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Parametric Evaluation of Cold-land Processes Measurement Technologies

Cold Land Processes Working Group

Terrestrial Hydrology Program

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Executive Summary

This report identifies major technology developments needed to support future global measurement of snow water equivalent (SWE) and snow wetness. These two variables have been identified as critical snowpack characteristics requiring accurate measurement to support several key science questions posed by NASA's Earth Science Enterprise (ESE). Results from the Cold Land Processes Experiment (CLPX) and other studies have demonstrated that within a broad range of landscapes these snowpack characteristics exhibit significant spatial variation at scales on the order of 100-m. However, current NASA capability to measure these characteristics is limited to coarse-resolution microwave sensors, such as the Advanced Microwave Sounding Radiometer (AMSR-E). The resolution of these sensors far exceeds the spatial variation of these snowpack properties and associated physical processes. This increases the measurement uncertainty, and constrains NASA's capability to assess and understand the variability of these critical cold-region characteristics and their effects on local, regional, and global water and energy cycles. To significantly improve the accuracy of remotely sensed snow measurements, resolutions of 100-m or better are necessary. The only spaceborne microwave remote sensing approaches capable of achieving this resolution are active (radar), and current research is showing great potential for retrieving these snowpack properties using this approach. However, a combined active/passive approach is considered optimal if a spatial resolution of 5-km or better can be achieved for the passive measurements in addition to 100-m or better active measurements. Frequent repeat measurements (1-3 days) are also required. The optimal sensor system for accurate measurement of snowpack characteristics to address NASA ESE science needs is thus an active or active/passive sensor system, flown on the same platform or on separate platforms in formation, at resolutions on the order of 100-m or better for active and 5-km or better for passive, with a repeat interval of 1-3 days. This report identifies and prioritizes the technology development needed to enable improved snow measurements with these characteristics.

Six technology scenarios (three active, three passive) were evaluated independently for their potential to support improved snow measurements. The three active microwave scenarios were:

1) Ku-band interferometric SAR (Ku IFSAR),
2) Ku-band SAR and L-band SAR (Ku/L-SAR),
3) Ku-band interferometric SAR and L-band SAR (Ku-IFSAR/L-SAR).

The three passive microwave scenarios were all dual-frequency with 19- and 37-GHz, and included:

1) Real-aperture microwave radiometers (RA),
2) Two-dimensional synthetic thinned array microwave radiometers (2D-STAR),
3) One-dimensional synthetic thinned array microwave radiometers (1D-STAR).

The potential compatibility between these active and passive approaches to support a combined active/passive system was considered in the evaluation. A downselection process narrowed these options to just two for additional study: the dual-frequency Ku/L-band SAR for active, and the 1D-STAR for passive.

Three technological approaches to the dual-frequency SAR antenna were considered: 1) a 50-m by 1-m planar phased-array antenna, 2) a 15-m by 2.5-m planar phased array antenna, and 3) a cylindrical reflector antenna. For the 15-m by 2.5-m planar antenna, only one enabling technology was identified: high-efficiency L-band and Ku-band TR modules (Table ES1).

Several cost-reducing technologies were identified for this approach, including lightweight structures, large membrane antenna materials, membrane-compatible electronics, signal distribution, shielding for radiation tolerance, thermal management, and several systems technologies. For the other two dual-frequency SAR antenna concepts, each of the above were enabling technologies. Cost-reducing technologies for all three options included high-power, high-efficiency solid state receivers, integrated rad-hard low-power components, and large-scale manufacturing.

Enabling technologies for the passive options included mesh development, STAR integration, and linked technology-science issues of instrument calibration and algorithm complexity. Cost reducing technology development for the passive approaches include low power receivers, sensor packaging, data downlinks, and on-board data processing (Table ES2).

Table ES1 (2.8) *Technology needs matrix for all antenna configuration options. Option 1: 50mx1m planar phased-array antenna. Option 2: 15mx2.25m planar phased-array antenna. Option 3: Cylindrical reflector antenna.* **CR** *– Cost Reducing technology or technology which will provide increased performance/capability.* **E** *– Enabling technology (required for mission feasibility).* **NR** *– Not required for this option.*

	Option 1	**Option 2**	**Option 3**
Technology	**50m Long SAR**	**15m SAR**	**Cylindrical Reflector SAR**
Lightweight structures: High-stiffness deployment systems with high packing-efficiency; inflatable/rigidizable and mechanically deployable structures; membrane tensioning.	E	**CR**	E
Large membrane antennas materials: Durable, low loss thin-film membrane antenna materials; array feed technique compatible with the membrane electronics and array architecture.	**E**	**CR**	**NR**
High-efficiency L-band & Ku-band T/R modules: Class-E/F L-band and Ku-band SSPA; membrane compatible T/R modules.	**E**	**E**	**E**
High-power, high-efficiency Solid State devices: Explore emerging semiconductor device technologies: Si, GaAs, SiC and GaN power amplifiers at L-band and Ku-band. SiGe digital circuits.	**CR**	**CR**	**CR**
Integrated, rad-hard, low power components: Low power DCG ASIC; TTD devices; L-band digital receivers; digital filters; MEMS and BST phase-shifters.	**CR**	**CR**	**CR**
Membrane compatible electronics: Advanced packaging technologies including die thinning and attachment technologies to enable the reliable, direct attachment of thinned die onto membrane; embedded electronics (vs. attachment alone) to embed the die in the structure for added reliability.	**E**	**CR**	**NR**
Signal distribution: Technologies to simplify the interconnection of thousands of unit cells on the array; reliable RF, control, power and data distribution. Lightweight, low-loss, membrane-compatible interconnects for RF, data and power distribution	**E**	**CR**	**E**
Shielding for radiation tolerance: Since the conventional bulky package is not envisioned for the T/R module, the radiation protection of the device has to be accomplished through other methods of shielding and coatings. Die thinning for improved radiation tolerance.	**E**	**CR**	**NR**
Passive and active thermal management: Radar transparent thermal control coatings; variable emissivity surfaces/coatings; integrated micro heat pipes.	**E**	**CR**	**E**
Large-scale manufacturing: Low-cost methods of attaching thousands of components on the membrane in such a way that the antenna is manufacturable, testable and re-workable. New technologies, such as roll-to-roll manufacturing process, are a crucial step to enable a cost effective solution.	**CR**	**NR**	**NR**
System: Digital beamforming and digital TTD steering; calibration, metrology and phase-correction.	**E**	**NR**	**E**

Table ES2 (3.5). *CLP technology development requirements and associated priority for component technologies (upper panel) and system technologies (lower panel).*

