapter 2.
3. *Technology Value:*
    a. *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).
    b. *Utility* – The number of measurement parameters that are served by a given technology.

These criteria remain valid in developing a robust technology development portfolio and indeed were used in the prioritization of the technology investment portfolio by ESTO. The Earth Science Decadal Survey of 2007 outlined the scientific measurements that were of priority I three distinct tiers [*NRC*, 2007]. Recommended measurements that required microwave active and passive technology investments were: ACE (aerosols and clouds), NISAR (surface topography – formerly DESDynI), XOVWM (sea surface winds), SWOT (water surface topography), SCLP (cold land processes), SMAP (soil moisture), PATH (precipitation), GACM (global circulation). The ESTO microwave technology investment strategy was aligned with scientific measurement priorities to support these missions.

Of the 2007 decadal recommended missions, SMAP launched in January 2015, and SWOT and NISAR have passed KDP-B with a 2020 scheduled launch date. It is noted that XOVWM has not launched although its predecessor, QuickScat [*NASA (2016c)*, *Ebuchi et al., 2002*] stopped collecting data in 2009. While technology development for XOVWM may still exist, RapidScat, a temporary replacement for QuickScat, was launched in September 2014 [*Ebuchi, (2015)*] and is planned to operate on the ISS until 2017 [*NASA, (2016b)*].

While much R&D has been invested in the last decade to enable many of the above measurements associated with the tiered missions (e.g. ACE, SWOT, PATH and GACM), implementation of the measurements has been limited by system TRLs including lack of space-qualification (e.g. GeoSTAR/PATH). In the meantime, potential alternative methods using SmallSats for carrying out the necessary PATH measurements are gaining more serious consideration. For GACM, technology improvements to RF front-end receivers and back-end digital spectrometers collectively aimed at improving the performance of limb sounding are underway that may be leveraged to meet the necessary science goals.

If the Decadal Survey of 2017 affirms the importance and priority of the above measurements, then the ESTO investment strategy should be accordingly harmonized by assigning higher priority to maturation of the related microwave technologies through a combination of focused investments and leveraging of prior microwave technology investments by other government agencies and international partners. Closer partnerships are needed in order to enable future Earth science microwave missions.

Because the scientific direction of the 2017 Decadal Survey and the priorities they will levy on measurements are unclear at the time of this writing, assessments contained herein were solely based on the current state-of-the-art, emerging trends, and priorities of the 2007 Decadal Survey. The ESTO microwave sensor technology investment strategy will be revised once the 2017 Decadal Survey recommended priorities become known.

6. References

Bandyopadhyay, S., et al. "A Review of Impending Small Satellite Formation Flying Missions," 53rd AIAA Aerospace Sciences Meeting, AIAA SciTech, (AIAA 2015-1623), 2015

Barath, F., et al. "The Upper Atmosphere Research Satellite microwave limb sounder instrument," J. Geophys. Res., **98**, D6, pp. 10,751-10,762, 20 Jun 1993. doi: 10.1029/93JD00798

Bradley, D., J. M. Morris, T. Adlai, J. T. Johnson, and M. Aksoy, "On the Detection of RFI Using the Complex Signal Kurtosis in Microwave Radiometry," Proceedings of the 13th Specialist Meeting on Microwave Radiometry and Remote Sensing of the Environment (MicroRad 2014), pp. 33-38, Pasadena, CA

Brown, S., P. Focardi, A. Kitiyakara, F. Maiwald, O. Montes, S. Padmanabhan, R. Redick, D. Russell, and J. Wincentsen, "The Compact Ocean Wind Vector Radiometer: A New Class of Low-Cost Comically Scanning Satellite Microwave Radiometer System," American Met. Soc. Ann. Meeting, Sat. Tech. Adv., 30th Conf. Environ. Info. Proc. Tech., Atlanta GA. 2014

Chapin, E., A. Chau, J. Chen, B. Heavey, S. Hensley, Y. Lou, R. Machuzak, and M. Moghaddam, "AirMOSS: An Airborne P-band SAR to Measure Root-Zone Soil Moisture," Proc. Int. Geosci. Remote Sensing Symp. (IGARSS 2012), pp. 0693 – 0697, 2012.

DLR (2010) TerraSAR-X and TANDEM-X, http://www.dlr.de/eoc/en/desktopdefault.aspx/tabid-5511/9218_read-17741/

Draper, D. W., D. A.; Newall, F. J. Wentz, S. Krimchansky, G. M. Skofronick-Jackson, "The Global Precipitation Measurement (GPM) Microwave Imager (GMI): Instrument Overview and Early On-Orbit Performance," IEEE J. Selected Topics Appl. Earth Obs. Remote Sens., 8(7), pp 3452 – 3462, 2015, doi 10.1109/JSTARS.2015.2403303

Durden S. L., S. Tanelli, L. Epp, D. Esteban-Fernandez, H. Fang, V. Jamnejad, R. Perez, A. Prata, L. Samoska, 2010: "A cloud and precipitation radar system concept for the ACE mission", International Geosc. Remote. Sens. Symposium 2010, Honolulu, Hawaii, July 30, 2010.

Durden, S. L., Tanelli, S., Epp, L. W., V. Jamnejad, E. M. Long, R. M. Perez, and A. Prata, "System Design and Subsystem Technology for a Future Spaceborne Cloud Radar", IEEE Geosci. Remote Sens. Ltrs. **13**(4), pp. 560 – 564, April 2016, doi: 10.1109/LGRS.2016.2525718

Ebuchi, N., H. C. Graber and M. J. Caruso, "Evaluation of wind vectors observed by QuikSCAT/SeaWinds using ocean buoy data," J. Atm. Oceanic Tech. **19**, pp. 2049—2062, (2002)

Ebuchi, N., "Evaluation of marine vector winds observed by rapidscat on the international space station using statistical distribution," *Proc. 2015 IEEE International Geoscience and Remote Sensing Symposium (IGARSS)*, Milan, Italy; 2015 July 26-31 4901-4904.

Entekhabi, D., et al., "The Soil Moisture Active Passive Mission (SMAP) Mission," *Proc. IEEE*, Vol **98** (5), pp. 704 – 716, doi:10.1109/JPROC.2010.2043918

ESTO (2004), Working Group Report: Active and Passive Microwave Technologies, NASA Earth Science Technology Office report (D. Evans, D. Glackin, D. Kunkee and A. Valinia eds.), esto.nasa.gov/files/MWGReport2004.pdf

Focardi, P., P. Brown, Y. Rahmat-Samii, “A 6-m mesh reflector antenna for SMAP: Modeling the RF performance of a challenging Earth-orbiting instrument” 2011 IEEE International Symposium on Antennas and Propagation (APSURSI), pp. 2987 – 2990, 2011. doi: 10.1109/APS.2011.5997157

Gaier, T., A. Tanner, P. Kangaslahti and B. Lim, “The Correlation Radiometer- A New Application in MM-Wave Total Power Radiometry,” Proc. 2013 IEEE Int. Geosci. Remote Sens. Symposium (IGARSS), pp. 1924 – 1926, 2013.

Gaiser, P. W., et al, “The WindSat spaceborne polarimetric microwave radiometer: sensor description and early orbit performance,” *IEEE Trans. Geosci. Remote Sens*., **42**(11), pp. 2347 – 2361, 2004, doi: 10.1109/TGRS.2004.836867

Guerci, J., and E. Jaska, *Proc. IEEE International Symposium on Phased Array Systems and Technology*, pp 45 – 51, 14-17, Oct 2003.

Houtz, D. A., D. K. Walker, D. Gu., “Progress towards a NIST microwave brightness temperature standard for remote sensing,” Microwave Measurement Conference (ARFTG), 2014 84th ARFTG, pp. 1 – 4, 2014, doi: 10.1109/ARFTG.2014.7013422

Iguchi, T., H. Hanado, N. Takahashi, S. Kobayashi, S. Satoh, “The dual-frequency precipitation radar for the GPM core satellite,” Proc. 2003 International Geoscience Remote Sensing Symposium, **3**, pp 1698 – 1700, 2003

JAXA (2006), Advanced Land Observing System, http://www.eorc.jaxa.jp/ALOS/en/about/palsar.htm

Jiang J. H., *et al*., “Evaluation of cloud and water vapor simulations in CMIP5 climate models using NASA ‘A-Train’ satellite observations,” J. Geophys. Res., **117**, D14105, 2012 doi:10.1029/2011JD017237

Kangaslahti, P., A. Tanner, D. Pukala, T. Gaier, B. Lambrigtsen, B. Lim, X. Mei, and R. Lai, “Miniature MMIC Low Mass/Power Radiometer Modules for the 180 GHz GeoSTAR Array,” NASA ESTO Earth Science Technology Forum, 2010, https://esto.nasa.gov/conferences/estf2010/papers/Kangaslahti_Pekka_ESTF2010.pdf

Lai, R., X. B. Mei, W.R. Deal, W. Yoshida, Y. M. Kim, P.H. Liu, J. Lee, J. Uyeda, V. Radisic, M. Lange, T. Gaier, L. Samoska, A. Fung, “Sub 50 nm InP HEMT Device with Fmax Greater than 1 THz,” Proc. IEEE Electron Devices Meeting, 10-12 Dec. 2007, Washington, DC, pp. 609 - 611.

Lambrigtsen, B., S. T. Brown, T. C. Gaier, L. Herrell, P. Kangaslahti, and A. B, Tanner, “Monitoring the Hydrologic Cycle With the PATH Mission,” *Proc. IEEE*, **98** (5), pp. 862 – 877, 2010 doi: 10.1109/JPROC.2009.2031444

Le Vine, D. M., G. S. E. Lagerloef, and S. E. Torrusio, “Aquarius and Remote Sensing of Sea Surface Salinity from Space,” *Proc. IEEE*, **98** (5), pp. 688 – 703, 2010 doi: 10.1109/JPROC.2010.2040550

Manney, G. L., et al., “Unprecedented Arctic ozone loss in 2011,” Nature, 478(7370) pp. 469-475, Oct 2, 2011

Mei, X. B., W. Yoshida, W. Deal, P.H. Liu, J. Lee, J. Uyeda, L. Dang, J. Wang, W. Liu, D. Li, M. Barsky, Y. M. Kim, M. Lange, T. P. Chin, V. Radisic, T. Gaier, A. Fung, R. Lai, 35nm InP HEMT for Millimeter and Sub-Millimeter Wave Applications,” 2007 Int. Conf. on Ind. Phosph. & Rel. Mat., 14-18 May 2007, pp.59 - 62

Meissner, T., and F. Wentz, "Ocean Retrievals for WindSat," Proc. 8th Specialist Meeting on Microwave Radiometry and Remote Sensing Applications (MicroRad 2006), San Juan, PR, 2006, doi: 200610.1109/MICRAD.2006.1677074

Misra, S., A. Tkacenko, S. Gowda, R. Jarnot, and S. Brown, "Implementation of a flexible wide-band on-board radio frequency interference mitigating digital back-end radiometer system," Radio science Meeting (USNC-URSI NRSM), 2014 US National Committee of URSI, 2014, doi: 10.1109/USNC-URSI-NRSM.2014.6928042

Moghaddam, M., Y. Rahmat-Samii, E. Rodriguez, D. Entekhabi, J. Hoffman, D. Moller, L. Pierce, S. Saatchi, and M. Thomson, "Microwave Observatory of Subcanopy and Subsurface (MOSS):A mission Concept for Global Deep Soil Moisture Observations," *IEEE Trans. Geosci Remote Sens.* **45**(8), pp2630 – 2643, Aug. 2007.