Section in Text	WBS.items for Component Technologies	Real Aperture	Y-STAR	Cylindrical	Cylindrical plus radar	Real Aperture plus radar
3.4.1.1	1C.Meshes	Enabling		Enabling	Enabling	Enabling
3.4.1.3	2C.Low power receivers	Enhancing	Infeasible	Cost reduction	Cost reduction	Cost reduction
3.4.1.2	3C.BAPTA	Cost reduction				
3.4.1.4	4C.Sensorcraft vs. fairing			Cost reduction	Cost reduction	
3.4.1.5	5C. downlink		Cost reduction		Cost reduction	Cost reduction
Section in Text	**WBS items for System Technology Trades**	**Real Aperture**	**Y-STAR**	**Cylindrical**	**Cylindrical plus radar**	**Real Aperture plus radar**
3.4.2.1	1S.STAR integration	Enhancing	Enabling	Enabling	Enabling	
3.4.2.2	2S.On-board data processing	Enhancing	Infeasible	Cost reduction	Cost reduction	Cost reduction
3.4.2.3	3S. instrument calibration/algorithm complexity	Enhancing	Enabling	Enabling	Enabling	

A technology development roadmap was prepared for both the active and passive approaches. Lightweight, high-power, deployable L-band and Ku-band phased arrays are the highest priority for the active concept (Table ES3 (2.9)). This includes: high-efficiency T/R modules, membrane antennas and lightweight deployment structures. Membrane antennas could reduce the cost of near-term missions as well as enable more advanced large aperture systems envision for the next decade. NASA needs to push this technology development since research in this field is limited. Incremental improvements in conventional rigid panels (to reduce mass and cost) is also important, although slightly lower priority since industry leads this work. Metrology and

Table ES3 (2.9). *Cold land processes mission technology development plan for dual-frequency (L/Ku-band) SAR with <100 m spatial resolution and >500 km swath width for snow water equivalent (SWE) and snow wetness with 10% relative accuracy over land above 50-deg latitude with 3 day repeat.*

Cold Land Process Mission (CLPM) Technology Development Plan

Dual-frequency (L/Ku-band) SAR with <100 m spatial resolution and >500 km swath width for snow water equivalent (SWE) and snow wetness with 10% relative accuracy over land above 50-deg latitude with 3 day repeat.

Estimate of Incremental Cost to Reach Indicated TRL

current TRL — TRL not applicable to this item

Technology Deliverable	Requirement Metric	Priority 1=highest 2=high 3=less urgent objective	TRL 1 Basic principles observed and reported	TRL 2 Technology concept and/or application formulated	TRL 3 Analytical & experimental critical function and/or characteristic proof of concept	TRL 4 Component and/or breadboard validation in laboratory environment	TRL 5 Component and/or breadboard validation in relevant environment	TRL 6 System /subsystem model or prototype demonstration in a relevant environment
Lightweight Deployable Antennas								
Rigid Deployment Structures								
50m deployable truss	<1kg/m	1				$1.5M	$3M	$5M
50m inflatable/ridigizable booms	<1kg/m	1				$3M	$5M	$10M
15m deployable truss	<5kg/m	1						
15m deployable truss	<1kg/m	1				$1.5M	$3M	$5M
High strength, low-loss membrane materials		1				$500K	$1M	
Membrane tensioning and adaptive shape control		1			$300K	$500K	$1M	$5M
L-band & Ku-band Long SAR Array Aperture (50m antenna)								
50m active membrane phased-array aperture (L-band)	5KW, $2kg/m^2$	1		$300K	$300K	$1M	$5M	$8M
50m active membrane phased-array aperture (Ku-band)	>8KW, $2kg/m^2$	1		$300K	$300K	$1M	$6M	$10M
Membrane compatible electronics and interconnects		1			$300K	$500K	$1M	
Metrology/calibration for membrane antenna deformation	1mm for Ku-band	1			$300K	$500K	$1M	
Signal distribution (RF, control, power)		1			$500K	$500K	$2M	$5M
High power thermal management of membrane arrays		1			$300K	$500K	$1M	
Digital beamforming techniques		3			$500K	$500K	$1M	$5M
L-band & Ku-band Active Phased Array (15m antenna)								
15m lightweight rigid panel phased-array aperture (L-band)	5KW, $10kg/m^2$	1					$2M	$5M
15m lightweight rigid panel phased-array aperture (Ku-band	>8KW, $10kg/m^2$	1					$3M	$7M
15m active membrane phased-array aperture (L-band)	5KW, $2kg/m^2$	2			$300K	$1M	$5M	$8M
15m active membrane phased-array aperture (Ku-band)	>8kw, $2kg/m^2$	2			$300K	$1M	$6M	$10M
Membrane compatible electronics and interconnects		2			$300K	$500K	$1M	
Metrology/calibration system for membrane antennas	1mm for Ku-band	2			$300K	$500K	$1M	
Signal distribution (RF, control, power)		1			$500K	$500K	$2M	$5M
High power thermal management		1			$300K	$500K	$1M	
5-beam ScanSAR		1					$1M	$2M
L-band & Ku-band Cylindrical Reflector Antenna								
7.5mx4.5m cylindrical mesh reflector (L/Ku-band)		3			$300K	$1M	$5M	$8M
4.5m rigid panel phased-array feed (L-band)	5KW, $10\text{-}15kg/m^2$	3					$2M	$5M
4.5m rigid panel phased-array feed (Ku-band)	>8KW, $10\text{-}15kg/m^2$	3					$3M	$7M
10-beam ScanSAR (L-band)		3			$300K	$1M	$2M	$5M
25-beam ScanSAR (ku-band)		3		$200K	$300K	$1M	$2M	$5M
Active thermal control for feed		3			$300K	$500K	$1M	$5M
Radar Sensor Electronics								
RF Components & Devices								
Rad-hard L-band T/R modules	10-30W, 60% efficient	1				$500K	$500K	$2M
L-band Class-E/F power amplifiers	10-30W, 70-90% efficient	1				$300K	$300K	
SiC & GaN L-band power transistors	10-30W	2			$200K	$200K	$300K	
Low loss L-band RF switches and phase shifters	<0.5dB per switch/bit	2					$500K	
Low loss L-band TTD devices		2		$200K	$300K	$1M	$2M	
Rad-hard Ku-band T/R modules	5-20W, 60% efficient	1				$500K	$500K	$2M
Ku-band Class-E/F power amplifiers	5-20W, 60-80% efficient	1				$500K	$500K	
GaN Ku-band power transistors	5-20W	2		$200K	$300K	$500K	$500K	
Low loss Ku-band RF switches and phase shifters	<1dB per switch/bit	2			$300K	$500K	$500K	
Low loss Ku-band TTD devices		2		$200K	$300K	$1M	$2000K	
Low Power/Rad Hard Digital Electronics								
On-board SAR digital processors		3			$300K	$500K	$2M	$5M
High-speed, low power8 to12 bit A/D converters	>2Gsps, mw	3					$2M	
High-speed integrated (ASIC) low power waveform generat	>2GHz, 1MRad	3		$ 200 K	$300K	$500K	$2M	
L-band digital receivers and digital filters	1GHz, 1MRad	3			$300K	$500K	$2M	

calibration is critical for the large aperture array option. Less urgent objectives include research in new materials and devices since there is sufficient investment already in these areas. Our approach is to incorporate new and emerging component technologies as they mature.

The mesh technology and receiver power technology are all needed immediately and will have important applications outside of CLP. Development of the platform, packaging/sensorcraft, and downlink technologies is also important, but must remain flexible to be responsive to both an evolving CLP measurement concept and emerging industry technology developments (Table ES4 (3.6)).

The most important technology investment for the passive-microwave and combined active/passive approaches discussed in this section is a tradeoff study of instrument-algorithm complexity relationships. It has the potential to guide all the other technology development efforts identified. And conversely, the outcomes of the component and systems technology efforts, as they become available, will likely influence the instrument-algorithm tradeoff. This study will have the largest and most global payoff with respect to reducing CLP measurement risk and cost. Yet because it must consider both technology and science issues together, it must be protected from “falling through the cracks” between traditional programmatic boundaries at NASA.

This report is organized in three sections. Section 1 provides brief background information that was used to guide the study. Section 2 reports on the active microwave components of the study. Section 3 reports on the passive microwave components of the study.

Table ES4 (3.6). *Passive microwave technology development roadmap.*

WBS.Component Technologies	2003-2004 Component Technology opportunity (e.g. ACT)	2005-2006 Component Technology opportunity (e.g. ACT)	2007-2008 Component Technology opportunity (e.g. ACT)
1C.Meshes	Characterize new materials and test emissivity__(37 Ghz)(TRL1)	Build reflector w/ new materials (37 GHz)	
2C.Low power receivers	Develop LP receivers 0.3 watts DC power (TRL3)________________	Repackage receivers as sensorcraft components discrete front ends/FPGAs to LP Designs to MMIC/ASIC	Convert to rad-tolerant low power designs
3C.BAPTA	Develop slip rings, roll rings w/ KW power handling,(TRL2)	Trade despun xmit horn vs. rotating w/ new KW BAPTA data.	Demo BAPTA in 1G for RA reflector ≥ 6m dia., MOIs , 8 rpm
4C.Sensorcraft vs. fairing	Design wraparound structure and components for reflectors Trade against larger fairings(TRL2)	Fit check by analysis in Delta II Demonstrate surface figure w/ sensorcraft components	
5C. downlink	K-band (TRL 6) optical (TRL 4)	Trade STAR/SAR imaging / vs. cost of downlink components	Reassess CLP downlink reqmt. Invest based on current on-bd. Processing/downlink trade

Technology Trades	2003-2005 System Technology Analysis and/or demonstration opportunity (e.g. IIP)			2006-2008 System Technology Analysis and/or demonstration opportunity (e.g. IIP)	
1S.STAR integration	Model and build facets prototype to required surface figure (0.3 mm @ 19 GHz)		Insert 1C, 2C	Demo STAR deployment	, Insert new components from 1C, 2C
2S.On-board data processing	Trade Image return vs. correlations Revisit TRLs of separate RA, SAR approach vs. combined STAR/SAR instrument approach			Insert 3C and/or Insert 4C based on 3S pick	Insert 5C based on d/l requirement
3S. Instrument-algorithm complexity	Study system stability of STAR		Compare CLP approaches – pick concept	Using CLP concept Calibrate and Generate performance data in thermal vacuum	

1. BACKGROUND

1.1. Science Background

The Cold Land Processes Working Group (CLPWG) was formed in 2000 by the NASA Terrestrial Hydrology Program to identify, develop, and implement the science, technology, and application infrastructure necessary to support advanced remote sensing measurements to the terrestrial cryosphere. The CLPWG has identified key science objectives that new measurements must address in order to be responsive to Earth Science Enterprise research priorities. The two principal microwave remote sensing measurement objectives that are necessary to support science objectives are: 1) snow water equivalent (SWE; the total amount of frozen or liquid water contained in a unit area of snow cover – a function of snowpack depth and density), and 2) snow wetness (the percentage of the liquid water in a snowpack).

Microwave sensors appear ideal to measure these and other properties of the terrestrial cryosphere because the microwave signal is sensitive to the dielectric constant of surface materials, which in turn is sensitive to the phase of water, ice or liquid. Passive microwave sensors are also sensitive to the physical temperature of surface materials. Both active and passive sensors have demonstrated sensitivity to snow properties. Microwave signal response is influenced by several snow properties, including depth, density, wetness, crystal size and shape, ice crusts and layer structure, surface roughness. It is also influenced by vegetation characteristics, soil moisture, and the freeze/thaw status of the soil (i.e. beneath the snowpack). This high sensitivity to snowpack properties, the ability to penetrate most cloud covers, and the ability to measure during winter when solar illumination is low, are important attributes that identify microwave remote sensing as the best approach for measuring SWE and snow wetness. The high sensitivity to many properties of the snowpack and its surroundings also fundamentally shapes the technology challenges for accurate measurement of SWE and snow wetness.

Multiple microwave measurements (e.g. multiple frequencies, polarizations, phase information, and measurement of both active backscatter and passive emissions) are necessary to isolate the complex effects of different snowpack, vegetation, and underlying soil properties and to distinctly determine SWE and snow wetness. A multiple-frequency approach to microwave measurement of SWE and snow wetness is based on differential response to snowpack properties at different frequencies. For radar backscatter measurements, higher frequencies (e.g. Ku-band) are scattered mainly by the surface of the snowpack, while lower frequencies are scattered within the volume of the snowpack (e.g. C-band) or at the interface between the snowpack and the ground (e.g. L-band). This differential scattering behavior, together with the additional effects of different polarizations, help isolate and determine snowpack properties. Similarly, scattering of terrestrial microwave emissions by the snowpack varies significantly between 19-GHz and 37-GHz, which allows further deduction of snowpack properties from microwave radiometer measurements. Achieving this suite of multiple measurements introduces some technology challenges.