NASA (2014), Global Precipitation Measurement overview, http://www.nasa.gov/mission_pages/GPM/overview/index.html

NASA (2014a): Outstanding Questions in Atmospheric Composition, Chemistry, Dynamics and Radiation for the Coming Decade, Jacob D., E. Fischer, R. Gao, K. Rosenlof, J. Mace, S. Massie, J. Reid, C. Dutcher, B. Wielicki, P. Zuidema, P. Newman, W. Robinson, R. Houze, M. Barth, M. Coffey, R. Eckman, K. Jucks, H. Maring, A. Pszenny, https://espo.nasa.gov/home/sites/default/files/documents/SMDWorkshop_report_final.docx

NASA, (2015), Workshop Report on Scientific Challenges and Opportunities in the NASA Weather Focus Area. X. Zeng, S. Ackerman, R.D. Ferraro, J.J. Murray, S. Pawson, C. Reynolds and J. Teixeira, eds.

NASA (2015a), *SMAP Soil Moisture Active Passive*, http://smap.jpl.nasa.gov/

NASA (2015b), QuickScaterometer, https://winds.jpl.nasa.gov/missions/quikscat/

NASA (2015c), Shuttle Radar Topography Mission, http://www2.jpl.nasa.gov/srtm/

NASA (2016), Ocean Surface Topology from Space, https://sealevel.jpl.nasa.gov/

NASA (2016a), *NASA-ISRO SAR Mission (NISAR),* http://nisar.jpl.nasa.gov/

NASA (2016b), NASA Internal Space Station (ISS) http://www.nasa.gov/mission_pages/station/research/experiments/1067.html

NASA (2016c) NASA QuickScat, https://winds.jpl.nasa.gov/missions/quikscat/

NOAA (2016), Advanced Technology Microwave Sounder, http://www.jpss.noaa.gov/atms.html

NOAA (2016a), Cross Track Infrared Sounder, http://www.jpss.noaa.gov/cris.html

NRC (2007*), Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond,* (National Academies Press, Washington DC), www.nap.edu/catalog/11820.html

NRC (2007a), *ibid*., p. 91.

NRC (2010), *Spectrum Management for Science in the 21st Century*, National Research Council http://www.nap.edu/catalog/12800/spectrum-management-for-science-in-the-21st-century

Olsson, R. (2016) "Arrays and Commercial Timescales,", Defense Advanced Research Projects Agency (DARPA), http://www.darpa.mil/program/arrays-at-commercial-timescales

Peral, E., S. Tanelli, Z. Haddad, O. Sy, and G. Stephens, "Raincube: A proposed constellation of precipitation profiling radars in CubeSat," *Proc. 2015 IEEE International Geoscience and Remote Sensing Symposium (IGARSS)*, pp. 1261 – 1264, 2015. doi: 10.1109/IGARSS.2015.7326003

Plagge, A. M., D. Vandemark, and B. Chapron, "Examining the Impact of Surface Currents on Satellite Scatterometer and Altimeter Ocean Winds," J. Atmos. Oceanic Tech., **29**, pp. 1776 – 1793, 2012. Doi: 10.1175/JTECH-D-12-00017.1

Randa, J., D. K. Walker, M Francis, and K. MacReynolds., "Linking Microwave Remote-Sensing Measurements to Fundamental Noise Standards," Precision Electromagnetics Digest, 2004 Conference, pp 465 – 466, doi: 10.1109/CPEM.2004.305312

Ruan, W., A. B. Milstein, W. Blackwell, E. Miller, "Estimation Theoretic Methods for Cubesat Data Interpolation in the Presence of Geolocation Errors," Proc. 2015 IEEE International Geoscience and Remote Sensing Symposium (IGARSS), pp. 5 – 8, 2015. doi: 10.1109/IGARSS.2015.7325683

Tanner, A. B., W. J. Wilson, B. H. Lambrigsten, S. J. Dinardo, S. T. Brown, P. P. Kangaslahti, T. C. Gaier, C. S. Ruf, S. M. Gross, B. H. Lim, S. B. Musko, S. A. Rogacki, and J. R. Piepmeier, "Initial Results of the Geostationary Synthetic Thinned Array Radiometer (GeoSTAR) Demonstrator Instrument," *IEEE Trans. Geosci. Remote Sens.,* **45** (7), pp. 1947 – 1957, July 2007 doi: 10.1109/TGRS.2007.894060

A. Workshop/Community Forum Info

JPL Microwave Workshop 1/21/2016

Location: **NASA Jet Propulsion Lab, Pasadena, CA**

Figure 11. Image taken at 2016 JPL Microwave Technology Workshop

Attendees:

Name	Organization	Email
Brown, Shannon	JPL	shannon.t.brown@jpl.nasa.gov
Bue, Brian	JPL	bbue@jpl.nasa.gov
Castano, Rebecca	JPL	rebecca.castano@jpl.nasa.gov
Chandler, Adam	The Aerospace Corporation	adam.chandler@aero.org
Chattopadhyay, Goutam	JPL	goutam@jpl.nasa.gov
Cooper, Ken	JPL	ken.b.cooper@jpl.nasa.gov
Deal, Bill	Northrop Grumman	william.deal@ngc.com
Doiron, Terry	NASA GSFC	terence.a.doiron@nasa.gov
Fernandez, Daniel	JPL	daniel@jpl.nasa.gov
Fung, Andy	JPL	andy.fung@jpl.nasa.gov
Gaier, Todd	JPL	todd.gaier@jpl.nasa.gov
Garrison, Jim	Purdue University	jgarriso@ecn.purdue.edu
Haddad, Ziad	JPL	zsh@jpl.nasa.gov
Hensley, Scott	JPL	scott.hensley@jpl.nasa.gov
Hodges, Richard	JPL	richard.E.Hodges@jpl.nasa.gov
Hoffman, Jim	JPL	hoffman@jpl.nasa.gov
Hyon, Jason	JPL	jason.hyon@jpl.nasa.gov
Im, Eastwood	JPL	eastwood.im@jpl.nasa.gov

Name	Organization	Email
Jarnot, Robert	JPL	robert.f.jarnot@jpl.nasa.gov
Kangaslahti, Pekka	JPL	pekka@jpl.nasa.gov
Kantrowitz, Frank	The Aerospace Corporation	frank.kantrowitz@aero.org
Kunkee, David	The Aerospace Corporation	david.kunkee@aero.org
Lambingtsen, Bjorn	JPL	lambingtsen@jpl.nasa.gov
Lavalle, Marco	JPL	marco.lavelle@jpl.nasa.gov
Lim, Boon	JPL	bhlim@jpl.nasa.gov
Livesey, Nathaniel	JPL	Nathaniel.livesey@jpl.nasa.gov
Lou, Yunling	JPL	yunling.lou@jpl.nasa.gov
Lowe, Steven	JPL	steve.lowe@jpl.nasa.gov
Mannuci, Anthony	JPL	anthony.j.mannuci@jpl.nasa.gov
Mayo, David	The Aerospace Corporation	david.b.mayo@aero.org
Mehdi, Imran	JPL	imran.mehdi@jpl.nasa.gov
Misra, Sidharth	JPL	sidharth.misra@jpl.nasagov
Moussession, Alina	JPL	alina.moussession@jpl.nasa.gov
Norton, Charles	JPL/ESTO	charles.norton@jpl.nasa.gov
Padmanabhan, Sharmila	JPL	spadmana@jpl.nasa.gov
Pellegrino, Sergio	Caltech	sergiop@caltech.edu
Peral, Eva	JPL	eperal@jpl.nasa.gov
Pett, Todd	Ball Aerospace	tpett@ball.com
Rahmat-Samii, Yahya	UCLA	rahmat@ee.ucla.edu
Rodriguez, Ernesto	JPL	ernesto.rodriguez@jpl.nasa.gov
Samoska, Lorene	JPL	lorene.samoska@jpl.nasa.gov
Sanghavi, Suniti	JPL	sanghavi@jpl.nasa.gov
Spencer, Michael	JPL	michael.w.spencer@jpl.nasa.gov
Stephens, Graeme	JPL	graeme.stephens@jpl.nasa.gov
Tanelli, Simone	JPL	simone.tanelli@jpl.nasa.gov
Tanner, Alan	JPL	alan.b.tanner@jpl.nasa.gov
Valinia, Azita	NASA/ESTO	azita.valinia@nasa.gov
Wye, Lauren	SRI	lcwye@stanford.edu
Yueh, Simon	JPL	simon.yueh@jpl.nasa.gov

GSFC Microwave Workshop 1/28/2016

Location: **USRA headquarters 7178 Columbia Gateway Dr., Columbia, MD 21046**

Figure 12. Image taken at 2016 GSFC Microwave Technology Workshop

Attendees:

Name	Organization	Email
Bradley, Damon	NASA/GSFC	damon.c.bradley@nasa.gov
Chandler, Adam	Aerospace Corporation/Data Systems	adam.chandler@aero.org
DeAmici, Giovanni	NASA/GSFC	giovanni.geamici@nasa.gov
Deshpande, Manohar	NASA/GSFC	manohar.d.deshpande@nasa.gov
Doiron, Terence	NASA/GSFC	terence.doiron@nasa.gov
Ehsan, Negar	NASA/GSFC	negar.ehsan@nasa.gov
Emory, Amber	NASA/GSFC	amber.emory@nasa.gov
Hyon, Jason	NASA/JPL	jason.hyon@jpl.nasa.gov
Kantrowitz, Frank	The Aerospace Corporation	frank.kantrowitz@aero.org
Kim, Ed	NASA/GSFC	ed.kim@nasa.gov
Komar, George	NASA/ESTO	george.komar@nasa.gov
Kunkee, David	The Aerospace Corporation	david.kunkee@aero.org
Li, Hsin	NASA/GSFC	hsin.a.li@nasa.gov
Li, Lihua	NASA/GSFC	Lihua.li@nasa.gov
Mayo, David	Aerospace Corporation	david.b.mayo@aero.org
Nguyen, Diep	NASA/GSFC	diep.t.nguyen-1@nasa.gov
Osmanoglu, Batuhan	NASA/GSFC	batuhan.osmanoglu@nasa.gov
Park, Richard	Northrop Grumman	richard.park@ngc.com
Piepmeier, Jeff	NASA/GSFC/550	jeff.piepmeier@nasa.gov

Name	Organization	Email
Racette, Paul	NASA/GSFC	paul.e.racette@nasa.gov
Rincon, Rafael	NASA/GSFC	rafael.rincon@nasa.gov
Spence, Thomas	Northrop Grumman	thomas.spence@ngc.com
Thompson, Willie	Morgan State University	willie.thompson@morgan.edu
Valinia, Azita	NASA/ESTO	azita.valinia@nasa.gov
Vega, Manuel	NSAS/GSFC	manuel.vega@nasa.gov
Wong, Mark	NASA/GSFC	mark.wong@nasa.gov
Wu, Dong	NASA/GSFC	dong.l.wu@nasa.gov

Microwave Technology Virtual Community Forum 3/17/2016

Link to Microwave Core Team Presentation:
https://esto.nasa.gov/MicrowaveStrategies/MicrowaveCommunityForumCharts.pdf

Event Agenda -

EDT/PDT:

- **11:00/08:00 Welcome/Overview of ESTO Investment Strategy Update (A. Valinia, NASA/ESTO)**
- **11:20/08:20 State-of-the-Art and Future Requirements in Radar (F. Kantrowitz, Aerospace)**
- **12:20/09:20 State-of-the-Art and Future Requirements in Microwave Radiometry (D. Kunkee, Aerospace)**
- **13:20/10:20 *Break***
- **13:35/10:35 Data and Information Processing Future Requirements (A. Chandler, Aerospace)**
- **14:15/11:15 Emerging Technologies and Trends (D. Kunkee, Aerospace)**
- **15:00/12:00 Additional Input from Workshop Participants (All)**
- **16:00/13:00 *Adjourn***

[Registrants and WebEx Logins]

Name	Organization	Email
Aksoy, Mustafa	The Ohio State University	aksoy.2@osu.edu
Biswas, Sayak	NASA/GSFC	sayak.k.biswas@nasa.gov
Chandler, Adam	The Aerospace Corporation	adam.chandler@aero.org
De Amici, Giovanni	NASA/GSFC	giovanni.deamici@nasa.gov
Dinnat, Emmanuel	NASA/GSFC	emmanuel.dinnat@nasa.gov
Dobson, Craig	NASA HQ	Craig.Dobson@nasa.gov
Doiron, Terance	NASA/GSFC	terence.doiron@nasa.gov
Fatoyinbo, Lola	NASA/GSFC	lola.fatoyinbo@nasa.gov
Gaier, Todd	NASA/JPL	gaier@jpl.nasa.gov
Garrison, Jim	Purdue University	jgarriso@ecn.purdue.edu
Heymsfield, Gerry	NASA/GSFC	gerald.m.heymsfield@nasa.gov
Hoffman, James	NASA/JPL	James.p.Hoffman@jpl.nasa.gov
Hyon, Jason	NASA/JPL	Jason.J.Hyon@jpl.nasa.gov
Jezek, Kenneth	The Ohio State University	jezek.1@osu.edu
Johnson, Joel	The Ohio State University	johnson.1374@osu.edu
Kantrowitz, Frank	The Aerospace Corporation	frank.kantrowitz@aero.org
Kunkee, David	The Aerospace Corporation	david.kunkee@aero.org
Larkin, Philip	NASA/GSFC	philip.larkin@nasa.gov
Le Vine, David	NASA/GSFC	david.m.levine@nasa.gov
Li, Luhai	NASA/GSFC	Lihua.li@nasa.gov
Lim, Boon	NASA/JPL	bhlim@jpl.nasa.gov
Mariano, Socorro	NASA/JPL	socorro.v.mariano@jpl.nasa.gov
Mayo, David	The Aerospace Corporation	David.B.Mayo@aero.org

Name	Organization	Email
McLinden, Matt	NASA/GSFC	matthew.l.mclinden@nasa.gov
Norton, Charles	NASA/JPL	Charles.D.Norton@jpl.nasa.gov
Padmanabhan, Sharmila	NASA/JPL	sharmila.padmanabhan@jpl.nasa.gov
Park, Jeonghwan	The Ohio State University	park.1558@osu.edu
Park, Richard	Northrop Grumman	richard.park@ngc.com
Pett, Todd	Ball Aerospace	tpett@ball.com
Piepmeier, Jeff	NASA	jeff.piepmeier@nasa.gov
Reising, Steven	Colorado State University	Steven.ReB37:B61ising@ColoState.edu
Roth, Tim	Northrop Grumman	timothy.b.roth@ngc.com
Skofronick-Jackson, Gail	NASA/GSFC	gail.s.jackson@nasa.gov
Spencer, Michael	NASA	Michael.W.Spencer@jpl.nasa.gov
Tanelli, Simone	JPL /JPL	simone.tanelli@jpl.nasa.gov
Tatum, Paul	NASA	paul.f.tatum@nasa.gov
Taylor, Robert	Harris	rtaylo20@harris.com
Valinia, Azita	NASA/ESTO	azita.valinia@nasa.gov
Williams, John	The Aerospace Corporation	john.s.williams@aero.org
Wirth, Susan	Harris	susan.wirth@harris.com
Yueh, Simon	NASA/JPL	simon.yueh@jpl.nasa.gov

B. White Papers Submitted

Name	Organization	Paper Title
J. T. Johnson	The Ohio State University	Low-Frequency, Multi-channel Microwave Radiometry for Cryospheric Monitoring A White Paper Submitted to the 2017 Decadal Survey for Earth Science and Applications from Space
J. T. Johnson	The Ohio State University	Low-Frequency, Multi-channel Microwave Radiometry for Cryospheric Monitoring A White Paper Submitted to the ESTO Microwave Technologies Strategy Update 2016
K. C. Jezek	The Ohio State University	Low-Frequency, Multi-channel Microwave Radiometry for Cryospheric Monitoring White Paper Submitted to the ESAS 2017 RFI # 2 Climate Variability and Change Theme
R. Taylor	The Harris Corporation	Radar Electronics Technologies/ Radiometer Electronics Technologies/ Antenna and aperture Technologies/ Interferometry and SAR/ Sounding/imaging – land, ocean, ice, weather, and snow/ Radiometric – salinity, soil moisture, snow/ Water and energy cycle
F.B. Abbott	Surrey US	TechDemoSat-1 GNSSR Update White Paper on Surrey GNSS-R Data Service
F.B. Abbott	Surrey US	White Paper on Surrey GNSS-R Data Service

C. Acronym List

A/D	Analog-to-Digital
ACT	Arrays at Commercial Timescale
ADC	Analog-to-Digital Converter
ARM	Advanced RISC Machine
ASIC	Application-Specific Integrated Circuit
BW	Bandwidth
COMM	Communications
CONOPS	Concept of Operations
DARPA	Defense Advanced Research Project Agency
DBF	Digital Beam Former
EIKA	Extended Interaction Klystron Amplifier
ENOB	Effective Number of Bits
FLOPS	Floating Point Operations Per Second
GEO	Geostationary Earth Orbit
GMTI	Ground Moving Target Indication
GNSS	Global Navigation Satellite System
HPA	High Power Amplifier
HW	Hardware
IC	Integrated Circuit
InSAR	Interferometric Synthetic Aperture Radar
ISAT	Innovative Space-based Radar Antenna Technology
KDP	Key Decision Point
LEO	Low Earth Orbit
LNA	Low Noise Amplifier
MEO	Medium Earth Orbit
MMIC	Monolithic Microwave Integrated Circuit
NCO	Numerically Controlled Oscillator
NF	Noise Figure
RF	Radio frequency
RFI	Radio Frequency Interference
RISC	Reduced Instruction Set Computing
RZSM	Root Zone Soil Moisture
SAR	Synthetic Aperture Radar
SoOp	Signal of Opportunity
SSA	Solid State Amplifier
SSPA	Solid State Power Amplifier
SWaP	Size Weight and Power
SWaP-C	Size Weight and Power – Cost
T/R	Transmit / Receive
TWT	Traveling Wave Tube

D1. Radar Technology Capability Breakdown Matrix

Technology	Instrument Type	Waveband	Needed Functional Product	Quantitative Requirement	Explanation	TRL @ Start	Development Period (years)
High Efficiency T/R Module (L-band)	Interferometric SAR	L-band	Freeze- Thaw, SWE, polar ice velocity, surface deformation , biomass, land cover	Overall Efficiency >70%; lower DC power Rx; Tx Power 10-200W Bandwidth >80MHz Mass <50g	Required for small array LEO applications with mass densities <10 kg/m2. Current ACT will raise from TRL 3 to TRL 5.		2
MMIC T/R module (L-band)	InterferometricSAR	L-band	Surface deformation and land topography	single chip T/R; 5- 10W, 70% eff, 2dB NF, rad hard >1MRad	Required for large aperture systems with mass densities <2kg/m2 with requirement for high volume T/R modules		4
Membrane High-Efficiency T/R modules (L-band)	SAR; Large aperture, possibly for MEO, GEO missions	L-band	Surface deformation and land topography	5-10W, 70% eff, membrane attached, rad hard >1MRad	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. Hazard monitoring from Geosync Orbit		4
Manufacturing, integration, and assembly of very large active non-rigid antennas electronic subsystems	SAR; Large aperture, possibly for MEO, GEO missions	L-band	Surface deformation and land topography	integrated subarray fabrication (>64 element subarray)	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	4
T/R Module (Ku-band) Multi-band & wideband (tunable), covering both Ku-band radar allocations	SAR, rain radar	Ku-band	SWE, precipitation, ice surface topography	1-60W 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.	High Power Ku- Band applications for phased or line arrays with electronic scan capability.	3	3 years (IIP)
Ku-band (Vacuum Tube Amplifiers-like TWTA)	scatterometers, interferometers	Ku-band	snow cover, precip, ocean surface topography, sea ice	500W TWT, >40% efficiency, HVPS	500W TWTA technology similar to existing 200W TWTA under development for OVWM & WSOA	4	3
Ku-Band MMIC devices for high-power radar applications (SSPA, LNAs, P/S, switches)	Interferometric SAR, cloud and precip radar	Ku-band	SWE, ice surface topography	Phase stable (0.1 deg) receive components (LNA, phase shifters, switches, filters). Rad hard with minimal shielding. Improved DC efficiency (>40% efficiency)	Required for phase stable receivers in phased-array antennas used for interferometry	3	3 years (IIP)
Ka-Band MMIC devices (PAs, LNAs, P/S, switches)	SAR, cloud and precip radar; 3CPR Raincube	Ka-band	river discharge, precipitation, ocean topography, cloud	>20W PA with >40% PAE, <3dB NF LNA, 5-bit phase shifter (<3dB loss), phase-stable receive components.	Development of basic Ka-band devices required for future T/R modules.	2	3
T/R Module (Ka-band)	SAR, rain radar, geostationary precip radar	Ka-band	river discharge, precipitation, ocean topography	1-20W 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.	For high power Ka- Band phased array or line arrays with electronic scan capability. Past ATIP raised from TRL 2 to TRL 4.	4	3 years (IIP)
Ka-band high power amplifier technology (SSPA, TWTA, EIKA, etc)	Ka-band SAR	Ka-band	river discharge, precipitation	2-5KW, >30% efficiency,	Similar technology to Cloudsat EIKA (Ka-band has more relaxed requirements)	4	3
W-band MMIC devices (PAs, LNAs, P/S, switches)	Cloud radar	W-band	cloud profiling	>1W PA with >40% PAE, <4dB NF LNA, 4-bit phase shifter (<3dB loss)	Development of basic W-band devices required for future T/R modules.	2	4