Given the need for multiple measurements, the technology challenge is made significantly greater by a need for high- to moderate-resolution data. An objective resolution of 100-m has been identified for remotely sensed snow measurements. A coarser threshold resolution (5-km) has been identified for passive microwave measurements, recognizing on one hand the physical resolution limitations of this approach, and on the other the benefits provided in a combined active/passive approach, even at this coarser resolution. There are two main science drivers for 100-m resolution. The first is that the natural heterogeneity of snowpack properties (that affect both microwave and hydrometeorological response) is typically very high. For example, results from the recent Cold Land Processes Field Experiment (CLPX) showed that the average correlation length scale (distance at which correlation of two measurements becomes zero) of snow depth in nine different environments was less than 150-m. This means that at resolutions approaching or exceeding the correlation length scale, interpretation of microwave measurements of snow and isolation of the effects of different snow properties is made more complex because there is a large variance in snowpack properties within the footprint. In this case, deduction of SWE and snow wetness based directly on physical principles of microwave interaction with the snowpack is very complicated at best. The second science driver for 100-m resolution is that predictive earth system models currently have land surface components operating at 1-km spatial resolution for continental and global-scale applications. It is conceivable and perhaps even likely that this resolution will increase in the next decade. This modeling resolution is driven by a scientific need to represent relevant physical processes correctly, and to capture the natural heterogeneity of land surface processes. The need to update these models with observed SWE and snow wetness is an important driver for remotely sensed measurements of these properties, and a fundamental requirement in this regard is that the measurement resolution should exceed the modeling resolution by at least a factor of two.

1.2. Technology Background

A combined active/passive approach to measurement of SWE and snow wetness currently has the greatest science benefit and interest. The CLPWG conducted a technology workshop in Ann Arbor, Michigan (November 19-20, 2002) to a) review the measurement objectives described above, b) identify appropriate technology approaches to accomplish these objectives, and c) identify technology development necessary to advance these approaches. For the active microwave component, the major technology issue identified was how to achieve retrieval accuracy through multiple radar measurements at an affordable cost. For the passive microwave component, the major technology issue identified was how to achieve greater spatial resolution. For the combined approach, the major issue is reduction of mass, power and costs associated with multiple instruments through innovative design and use of new technologies. It was also recognized that there are many common technologies shared by both the active and passive approaches, whether they are integrated or not.

Six independent technology scenarios were developed in the Ann Arbor workshop. The three active microwave scenarios were:

1) Ku-band interferometric SAR (Ku IFSAR),
2) Ku-band SAR and L-band SAR (Ku/L-SAR),
3) Ku-band interferometric SAR and L-band SAR (Ku-IFSAR/L-SAR).

The three passive microwave scenarios were all dual-frequency with 19- and 37-GHz, and included:

1) Real-aperture microwave radiometers (RA),
2) Two-dimensional synthetic thinned array microwave radiometers (2D-STAR),
3) One-dimensional synthetic thinned array microwave radiometers (1D-STAR).

Each of these measurement approaches was briefly developed and evaluated during the Ann Arbor workshop, and the results for all six scenarios were input to the ESTO Technology Needs Assessment Database as measurement scenarios for “Snow Cover over Land” (Appendix One).

Considered either independently or in combination, these scenarios involve multiple inter-linked trade-offs for both science and technology. In this study, the six scenarios were evaluated in detail to better understand these trade-offs, to identify the technological challenges of each scenario, and to identify the technological challenges of combining the active and passive scenarios.

1.3. Evaluation Approach

For each measurement scenario, a more complete measurement concept was developed that included the instrument configuration and flight geometry. Science objectives and technological approaches are both intrinsically linked to how a sensor might ultimately be flown, so nominal orbital parameters (e.g. temporal revisit, spatial resolution, and basic orbital parameters) were developed from the science measurement objectives to guide the study. An orbit analysis was performed to ensure that the concept would meet basic science measurement requirements. Once each instrument configuration was identified, an instrument system analysis was performed to determine key system parameters, such as transmit power, polarization, pulse repetition frequency, receiver noise figure, antenna gain, etc. The projected science measurement performance was then evaluated over a range of key system parameters to examine the sensitivity of performance to key parameters.

From the results of the system-level analysis, the technology drivers were identified and prioritized, with particular consideration to those technologies common to both the active and passive scenarios. From the preliminary design parameters candidate antenna technologies and instrument approaches were assessed with consideration for relevant deployment and packaging technologies. The cross-compatibility of each concept was explored to identify which scenarios were scalable within performance metrics for accuracy and resolution, and which possess the greatest potential for a combined active/passive measurement system.

The six scenarios were then down-selected to two for further assessment. The surviving active and passive scenarios (the Ku/L-SAR and the 1D STAR) were further evaluated to identify significant technology challenges peculiar to either scenario, and any technological challenges imposed on the sensor platform by these scenarios. Last, to ensure a thorough study, completeness of the overall conceptual measurement system, and the system-level compatibility of the technology components, the technologies for each surviving scenario were evaluated in an end-to-end mission-design context. A scenario combining the 1D-STAR approach with a Ku/L SAR approach was also considered in an end-to-end mission design context, because these two approaches could share a similar cylindrical reflector concept and the potential for a shared-aperture active/passive system was recognized.

1.4. Nominal Measurement System Parameters Used for Study Guidance

The capability of a given measurement scenario to address science objectives depends to some extent on the resolution, accuracy, and coverage required for the measurement, and on how the sensor might ultimately be flown to achieve these requirements. Nominal parameters for the six measurement scenarios were identified to guide the study.

1.4.1. Measurement Spatial and Temporal Resolution

The nominal measurement resolution used for all scenarios was 100-m for the active microwave component and 5-km for the passive microwave component. A repeat interval of 1-3 days was considered.

1.4.2. Measurement Accuracy

The technology necessary to make a measurement of snow properties from a remote sensor depends on the accuracy necessary for the measurement. For purposes of this study, measurement accuracy objectives were imposed that are desirable scientifically, but known to be technologically challenging. For snow water equivalent, the guideline objectives were 10% relative accuracy for SWE of 0.3 m or greater, and 0.01 m absolute accuracy for SWE less than 0.3 m. For snow wetness, the guideline objective was 2% absolute accuracy. Snow wetness typically exhibits only a narrow range between 0-8%, so 2% absolute accuracy is roughly equivalent to 25% of the range.

1.4.3. Flight Parameters to Guide Measurement Scenario Development

Four measurement goals have a direct effect on flight characteristics, which in turn influence technology needed to obtain the measurement. First, the optimal measurement times for cold-land process observations are during mid-afternoon and early morning (pre-dawn) to capture the extremes of diurnal warming and cooling cycles. Second, the measurements need to be repeated every 1-3 days at the same time each day. Third, the highest quality and availability of measurements are preferred for the northern hemisphere. These objectives lead to a polar, sun-synchronous orbit at 600-775 km altitude with a nominal ascending equatorial crossing time of 7:00 p.m. Deviation from a 6:00 pm equatorial crossing increases the eclipse period with consequences for battery power requirements and other technology components; these effects are considered in this study. Fourth, measurement coverage is needed over all land areas at latitudes greater than 30^o (north or south) latitude and over oceans at latitudes greater than 50^o (also north or south).