Technology	Instrument Type	Waveband	Needed Functional Product	Quantitative Requirement	Explanation	TRL @ Start	Development Period (years)
T/R Module (W-Band)	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.	Addresses the integration of MMICs. Requires MMIC devices developed separately.	2	4
W-band EIKA (10KW)	Cloud radar	W-band	cloud profiling	10KW EIK, >30% PAE, >20KV HVPS	Further development of Cloudsat EIKA for increased power	3	3
W-band electronicaly scanning feed	Cloud radar	W-band	3D cloud structure	+/-20deg scanning, kW Transmit			
G-Band (140, 183, 239 GHz) MMICs (PAs, LNAs, P/S, switches)	Cloud radar	140, 183, 239 GHz	cloud/humidity profiling, volcanic plumes	1W PA & CW source, 10% PAE, 5%BW 6dB NF LNA	Development of basic G-band devices required for future T/R modules.	1	6
T/R Module (G-band) (140, 183, 239 GHz)	Cloud radar	140, 183, 239 GHz	cloud/humidity profiling, volcanic plumes	1-10W W-band T/R modules with integrated PA, LNA, phase shifter (4-bit), low loss T/R switches	Addresses the integration of MMICs. Requires MMIC devices developed separately.	1	6
Waveform Generators	SAR, scatteromet ers, 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	Direct to L or higher; >300MHz max BW, >50dB SFDR, <2W, 60dBc frequency notching capability, real-time programmable, Rad-Hard (>1MRad)	Enhancing for nearly all radar applications; low power single-chip DCG is enabling for large array applications.	3	4
Analog to Digital Converters	SAR	L-band, C-band, X- band, Ku- band,Ka-band		Need high ENOB (>10bit) ADC, <1W/channel	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	4
Enabling technologies for active arrays (thermal, control)	radar			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.passive and active thermal management, high heat flux removal, temperature stability.precise thermal control for phase stability of phasedarray antennas	While all Phased-Array antennas would be enhanced by improved sig dist technology, large aperture SARs require it applies to thermal management and control of high power, large aperture membrane antennas with integrated electronics	2	4
Thermal Management for membrane antennas	InSAR	L-band	Surface deformation and land topography		applies to thermal management and control of high power, large aperture membrane antennas with integrated electronics	1	4
Thermal Control for Interferometric SAR	Single Pass Interferometric SAR	X,-band, Ku-band & Ka-band	land, ice, ocean topography		Applies to singlepass interferometers using active phased array antennas.	2	4
Active array with Adaptive waveform sensing and correction technology	InSAR	L-band, UHF/VHF & Ka-Band		aperture flatness toaperture flatness to 1/20 wavelength, aperture separation accuracy to 1/10 of separation	applies to large aperture antennas, targetting 100g/m^2	2	6
X-band TR and phased array technologies			SWE, precipitation, ice surface topography, agriculture	1-60WT/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.			

Technology	Instrument Type	Waveband	Needed Functional Product	Quantitative Requirement	Explanation	TRL @ Start	Development Period (years)
Radar common backend electronics (especially for multi-frequency)		All	Modular, reusable backend		Reduce multi mission costs		
Radar subsystems on PC104 form factor (cubesat)					Evrything from HPA to Waveform Generators, Synthesizer, etc to enable small platform instruments		
Bistatic radar technologies					General technolgies for enabling bistatic radar measurements		
Distributed radar electronics technologies					Technologies enabling formation flying radars, such as LO, clock, timing, etc distribution over wide, possibly free-space, areas		
Assembly of precision large aperture on orbit technologies	Large aperture	All		Need high precison control or adaptive			
Digital TR				TR modules incorporating ADC and/or DAC (for 1D)	TR, with ADC and or DAC		
Processing ASIC (FFT, ?)							
GNSS-R low power front-end downconverter		GPS-band		low power ?Watts; L-band to baseband			
GNSS-R Deployable antenna, with scanning		GPS-band		>1.5m, multi-element, steerable, polarimetric for CubeSat (smallsat), receive only			
Antennas for Signals of Opportunity		P-S band; Ku-Ka		Ultrawideband antenna, (like GNSS-R but very wideband, for both H and V)			
G-band Phased Array Technologies		G-band		Steerable G-band array			
SoOp-R tunable receivers and onboard processor		200 MHz to 20 GHz	Instrument Front-end; important aspects: system architeture,receiver and processor design, antenna technology, calibration; surface measurements				
Adaptive, low sidelobe pulse compression for Doppler radar		Ku, Ka, W-band cloud and precipitation	cloud and precipitation profiling/imaging,	better than -70 dB sidelobe and minimum side effect on Doppler performance	applies to spaceborne and airborne radars		
P-band MMIC							
FPGA based reconfigurable digital system including waveform generation, digital beam forming, pulse compression							

Technology	Instrument Type	Waveband	Needed Functional Product	Quantitative Requirement	Explanation	TRL @ Start	Development Period (years)
Multi-band phase array feed		X-band, Ku-band, Ka-band, W-band					
MIMO SAR							
UHF transceiver							
Light weight phased array/ Multiple frequency	Tri- frequency (14/35/94 GHz) Precipitation Radar	14/35/94 GHz	Precipitation (Rain rate, Doppler velocity and other characteristic s) 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	The current IIP (PR-2) will improve the technology from TRL 1 to TRL 3	4	4
Light weight structure/ Phased array feed	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)	The current IIP (INexrad-In-Space (NIS)) will improve the technology from TRL 2 to TRL 4	5	4
Light weight antenna structure (Reflector)/ Multiple frequency/ Adaptive waveform sensing and correction	UHF/VHF Polarimetric SAR	UHF/VHF	Deep soil moisture	Antenna length: 30m; antenna width: 11m at VHF, 3m at UHF		5	2
Combined L-band, P-band antenna for radar/radiometer	L/P Polarimetric SAR	L,P	Deep soil moisture				
Sounder antenna boom technologies HF and VHF (such as OASIS)					Ice, Aquifier sounding		
Multi-frequency antennas for X-thru-K (snow science)					Snow sounding		
Electrically small GPR antennas MHz-range	Airborne?		Permafrost	Need high bandwidth (>50% BW at 100's MHz)	Ground penetrating radars from ground or airborne		
Deployable Cubesat Reflector	Cubesat, small platform, 2m deployable reflector, suitable for scanning feed		Precipitation	"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			
Reconfigurable array				Freq, polarization, pattern, etc			
Conical scanned antennas (non-mechanical)	Scatterometers		Methods for conically scanned arrays, with mechanical spinning				

D2. Radiometer Technology Capability Breakdown Matrix

Technology	Measurement Scenarios	Instrument Type	Frequency Range	Needed Functional Product	Quantitative Requirement	Task	Subtask	Explanation	TRL @ Start	Development Period (short, medium, long)
Integration with radar transmitter and reciever modules.	Active Passive constellation for precipitation missions	Atmospheric Temp/Hum/Precip	Ka-G-band	Instrument Front-end (small SWaP); 1 unit on a small platform with many platforms: Technology challenge: co-existence with radar unit	Power; 10-30W Efficiency; 40%				4	Medium
Broadband Integration with radar transmitter and receiver modules.	Root zone soil moisture/SSS/Air-Sea Flux/Sea Ice	surface radar radiometer	P/L/S-band (430 MHz - 2000 MHz)	Instrument Front-end; stable internal calibration					4	Medium
Integration with radar transmitter and receiver modules.	Ocean Altimetry	Altimeter/path delay measurment	K-Ka Band	Instrument					4	Medium
Integration with radar transmitter and receiver modules.	Ocean Surface Winds	Combined polarimeter and radar	X- - Ka band	Intergrated polarimeter and radar recevers						
Polarimetry	Ocean Surface Winds	Polarimetric Radiometer	L- to SMMW	Instrument					varies	
Analog/Digital Cross Correlator	Atmospheric Sounding		1 GHz IF band	Subsystem	250 uW-correlation, 256x256 input, 500 MHz BW				6	
Low-Mass, Low-Noise Broadband Millimeter-wave Receiver	Atmospheric sounding and imaging/ATMS/GMI/TEMPEST/CAPPM	Super-heterodyne radiometer front ends	118 and 183 GHz (W- to G-band)	Instrument front-end	MMIC-based superheterodyne integrated receivers: 300K at room temp @183 GHz Power <0.05W;mass<100g				5	None
Broadband Digital Signal Processor- Integrate SigOp, passive uW and 1.2 GHz RADAR processing in one subsystem	SMAP FO; Combined Radar/Radiometer/ SoOp;	Combined Radar/Radiometer/SoOp; Multi-purpose SDR; reconfigurable frequency agile systems	depends on how and this is used	backend data processing (universal)	ASIC or FPGA based system					
Submm-wave frontends	GACM	Atmospheric Temp/Hum/Precip	500-600 GHz	high sensitivity receiver frontends	MMIC-based superheterodyne integrated receivers:300K at 20K @500 GHz Power <0.1W;mass<200g					
Broadband tunable notch filter	Root zone soil moisture/SSS/Air-Sea Flux/Sea Ice		large signal interference removal tunable from 600 to 2000 MHz	large signal interference removal tunable from 600 to 2000 MHz	Low loss					

Technology	Measurement Scenarios	Instrument Type	Frequency Range	Needed Functional Product	Quantitative Requirement	Task	Subtask	Explanation	TRL @ Start	Development Period (short, medium, long)
Water vapor radiometer	Tropospheric 2.5D Winds/Weather Decadal trends	Repeat Pass Radiometers	5 minute repeat time, 5 layers	low-cost, high performance radiometers (arrays or cubesats/smallsats	TRL very high, need field demos for the science.					
Miniature 230/310/650 GHz direct detection radiometers	TWICE, etc.	Cloud Ice	20 GHz BW @230, 310. 650 GHz	Dual-Pol Instrument Front-end	Power <.5W, sufficiently small to fit in a single focal plane					
Miniature 118, 183, 380 GHz sounders	TWICE, etc.	Cloud Ice	118, 183, 380 sounding channels	Instrument Front-end	Power <1.5W, sufficiently small to fit in a single focal plane			lower TRL considering wideband		
Ultra low-power mm-wave receiver front ends	Atmospheric sounding and imaging/ATMS/GMI/TEMPEST/CAPPM	Super-heterodyne radiometer front ends	183 GHz	Instrument front-end	300K noise temperature at room temp @183 GHz;Power <0.05W;mass<100g				4	Long
Integration with radar transmitter and reciever modules.	CAPPM	Atmospheric Temp/Hum/Precip	Ka-G-band	Instrument Front-end	Power; 10-30W Efficiency; 40%			Ultra Low Mass MMIC Radiometers	2	Medium
2m class deployable antenna (1-350; 600-GHz); low cost (higher frequencies also useful); multi-spectral and multi-angle;	Better characterizations of ice and land separation of ice and moisture	Antenna	1 - 350 GHz; 600 GHz	Deployable 2-Meter class antenna to enable smaller and lower cost missions where greater spatial resolution is needed in diffraction limited scenarios	Fit within smaller launch vehicle fairings e.g. Min I				3	medium
Ultra Wideband radiometer	RFI dodging	Instrument	0.5 - 50 GHz	well-calibrated frequency agile radiometer (imager); may extend to sounding as well (50-60 GHz)	25 kHz (TBR) Nband segements from 1 - 50 GHz;					
Low Power Cryo-Cooler (50 - 20K); front-ends only for small sats	CubeSat and Small sats; and more (Limb sounding)	Nadir/Off-nadir and Limb sounders	Use for receivers above 180 GHz	Low Power Cryo-Cooler (50 - 20K); for small sat front-ends	cool radioemter hardware to 50 - 20 K (need power requirements for small sats)					medium
Distributed Correlators	Root Zone SM and Sea Ice	Distributed STAR Systems	P/L/S/C	Distributed Correlators	<100 MHz; limited baselines					
Low power, high efficiency LO (target: cubeSats) other uses as well	cases that require high frequencies or frequency conversion	high frequency superheterodyne recevers in cubesats	~> 100 GHz	Low Power high effiency Local Oscillators	<1W; high level of integration; 5-10mW output up to 900 GHz					
internal calibration noise sources for f > 183 GHz	small sat high frequency measurements	polarimetric and dual-pol	>100 GHz	Internal calibration noise sources and swithcing for radioemters oeprating above 100 GHz	ENR (TBD); stability (TBD)					
Small-size feed array for pushbroom beam forming	SMAP FO, Aquarius FO, atmospheric sounding, ice/snow studies (depends on operating frequency)	direct RF-gain radiometer, heterodyne radiometer, front-end for interferometer	sub-GHz to K (multiple units, optimized to the mission)	feed array and cylindrical reflector	combined HPBW 1 deg or less, efficiency 90% or more			leave in electronics because feed array likely combines antenna and electronics		medium-long

Technology	Measurement Scenarios	Instrument Type	Frequency Range	Technology	Quantitative Requirement	Task	Subtask	Explanation	TRL @ Start	Development Period (short, medium, long)
Cyclindrical reflector antenna for pushbroom footprint	SMAP FO, Aquarius FO, atmospheric sounding, ice/snow studies (depends on operating frequency)	direct RF-gain radiometer, heterodyne radiometer, front-end for interferometer	sub-GHz to K (common design but multiple units whose surface requirements are optimized to the mission)	feed array and cylindrical reflector	combined HPBW 1 deg or less, efficiency 90% or more					short-medium
SoOp-R tunable receivers	Surface measurements		200 MHz to 20 GHz	Instrument Front-end, back-end						
Delay-doppler processors for GNSS-R and SoOp reflectometers	Ocean winds, soil moisture, sea ice	GNSS-R, SoOp-R	any	Estimate cross correlation in delay-doppler bins to compute a DDM	100-kHz to 100-MHz bandwidths					
distributed calibration for STAR										
SI Calibration				SI-traceability of radiometers (through antenna)				Black body standards, traceability techniques		
Calibration of UAV radiometers				Combine infomration about ambient environment to improve unattended airbone (vs. space-based) instrument calibration				System analysis of UAV-based radieomters and calibration techniques - including effectiveness of various ConOPs		
Broadband/multiband Focal Plane Array Feed Technologies for large (e.g. >7m) antennas	Root zone soil moisture/SSS/Air-Sea Flux/Sea Ice	Combined Radar/Radiometer/SoOp; Multi-purpose SDR; reconfigurable frequency agile systems	P/L/S/C-band	10-1 band feeds (options); non moving conical scan	40 deg ONA; Multi-angle may be useful as well					
Large deployable antenna	Ultrahigh Res Microwave Imaging (URMI)	Conical Scanning Microwave System	10m, 40 GHz,		90% or better efficiency					
Antennas for UAV-based radiometry	Global hawk/ scan eagle…		400 MHz - 350 GHz	conformal, high efficiency antennas	precise antenna pattern knoweldge and stabiliy					
Reliable CubeSat bus	TEMPEST-D, PATH				5 year lifetime, reliable comms for 50 kbps continuous sampling, <$2M, >15W OA power					

Technology	Measurement Scenarios	Instrument Type	Frequency Range	Needed Functional Product	Quantitative Requirement	Task	Subtask	Explanation	TRL @ Start	Development Period (short, medium, long)
Ultra Broadband Digital Spectrometer	GACM	Atmospheric Temp/Hum/Precip	20 GHz BW	compact low-power backends	20 GHz BW, 1 MHz resolution with <10 W				3	Long
3-D ranging and data transmission	Root Zone SM and Sea Ice	Distributed STAR Systems	P/L/S/C		500 M separation					
Formation flying 500m; 1 cm precision										
SubMMW receivers (room temperature)	Ice Clouds		200 –1000 GHz	Instrument front-end (including LNAs); SubMMW filters; detectors; calibration noise sources and switches	LNAs < 5dB NF; filters to allow SSB operation e.g << 10% bandwidth; room temperature detectors to allow direct detection; 100 K coupled added noise temperature				3	short
Miniaturized isolators for MMIC	Any RF or IF			Miniaturized isolators for MMIC						
2 Meter deployable antenna	Low cost radioemeter aplications that require higher resolution	small stowed space	L-band through 350 GHz	foldable to <<1M (within 2.5U)						
6 or 10-GHz through 90 GHz, spatial resolution substantially better than AMSR-2. (e.g., 6-meter deployable)				~6-m reflector radiometer antenna; spatial resolution substantially better than AMSR-2. (e.g., 6-meter deployable)						

D3. Information and Data Processing Capability Breakdown Matrices

Technology	Measurement Scenario	Instrument Type	Frequency	Needed Functional Product	Quantitative Requirement	Task	Explanation	TRL @ Start	Development Period (short, medium, long)
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), Freezethaw 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, ***cloud and precip radar,*** 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 size	Research is required to achieve high packing density of available memory chips to minimize volume while maintaining adequate thermal control	4	1.5 ~ 2 years

Technology	Measurement Scenario	Instrument Type	Frequency	Needed Functional Product	Quantitative Requirement	Task	Explanation	TRL @ Start	Development Period (short, medium, long)
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 nonscanning 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 ultralow power ICs, MEMS, ASICs, Gate Arrays, FPGAs, SOCs, DSPs, Microprocessors, Memory (NVRAM, SRAM, SDRAM), using SiGe, InP, InAs, SOI, CMOS processes.	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
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).	Having the right tools facilitates the design process, reduces the design cycles, and helps the technology reaching the desired TRL sooner.	2	3
High- Performance RHP	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 nonscanning microwave radiometer sounder at GEO (67)	Atmospheric sounder, atmospheric profiler, SAR, scatterometer, radar altimeter	Ku, X, S, C, L, P	PRECIPITATION 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.	When rad-hard devices are not available to satisfy the throughput, cost, and power consumption requirements, faulttolerant 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	3

Technology	Measurement Scenario	Instrument Type	Frequency	Needed Functional Product	Quantitative Requirement	Task	Explanation	TRL @ Start	Development Period (short, medium, long)
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 PARAMETER S: 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.	Large participation of experts will bring more innovations and speed up the TRL readiness.	2	3
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	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	4

Technology	Measurement Scenario	Instrument Type	Frequency	Needed Functional Product	Quantitative Requirement	Task	Explanation	TRL @ Start	Development Period (short, medium, long)
fast 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, 2-bit, and 3-bit A/D converters	2 GHz, 5mW, 20GHz bandwidth,1 mV/quantum	Develop, fabricate and test A/D ASIC including total-dose and SEU radiation testing		3	2.5

Technology	Measurement Scenario	Instrument Type	Frequency	Needed Functional Product	Quantitative Requirement	Task	Explanation	TRL @ Start	Development Period (short, medium, long)
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	3

Technology	Measurement Scenario	Instrument Type	Frequency	Needed Functional Product	Quantitative Requirement	Task	Explanation	TRL @ Start	Development Period (short, medium, long)
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	breadboard laboratory signal distribution testbed - multiplexing high speed, low bit resolution digital samples onto a common and bus and demuxing them at the receive end	3	1
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	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	1.5
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	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	2

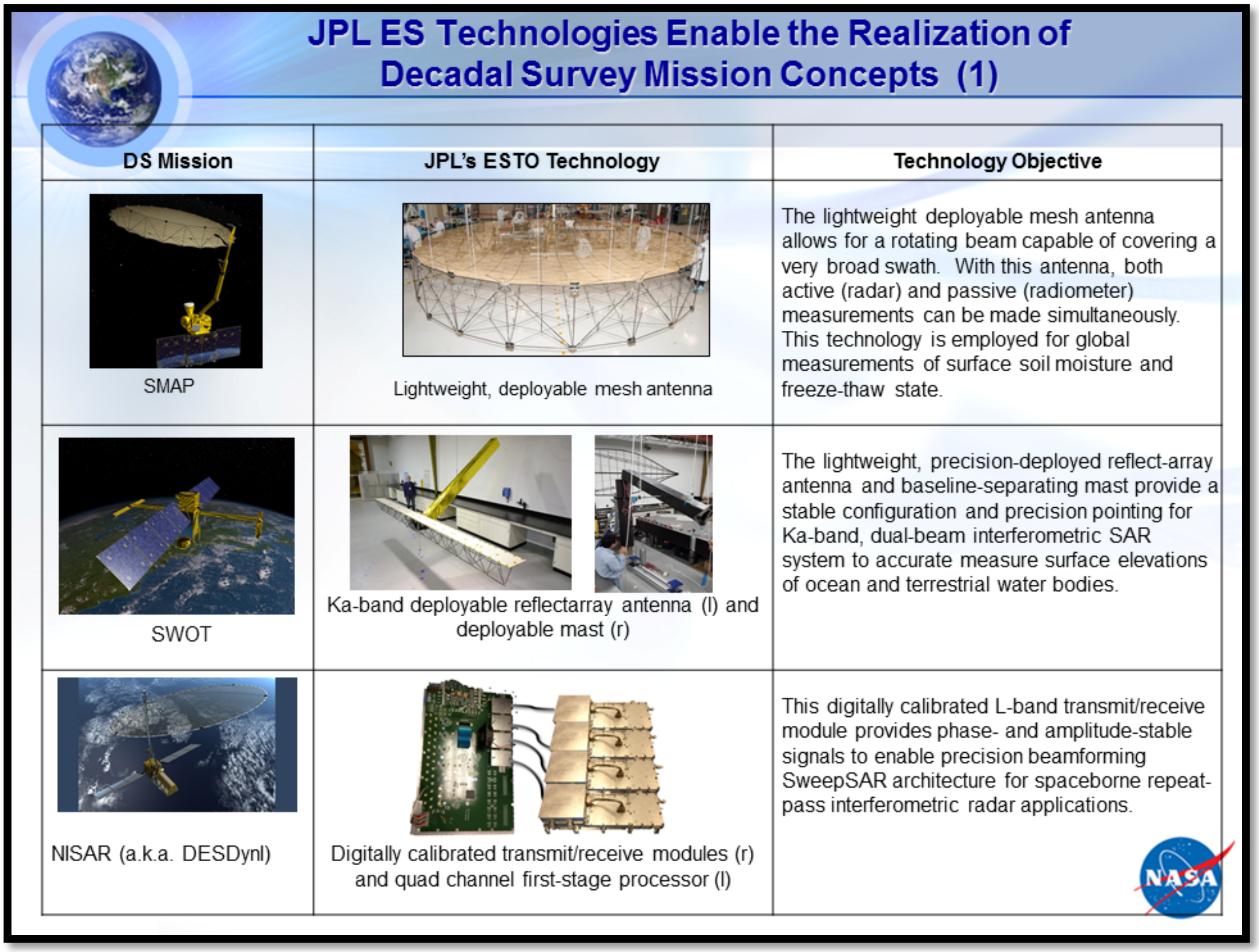
Technology	Measurement Scenario	Instrument Type	Frequency	Needed Functional Product	Quantitative Requirement	Task	Explanation	TRL @ Start	Development Period (short, medium, long)
High speed, high resolution Digital Spectrometers for Sounding	Tropospheric ozone and precursors,Ozone vertical profile,Atmospheric 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, hires analog 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	4
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 crosscorrelation (multiply & accumulate) of low bit resolution digitized samples of signals	10,000 (threshold) / 90,000(objectiv e) (multiplyaccumulate- MAC)1-bit crosscorrelations 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	TRL 2 to 3: 1.
on-board correlator for beam-forming (interferometry)	pushbroom footprint layout; SMAP FO, Aquarius FO.	radiometer with option to conduct small-areas in-depth studies both with enhanced spectral (see spectrometer above) and spatial resolution.	sub-GHz to X for surface investigations.						
on-board correlator for RFI mitigation	any RFI-susceptible space-borne instrument	radiometer, radar, interferometer	sub-GHz to X						