2. RESULTS FOR THE ACTIVE MICROWAVE SCENARIOS

2.1. Measurement Concept Development

The measurement goal of 100-m spatial resolution requires the use of synthetic aperture radars (SAR). Two approaches have been identified, including the Interferometric SAR (InSAR) and the dual-frequency, polarimetric Synthetic Aperture Radar (POLSAR). The third measurement scenario suggested in the Ann Arbor Workshop is a hybrid of these two approaches. The InSAR measurement technique directly detects the changes of surface topography to estimate the temporal changes of SWE. The POLSAR measurement technique uses the distinctive frequency and polarization response of snow layer to delineate the volume scattering from snow and surface scattering from snow-ground interface.

Both InSAR and POLSAR measurement scenarios are evaluated to determine the key system parameters. Also completed was a sensitivity analysis to show how the measurement performance respond to the changes of key system parameters, including baseline length for InSAR and peak radar transmit power and chirp bandwidth, which influences the data rate.

2.1.1. InSAR

The InSAR instrument is a Ku-band interferometric SAR, which in its most basic form uses two antennas (one transmit, both receive) to obtain two radar images of the illuminated area (Figure 2.1). A more realistic InSAR deployed configuration is depicted in Fig. 2.2. After processing, the phase difference between the two images allows accurate estimation of the angle to each pixel, and thus when combined with range knowledge gives the 3-dimensional position of each pixel in the image.

Figure 2.1. *Cartoon depicting the InSAR measurement*

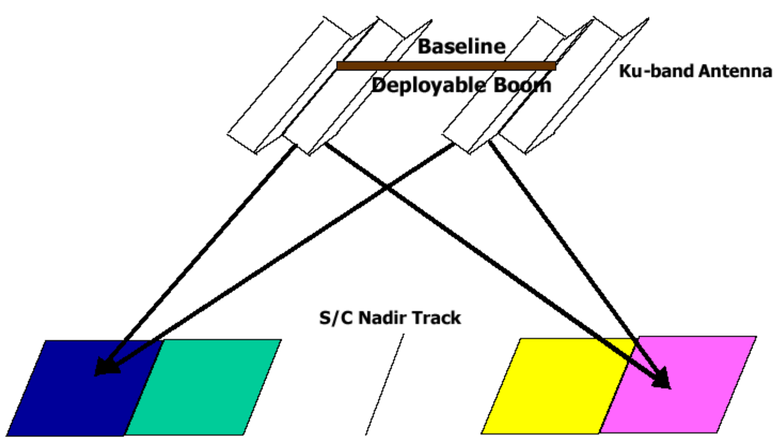
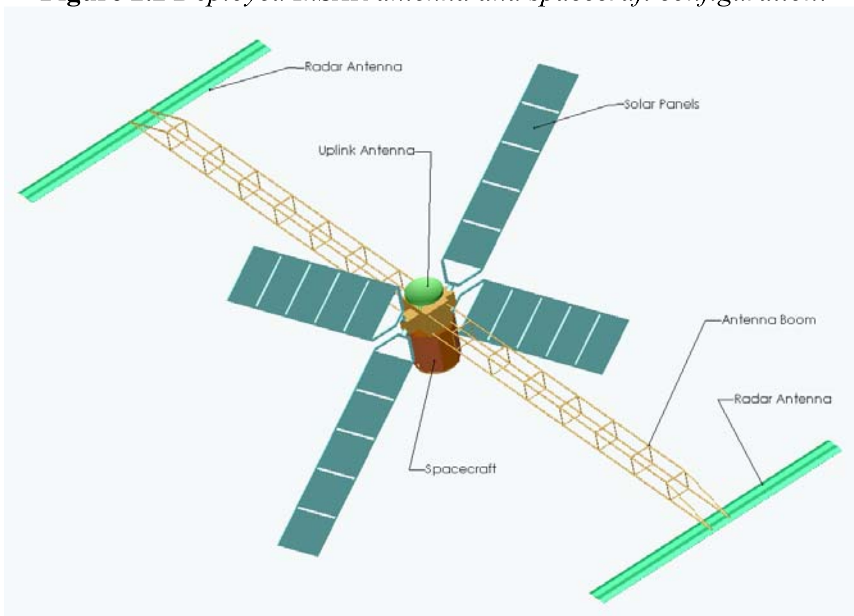


Figure 2.2 *Deployed InSAR antenna and spacecraft configuration.*



This instrument has 2 radars combined, one looking at the nearer 100-km of the swath, and the other looking at the farther 100-km. The instrument also alternates its look direction, so both sides of the trajectory are covered simultaneously, giving 600-km-wide coverage with the middle 200-km under the spacecraft missing. Figure 2.3 illustrates the swath coverage of the described sampling geometry for 3-day repeat, sun-synchronous, polar orbit at 613-km altitude. There is no complete coverage above 30-degree latitudes over three days. As will be shown later, an extra swath width of 150-km to 200-km is needed to complete the coverage over three days. This could be achieved by adding antenna panels.

To provide a reference for performance comparison and further sensitivity analysis, a baseline InSAR design concept is established with the key system parameters summarized in Table 2.1. The antennas are 10-m long by 0.16-m wide, to get sufficient range beam width at Ku band from a 600-km orbit altitude. The desired height error performance of less than 5-cm can be obtained for a 1-km cell size over most of the swath using a 40-m horizontal baseline, 50-MHz bandwidth, and 10-kW of radiated power. The height error performance is illustrated in Fig. 2.4 for three baseline lengths, 30-m, 40-m, and 50-m. In general 10-cm height accuracy corresponds to a nominal SWE of 3-cm, assuming 300 kg/m^3 for snow density. The minimal baseline length to achieve <3-cm SWE across the entire swath will be 40-m. However the performance degradation is gentle as the baseline length reduces to 30-m.