Technology	Measurement Scenario	Instrument Type	Frequency	Needed Functional Product	Quantitative Requirement	Task	Explanation	TRL @ Start	Development Period (short, medium, long)
	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	L-band to 40 GHz	RFI mitigation algorithms	0.05 K for ocean temperature 0.3 K for land (soil moisture)		Test and verify against known RF environments	2	3 to 4
Radar waveform generation		ACE - radar; CAPPM (+ RainCube constellation)		Generation of ultra-low-range-sidelobe pulses (ACE); advanced waveform generation and processing; advanced waveform diversity techniques (coding, frequency, etc) to produce multiple independent looks simultaneously, given short integration time available (CAPPM)					
On-board processing		CAPPM (+ RainCube constellation)		multichannel processing; realtime adaptive turning on and off of channels					
Algorithms/Software		Various		Optimize instrument operations, e.g. power use, in response to onboard health monitoring					
Coordination of multiple sensors		CAPPM + RainCube		adaptive coordination of observations (master with drones) (3-4 cubesats and several larger spacecraft) might need realtime adaptive coordination					
software-defined/cognitive radar/lidar				more efficient spectrum utilization; rfi mitigation					
Inter-spacecraft metrology & comm, on-board processing		Small/cubesats		inter-spacecraft communication, metrology for formation control (~cm level stationkeeping)					
digital beam forming		Small/cubesats		digital beamforming with formation flying					
Algorithms/Software		Various		(Self-) Tipping and cueing; coordinated, event-driven operation; rapid response (to storms, earthquakes, e.g.)					
Multi-sensor coordination		GeoStorm with LEO array		Short-latency retasking of GEO based on detections from constellation of LEO sensors					
Compressive sensing and sparse-sampling instrument network (eg, aperture) signal processing and infrastructure		all		enable sparse multi-mini-sat apertures; reduce downlink requirements					
compression, RFI mitigation		GACM (microwave limb sounder)		Information-aware compression algorithms for downlink and RFI mitigation					
Technology	**Measurement Scenario**	**Instrument Type**	**Frequency**	**Needed Functional Product**	**Quantitative Requirement**	**Task**	**Explanation**	**TRL @**	**Development Period (short,**

								Start	medium, long)
sar data compression				accommodate large data sets, reduce downlink requirements					
Delay-doppler processors for GNSS-R and SoOp reflectometers	Ocean winds, soil moisture, sea ice	GNSS-R, SoOp-R	any	estimate cross correlation in delay-doppler bins to compute a DDM	100-kHz to 100-MHz bandwidths	system design depending upon bandwidth, FPGA/DSP development. Test in benchtop, sub-orbital, and ortibal environments.			
extract geophysical information from communication systems and other assets									
Expand downlink capabilities		CAPPM + RainCube; GACM; GeoStorm with LEO array; others…		real time/constant (reliable) downlink could overwhelm existing infrastructure; consider possible expansion of relays, additional ground stations; direct downlink to users could enable real-time applications such as weather, aviation					
large-scale ground data storage, processing, distribution		All		next-generation architecture for data management, processing, dissemination					
Big Data fusion				e.g., real-time comparison of instrument measurements with model predictions; model predictions on same time- and spatial- scale as measurements; quick turnaround tipping and cueing; data fusion/synthesis between all available sources - space, airborne, ground, buoys…					L
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
	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; ***DTED-4 can be considered (maybe isolated areas at first, eventually 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	3

Technology	Measurement Scenario	Instrument Type	Frequency	Needed Functional Product	Quantitative Requirement	Task	Explanation	TRL @ Start	Development Period (short, medium, long)
Processing Algorithms	Vegetation height and vertical structure using Polarimetric-Interferometric SAR (PolInSAR) technique	Repeat-pass polarimetric interferometer or single-pass interferometer with variable interferometric baseline	0.3-1.25 GHz	Tree height and vegetation vertical structure. Canopy density.	Global mapping of tree height with 20% accuracy. Vertical structure with 5-10m vertical resolution. 100m horizontal resolution	Development of optimum baseline scenarios and tomographic algorithms capable of resolving the vertical structure of forests from the multi-baseline measurements	Initial demonstration was conducted using Airborne radars but more algorithm development is needed to cope with the effects of temporal decorrelation and to reduce the side lobes in tomographic processing	1	3
Algorithms/Software		SAR		Automated quality assurance to prioritize ground processing					
Ground processing		ACE - radar		OSSE, mission configuration and performance studies, retrieval algorithm development (esp. in multi-instrument context)					
Ground processing		CAPPM + RainCube		OSSE, mission configuration and performance studies, retrieval algorithms					
Ground processing		GACM (microwave limb sounder)		Advanced 3D tomographic retrieval algorithms					
Ground processing		GeoStorm with LEO array		Rapid identification of features; quick-response tasking					
Ground processing		SCLP		Retrieval algorithms					
super-resolution techniques		radar, lidar, radiometer, hyperspectral…		sub-pixel detection, calssification; physical anomaly detection					M
multi-function processor for atmoshperic profiling radar to also do SAR									
constellation modeling	Ocean winds, soil moisture, sea ice, atmospheric sounding	miniature instruments flown in constellation		design and analysis tools for constellations of small instruments; modeling and simulation of data processing/retrieval algorithms					
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	L-band to 40 GHz	RFI mitigation algorithms	N/A		RFI environment is currently unknown	1	0.5 followed by updates to identify new RFI sources

E. Summary of ESTO Investments in Earth Science (JPL)

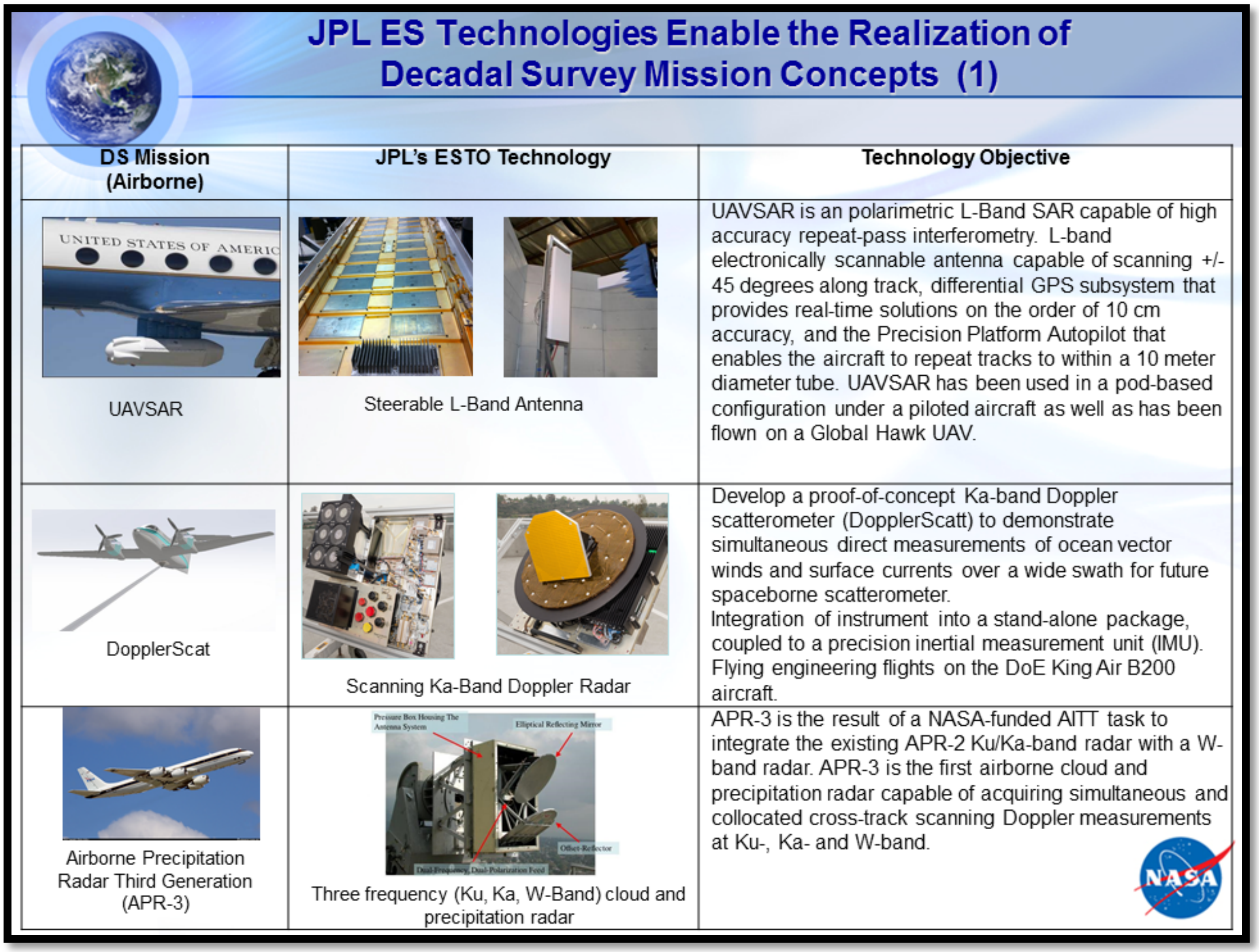


JPL ES Technologies Enable the Realization of Decadal Survey Mission Concepts (1)

DS Mission	JPL's ESTO Technology	Technology Objective
SMAP	Lightweight, deployable mesh antenna	The lightweight deployable mesh antenna allows for a rotating beam capable of covering a very broad swath. With this antenna, both active (radar) and passive (radiometer) measurements can be made simultaneously. This technology is employed for global measurements of surface soil moisture and freeze-thaw state.
SWOT	Ka-band deployable reflectarray antenna (l) and deployable mast (r)	The lightweight, precision-deployed reflect-array antenna and baseline-separating mast provide a stable configuration and precision pointing for Ka-band, dual-beam interferometric SAR system to accurate measure surface elevations of ocean and terrestrial water bodies.
NISAR (a.k.a. DESDynl)	Digitally calibrated transmit/receive modules (r) and quad channel first-stage processor (l)	This digitally calibrated L-band transmit/receive module provides phase- and amplitude-stable signals to enable precision beamforming SweepSAR architecture for spaceborne repeat-pass interferometric radar applications.