Figure 2.3. *Swath coverage of the interferometric synthetic aperture radar (InSAR) concept for three-day repeat, polar sun-synchronous orbit at 613-km altitude. Each satellite pass produces two sub-swaths separated by 200-km around the nadir. Each sub-swath starts and ends at 100-km and 300-km off the nadir, respectively. The total swath width is 400-km.*

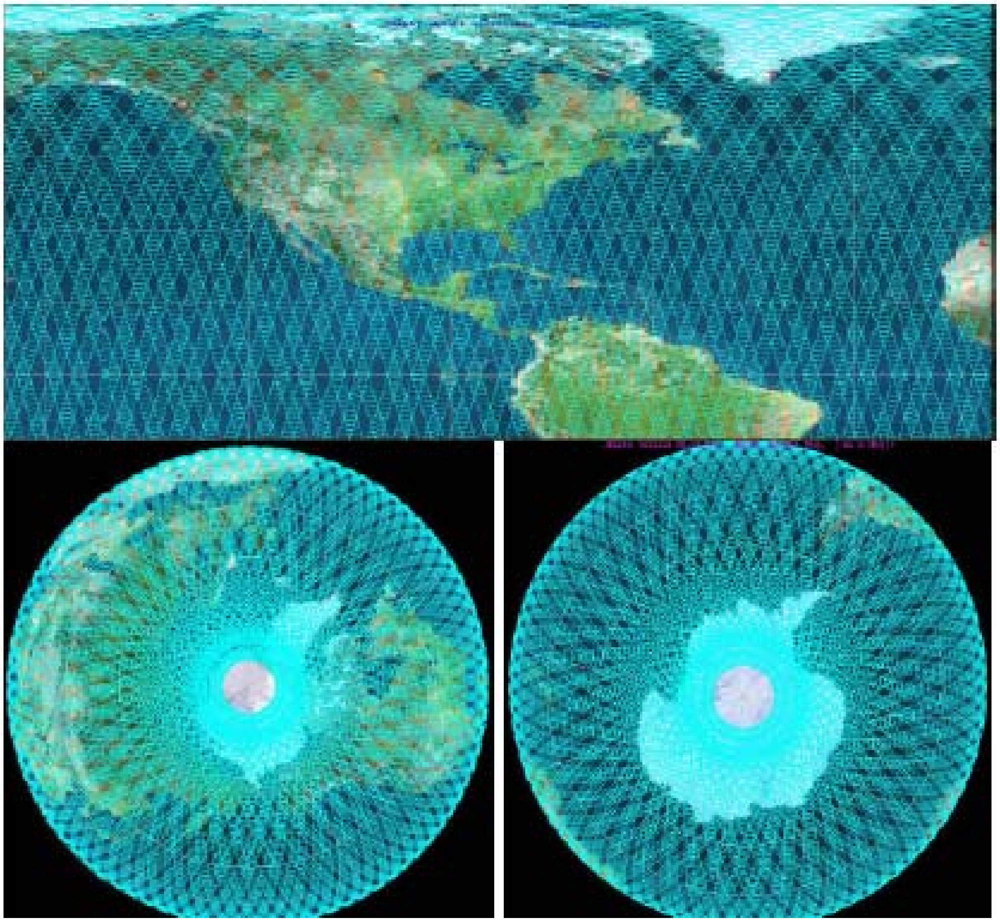
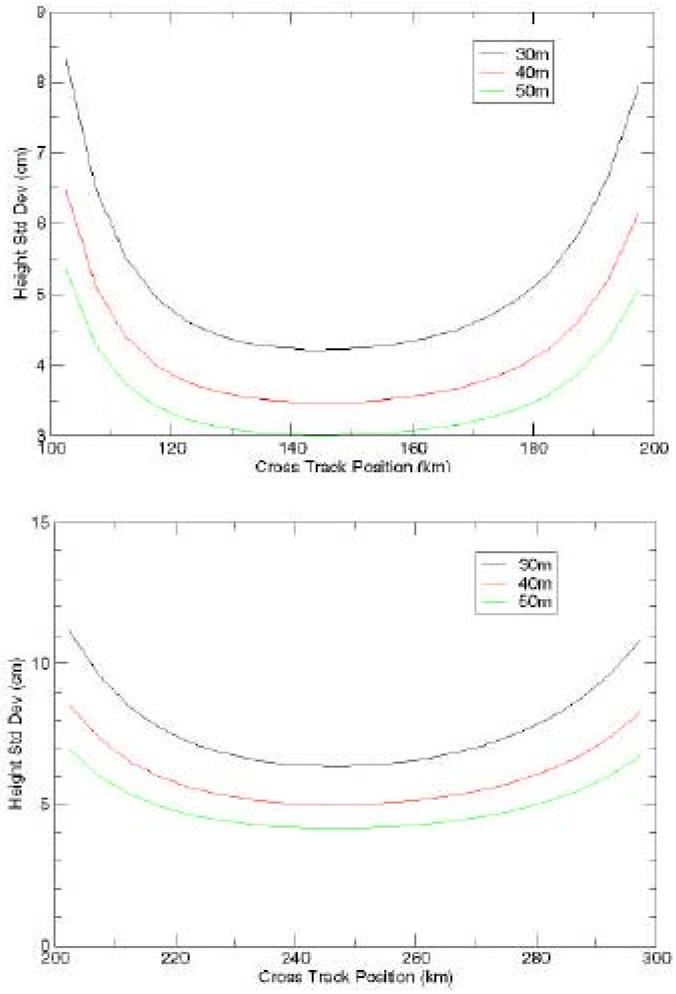


Table 2.1. *InSAR parameters.*

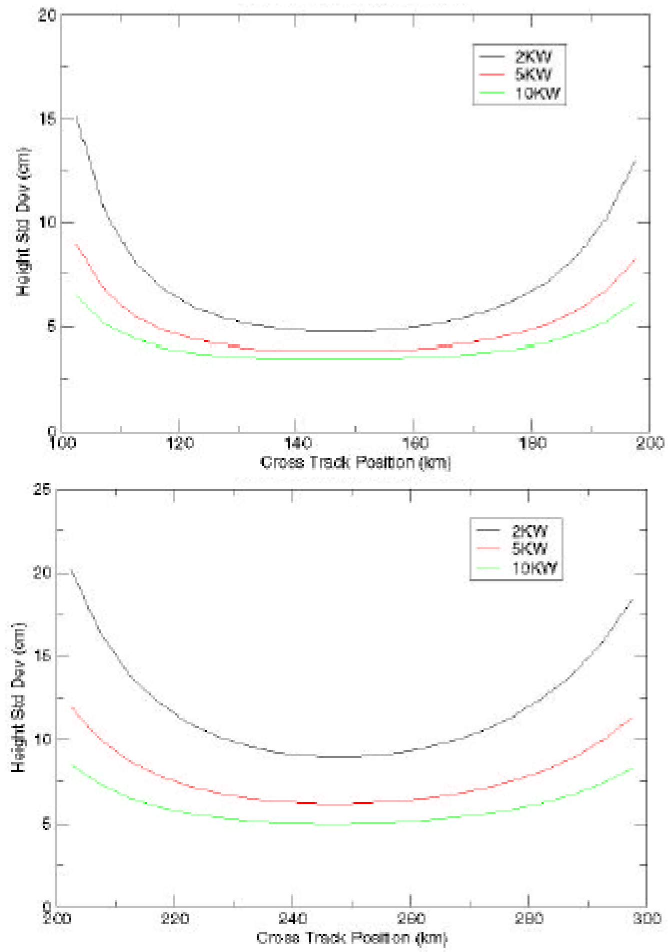
Parameters	Ku-InSAR-1	Ku-InSAR-2
S/C Orbit	Sun-synchronous, 600 km	
Frequency (GHz)	13.4	13.4+Offset
Antenna Size (each)	10 m x 0.17 m	10 m x 0.15 m
Number of antenna pairs	2	2
Antenna Beam Look Angle	14.5 degrees	23.0
Baseline length	30-50 m	30-50 m
Baseline angle	0 deg	0 deg
Swath width (location in cross track)	200 km (100-200 km)	200 km (200-300km)
Polarization	VV	VV
Radar Peak Transmit Power	2-10 kW	2-10 kW
Radar Chirp	50 MHz	50 MHz
PRF	1550 Hz	1480 Hz
Radar Transmit Pulse Length	200 us	175 us
Interferometric cell size	1 km	1 km
A/D	8 bit (4-bit BFPQ)	8 bit (4-bit BFPQ)
Raw Data Rate	250 Mbps	250 Mbps
Model Sigma0	-10 dB	-10 dB

Figure 2.4. *InSAR height measurement accuracy versus cross-track distance for 10-kW peak radar transmit-power. Each panel illustrates the performance for three baseline lengths: 30-m, 40-m, and 50-m. The upper panel is for cross-track positions from 100-200 km. The lower panel is for cross-track positions from 200-300 km. The spatial resolution is 1-km.*



Because the power consumption is a key cost driver for mission implementation, a performance analysis with varying radar transmit power was performed for a baseline length of 40-m. The results are illustrated in Figure 2.5. The performance degrades to about 7-8 cm (or 2-3 cm SWE) if the power is reduced to 5-kW, and increases to more than 10-cm if the power is reduced to 2-kW. Similarly, if the baseline is decreased to 30-m while the power is maintained at 10-KW, the random error increases to 9-11 cm, while if the baseline is increased to 50-m, the error decreases slightly to 5-7cm. There are serious difficulties increasing performance beyond this point, no matter how much transmitted power is available. One can continue to increase the baseline, but beyond 50-m, the geometric de-correlation increases, and so performance drops. It would be possible to increase looks by increasing bandwidth, but the SNR is decreased, so the error is not reduced. Decreasing the antenna length can also increase the number of looks, but the curvature decorrelation then becomes the dominant correlation factor, and the performance again degrades.

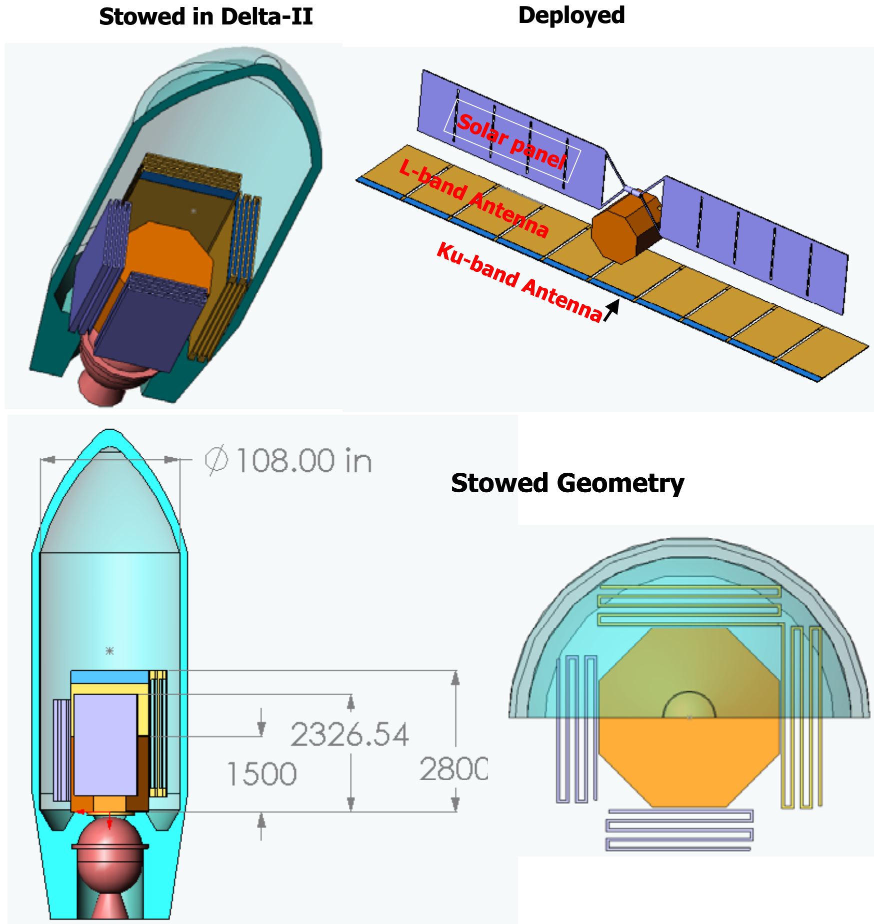
Figure 2.5. *InSAR height measurement accuracy versus cross-track distance for 40-m baseline length. Each panel illustrates the performance for peak radar transmit power of 2-kW, 5-kW, and 10-kW. The upper panel is for cross-track positions from 100-200 km. The lower panel is for cross-track positions from 200-300 km. The spatial resolution is 1-km.*



The performance trades for a reduced transmit power of 2-kW are illustrated for various baseline length in Figure 2.6. The shape of performance curves is similar to what is plotted in Figure 2.4.

In summary, there are a number of substantial technological challenges required for the InSAR system. First, there is the very large power requirement for 10-kW of radiated power at 30% duty cycle, for each radar channel. This power requirement could increase further, because the near-swath 100-km is probably too close and requires incidence angles which will produce a high degree of layover and loss of data. A viable system will probably have the swath between 200-km and 400-km from nadir, and at that distance the sub-swath will require even more power for the same performance. Second, both the antenna and baseline structures are quite large (40-m baseline) and must be very rigid as well. Third, metrology systems must be provided for absolute knowledge of baseline length and attitude, and if the revisit time is too large to allow cross-calibration of ascending and descending data takes, the absolute knowledge requirement on the

Figure 2.7. *Stowed and deployed concepts for the dual-frequency SAR using the Delta-II launch vehicle.*



baseline attitude for a 5-cm systematic error in the far swath is 0.034-arcsec, a very challenging requirement.