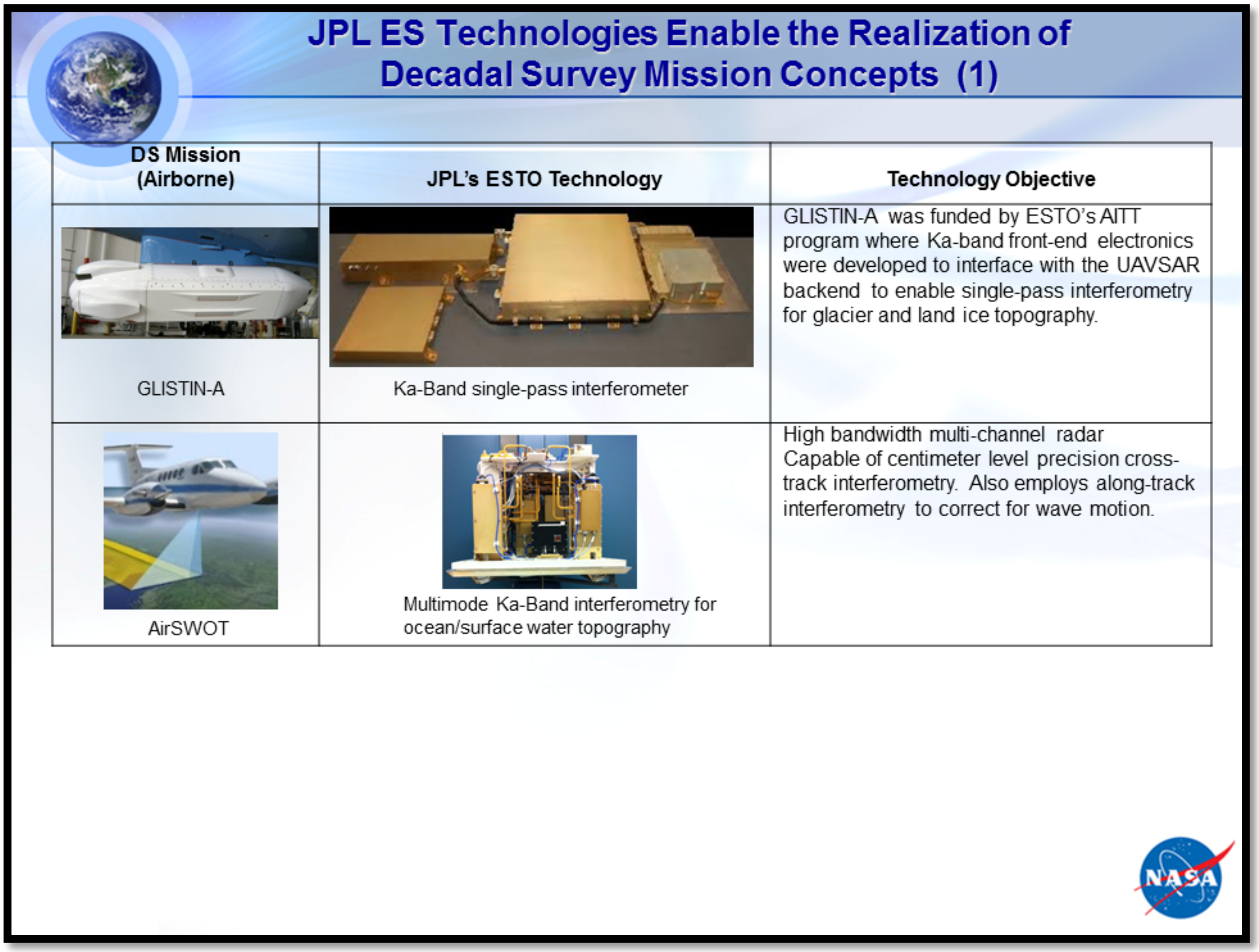
JPL ES Technologies Enable the Realization of Various Other Instruments

Mission/CubeSat	JPL's ESTO Technology	Technology Objective
RainCube	Deployable 1.5 U antenna, and miniaturized radar electronics	RainCube is the first demonstration of a cubesat-based remote sensing radar in space. Constellations of cloud and precipitation radars can dramatically improve revisit times for evolving storms. RainCube required the development of both miniaturized radar electronics and a 0.5 m deployable Ka-Band reflector antenna that can stow within 1.5 U.
TEMPEST	TEMPEST-D spacecraft concept, MASC prototype instrument and RF filterbank	The TEMPEST mission will study cloud microphysics through global temporal observations of convective systems. TEMPEST-D will demonstrate the mission capability with a low-cost, 6U CubeSat and radiometer instrument capable of precision measurements of atmospheric brightness.



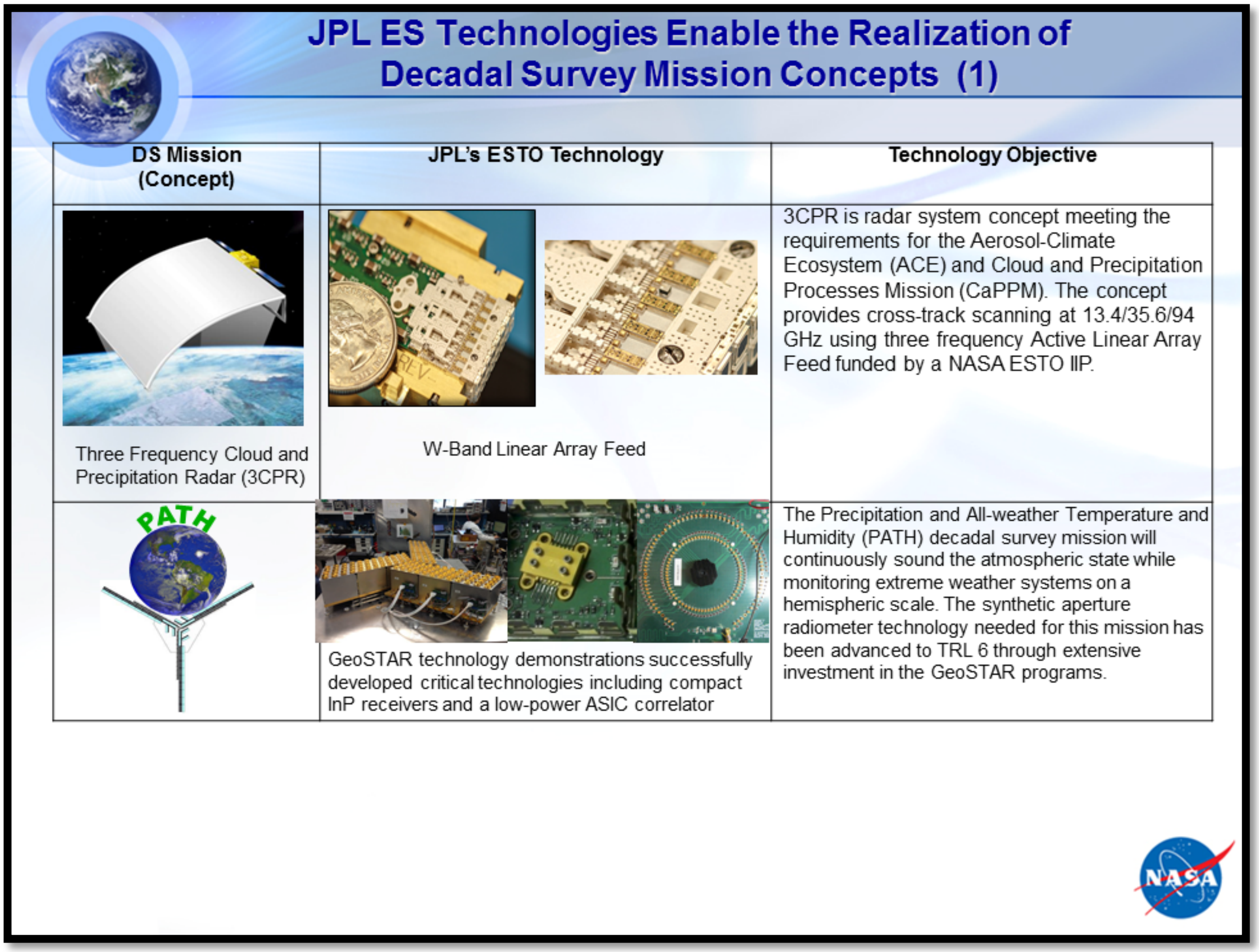
JPL ES Technologies Enable the Realization of Decadal Survey Mission Concepts (1)

DS Mission (Airborne)	JPL's ESTO Technology	Technology Objective
UAVSAR	Steerable L-Band Antenna	UAVSAR is an polarimetric L-Band SAR capable of high accuracy repeat-pass interferometry. L-band electronically scannable antenna capable of scanning +/- 45 degrees along track, differential GPS subsystem that provides real-time solutions on the order of 10 cm accuracy, and the Precision Platform Autopilot that enables the aircraft to repeat tracks to within a 10 meter diameter tube. UAVSAR has been used in a pod-based configuration under a piloted aircraft as well as has been flown on a Global Hawk UAV.
DopplerScat	Scanning Ka-Band Doppler Radar	Develop a proof-of-concept Ka-band Doppler scatterometer (DopplerScatt) to demonstrate simultaneous direct measurements of ocean vector winds and surface currents over a wide swath for future spaceborne scatterometer. Integration of instrument into a stand-alone package, coupled to a precision inertial measurement unit (IMU). Flying engineering flights on the DoE King Air B200 aircraft.
Airborne Precipitation Radar Third Generation (APR-3)	Three frequency (Ku, Ka, W-Band) cloud and precipitation radar	APR-3 is the result of a NASA-funded AITT task to integrate the existing APR-2 Ku/Ka-band radar with a W-band radar. APR-3 is the first airborne cloud and precipitation radar capable of acquiring simultaneous and collocated cross-track scanning Doppler measurements at Ku-, Ka- and W-band.



JPL ES Technologies Enable the Realization of Decadal Survey Mission Concepts (1)

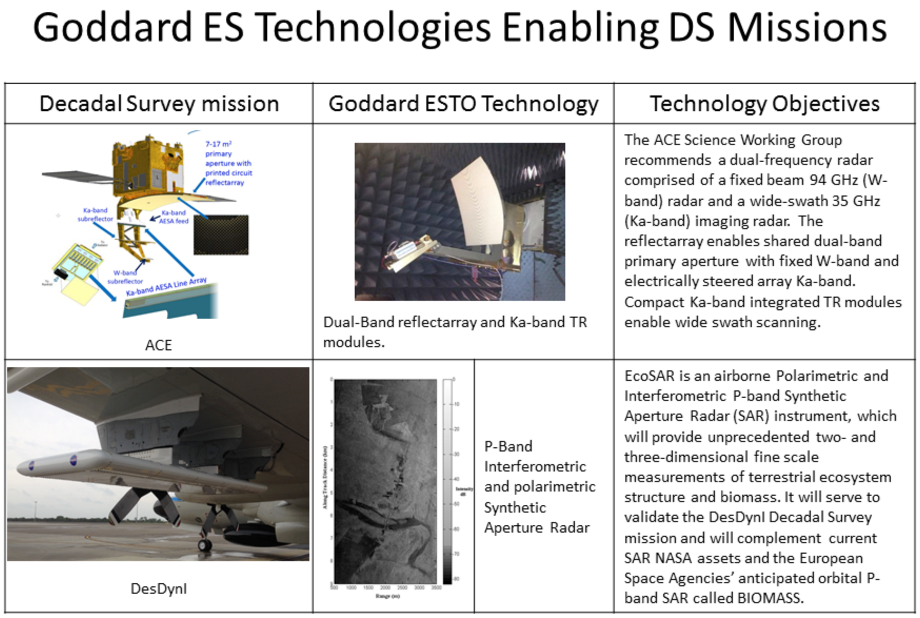
DS Mission (Airborne)	JPL's ESTO Technology	Technology Objective
GLISTIN-A	Ka-Band single-pass interferometer	GLISTIN-A was funded by ESTO's AITT program where Ka-band front-end electronics were developed to interface with the UAVSAR backend to enable single-pass interferometry for glacier and land ice topography.
AirSWOT	Multimode Ka-Band interferometry for ocean/surface water topography	High bandwidth multi-channel radar Capable of centimeter level precision cross-track interferometry. Also employs along-track interferometry to correct for wave motion.



JPL ES Technologies Enable the Realization of Decadal Survey Mission Concepts (1)

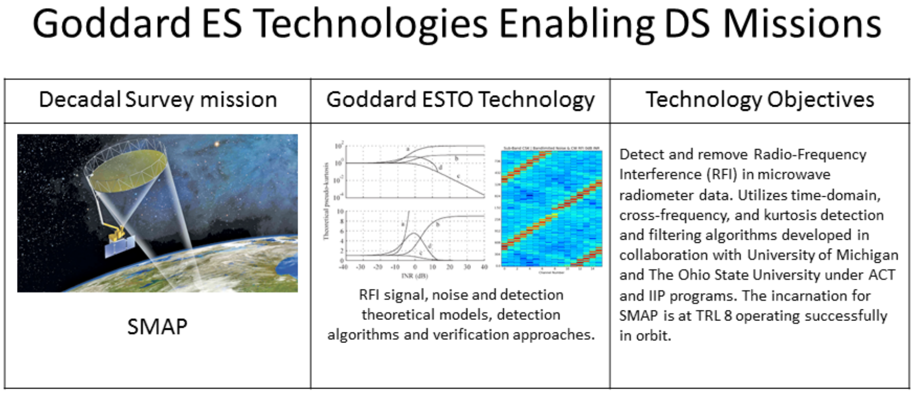
DS Mission (Concept)	JPL's ESTO Technology	Technology Objective
Three Frequency Cloud and Precipitation Radar (3CPR)	W-Band Linear Array Feed	3CPR is radar system concept meeting the requirements for the Aerosol-Climate Ecosystem (ACE) and Cloud and Precipitation Processes Mission (CaPPM). The concept provides cross-track scanning at 13.4/35.6/94 GHz using three frequency Active Linear Array Feed funded by a NASA ESTO IIP.
PATH	GeoSTAR technology demonstrations successfully developed critical technologies including compact InP receivers and a low-power ASIC correlator	The Precipitation and All-weather Temperature and Humidity (PATH) decadal survey mission will continuously sound the atmospheric state while monitoring extreme weather systems on a hemispheric scale. The synthetic aperture radiometer technology needed for this mission has been advanced to TRL 6 through extensive investment in the GeoSTAR programs.

F. Summary of ESTO Investments in Earth Science (GSFC)



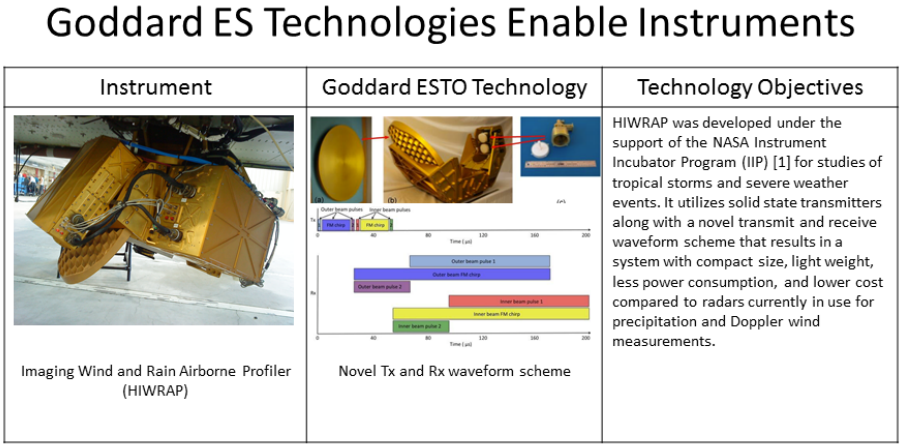
Goddard ES Technologies Enabling DS Missions

Decadal Survey mission	Goddard ESTO Technology	Technology Objectives
ACE	Dual-Band reflectarray and Ka-band TR modules.	The ACE Science Working Group recommends a dual-frequency radar comprised of a fixed beam 94 GHz (W-band) radar and a wide-swath 35 GHz (Ka-band) imaging radar. The reflectarray enables shared dual-band primary aperture with fixed W-band and electrically steered array Ka-band. Compact Ka-band integrated TR modules enable wide swath scanning.
DesDynI	P-Band Interferometric and polarimetric Synthetic Aperture Radar	EcoSAR is an airborne Polarimetric and Interferometric P-band Synthetic Aperture Radar (SAR) instrument, which will provide unprecedented two- and three-dimensional fine scale measurements of terrestrial ecosystem structure and biomass. It will serve to validate the DesDynI Decadal Survey mission and will complement current SAR NASA assets and the European Space Agencies' anticipated orbital P-band SAR called BIOMASS.



Goddard ES Technologies Enabling DS Missions

Decadal Survey mission	Goddard ESTO Technology	Technology Objectives
SMAP	RFI signal, noise and detection theoretical models, detection algorithms and verification approaches.	Detect and remove Radio-Frequency Interference (RFI) in microwave radiometer data. Utilizes time-domain, cross-frequency, and kurtosis detection and filtering algorithms developed in collaboration with University of Michigan and The Ohio State University under ACT and IIP programs. The incarnation for SMAP is at TRL 8 operating successfully in orbit.



Goddard ES Technologies Enable Instruments

Instrument	Goddard ESTO Technology	Technology Objectives
Imaging Wind and Rain Airborne Profiler (HIWRAP)	Novel Tx and Rx waveform scheme	HIWRAP was developed under the support of the NASA Instrument Incubator Program (IIP) [1] for studies of tropical storms and severe weather events. It utilizes solid state transmitters along with a novel transmit and receive waveform scheme that results in a system with compact size, light weight, less power consumption, and lower cost compared to radars currently in use for precipitation and Doppler wind measurements.

G. Emerging Technology Goals for Measurements

Table G.1. High frequency RF Components and Systems Technology Assessment.

Technology Thrust Area	**Measurement**	**State-of-the-Art**	**Notional Requirements**
Front-end LNAs	Cloud Ice Atmospheric Composition Humidity	T_{sys}~350 K at 183-GHz; T_{sys}>800 K at 500 – 600 GHz	T_{sys}~300 K @ 500-GHz and 20 K ambient Power < 0.1W; Mass < 200g
Low Power Consumption LOs;	Cloud Ice Atmospheric Composition Humidity	GDOs or DROs + Multipliers >100mW DC power for ~10dBm RF output	MMIC-based superheterodyne integrated receivers: 300K at room temp @183 GHz Power <0.05W;mass<100g <1W; high level of integration; 5-10mW output up to 900 GHz
Ultra low power mmW front-ends	Water vapor and aerosol/cloud profiles	Combination of MMIC followed by CMOS receiver chipset has been demonstrated but only to 94 GHz; 300K at room temp @94 GHz Power <0.2W;mass<100g	300K noise temperature at room temp @183 GHz; Power <0.05W; mass<100g
G-band MMICs T/R modules; HPAs	Humidity; Cloud Ice	LNAs at 350K noise temperature; 1W GaN PA is TRL 6, internal switches with 1.5 dB loss at 183- GHz	1-10W W-band T/R modules with integrated PA, LNA, phase shifter (4-bit), low loss T/R switches;. 1W PA and CW source; GaN

Table G.2. Multiple Frequency Integrated Antenna Elements Technology Assessment

Technology Thrust Area	Measurement	State-of-the-Art	Notional Requirements
Broadband integration of radiometer and radar transmitter and receiver modules	Root Zone Soil Moisture Sea Surface Salinity Air-Sea Flux Sea Ice	Separate instruments or narrow band diplexer	Frequency range P/ L/ S-bands (400 MHz through 2-GHz) Low impact to the operation and performance of either sensor while reducing SWaP-C for multiple band measurements
Integration of Radar transmitter and receivers with radiometry	Precipitation	Frequency multiplexors and separate receiver chains	Instrument front-end with small SWaP; allows use of many units with fleet of cubesats
Integration of radar transmitter and receiver/ polarimeter	Ocean Altimetry Ocean Winds	Separate instruments	Single radar/ radiometer/ polarimeter to perform Ocean altimetry and/or scatterometry combined with polarimetry (passive)

Table G.3. Technology Assessment to Support Overall Miniaturization of Microwave Sensors (SWaP; Deployables)

Technology Thrust Area	Measurement	State-of-the-Art	Notional Requirements
2-m class deployable antenna	Improved HSR for traditional measurements from small satellites; Precipitation Ocean Surface Winds Sea Ice Cloud liquid	6-m+ class deployable from larger rocket fairings; 0.7m deployable (TRL 6) from 1.5U; up to ~40 GHz for communication applications	Performance to ~600 GHz; stowed volume ~ 2.5U
MMIC-based radiometers and focal plane arrays covering multiple bands	Precipitation; Sea Ice; Cloud Liquid; Land Surface Characteristics	Discrete components and large feedhorn arrays driving SWaP for multi-band radiometer systems	Compact radiometer and reflector feed systems with deployable antennas reducing SWaP-C of traditional radiometer systems

Table G.4. Technology Assessment for Large Reflectors and Lightweight Materials

Technology Thrust Area	**Measurement**	**State-of-the-Art**	**Notional Requirements**
Very Large Antennas	Weather Radar, Surface Deformation, Volcanic Ash, Ice	10-m class reflector antennas (Communications pedigree)	Larger deployable antennas
Lightweight antenna structures	Weather Radar (persistent cloud /storm observation), Seismology, Hazard monitoring	Ground based, L-band, Doppler Weather radar	Space-based persistent observation

Table G.5. Sensor Calibration Technology Assessment

Technology Thrust Area	**Measurement**	**State-of-the-Art**	**Notional Requirements**
Direct SI-Traceable Calibration	In order of priority: Atmospheric Temperature Profile, Precipitation (multiple radiometers); water vapor, ocean surface and clouds	Individual radiometer cal/val and Cross calibration analysis with other radiometers	Uniform calibration between fleet sensors all traced to SI-standard
Improved Calibration of UAV-based Radiometers	Tasked observations of Precipitation/ Hurricanes or atmospheric temperature	Internal calibration targets and thermal sensors	Combine information about ambient environment to improve unattended airborne (vs. space-based) instrument calibration and achieve uniform calibration among several sensors and platforms
Distributed calibration for Synthetic Thinned Aperture Radiometers	Atmospheric Temperature, Water Vapor and Precipitation	TRL 6	Space qualification to <1K

Table G.6. Technology Assessment of Digital Processing Performance Improvements

Technology Thrust Area	Measurement	State-of-the-Art	Notional Requirements
High Speed Digital Backends	Atmospheric Composition; Polarimetry (OSWV; EPBR)	20-GHz Digital back-end	50-GHz
Broadband Radiometers	Imaging radiometry in areas of significant RF contamination	RFI detection and mitigation in BWs up to ~500 MHz	Spectrometer to support measurements anywhere from 1 – 50 GHz
Distributed Correlators	Root Zone Soil Moisture	Correlation of several small antennas within fixed frame	< 100 MHz BW with limited baselines in constellation

Table G.7. Assessment of Next Generation Data Processing and Management Needs

Technology Thrust Area	Measurement	State-of-the-Art	Notional Requirements
Ground data management	Weather prediction; L3 / L4 products from L2 products; Atmospheric boundary layer dynamics; global circulation	Mission centric data processing to L2 data and distribution to a few centers	Evolving data assimilation and fusion of L1/2 data to larger systems (e.g. NWP); 'global' distribution of vetted higher level products
Inter-spacecraft metrology for formation control	Root Zone Soil Moisture; Precipitation	Independent platform attitude control; limited control; limited dual satellite control (GRACE)	Inter-spacecraft metrology for formation control; control/knowledge adequate to synthesize larger apertures using formation flying of small satellites
Fast external data links	Weather imagery; precipitation events	Data downlinks and ground based data exchange	Fast external data links; data sharing information to facilitate data processing/ attitude control; autonomous tasking