2.1.2. Dual-frequency SAR

The dual-frequency SAR design concept consists of an L-band/Ku-band polarimetric radar system (Figure 2.7). A point design with five ScanSAR beams to cover the desired swath width has been established for performance benchmark (Figure 2.8). The system parameters are listed in Table 2.2. There are three antenna concepts (Figures 2.9, 2.10, and 2.11) applicable to the dual-frequency polarimetric SAR measurement scenarios. Our analysis concluded that the power and data rate required by these concepts are very similar for the same measurement performance. Therefore we will use the five-beam ScanSAR concept as an example to illustrate the resource needs versus performance. Detailed discussions of alternate antenna options are provided in the next section.

The dual-frequency SAR images the earth at a side-looking orientation (Figure 2.8). The electrical bore sight of the antenna points at about 30^o off-nadir. An orbit sampling analysis was performed to examine the swath coverage requirement for 3-day revisit. Figure 2.12 illustrates the spatial coverage over 3-day period for 6 swath widths in the range of 300-650 km for 3-day repeat polar, sun-synchronous orbit with 98.6^o inclination angle at 775-km orbit. A swath width of slightly greater than 600-km is needed to achieve complete coverage above 30^o latitude. However, a reduced swath width of 550-km can provide nearly complete coverage, only with some small gaps at about 45^o latitude.

The L-band and Ku-band radars share many common subsystems such as the control and timing unit, the chirp generator, and the digital subsystem. However, these two radars have separate RF subsystems to handle the frequency up/down-conversion and separate antenna subsystems. The antennas are active phased-array antennas with beam steering capability in the cross-track direction to operate in ScanSAR mode. The estimated radar performance is summarized in Table 2.3 assuming an output pixel size of 100-m by 100-m.

Table 2.2. *Summary of the system parameters for the dual-frequency SAR parameters.*

Parameters	**L-band Radar**	**Ku-band Radar**
S/C Orbit	Sun-synchronous, 800 km	
Frequency (GHz)	1.26	13.4
Antenna size (each SCANSAR beam)	15 m x 2.25 m	15 m x 0.23 m
Antenna peak gain	39.1 dB	49.4 dB
Number of Scan SAR beams	5	5
Antenna Bore sight	40 degrees	
Antenna Look Angle	20-45 degrees	
Antenna Beam Incidence	23-53 degrees	
Antenna Beamwidth (Elevation, Azimuth)	5.2 deg, 0.75 deg	4.9, 0.075deg
Antenna Side lobe (Elevation, Azimuth)	15 dB, 13.3 dB	15 dB, 13.3 dB
Swath Width	560 km	560 km
Polarization	VV, HV	VV, HV
Radar Peak Transmit Power	4 kW	5-7 kW
Radar Chirp	20 MHz	20 MHz
PRF	0.9-1.5 kHz	0.9-1.5 kHz
Radar Transmit Pulse Length	80 us	80 us
Radar Sensitivity for 100 m Resolution	0.7 dB (20 looks)	0.7 dB (20 looks)
A/D	8 bit	8 bit
Noise-Equivalent Sigma0	-30 dB	-22 dB
Data Rate (4-bit BFPQ compression)	240 Mbps	240 Mbps
Data Rate (pre-sum over 2 pulses)	120 Mbps	120 Mbps
DC Power for Antenna with T/R Module (35% efficiency)	2200W	2300W
DC Power for Instrument (inc. antenna)	2400 W	2500W

Figure 2.9. *Antenna option 1 for dual-frequency SAR: array antenna element/module layout configuration. The total aperture is 50-m x 1.08-m.*

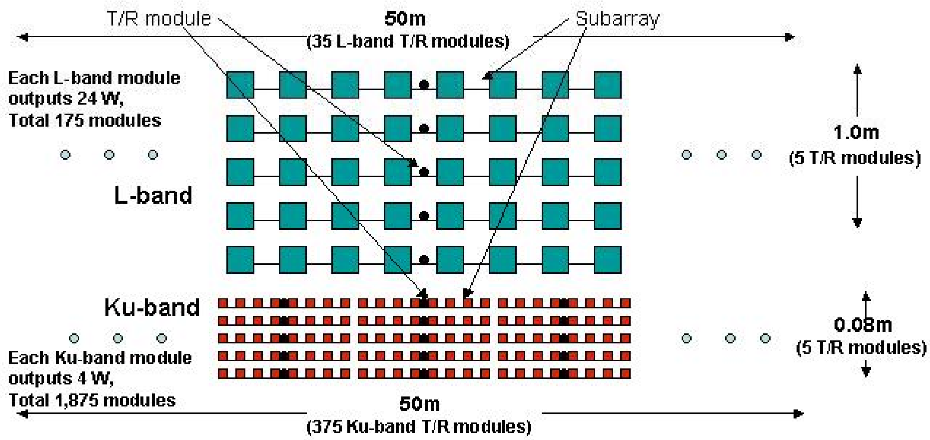


Figure 2.10. *Antenna option 2 for dual-frequency SAR: array antenna element/module layout configuration. The total aperture is 15-m x 2.5-m.*

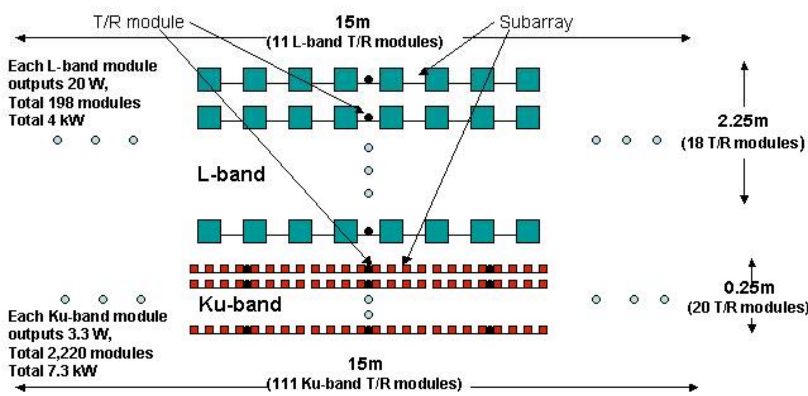


Table 2.3. *Summary of the estimated radar performance for the dual-frequency SAR design concept.*

	L-band	**Ku-band**
Single-look ground range resolution	8 - 16 m	
Azimuth resolution	5 - 9 m	
Number of looks in a 100-m x 100-m pixel	18 – 22	
Noise Equivalent σ_o	-30 dB	-22 dB

Figure 2.11. *Antenna option 3 for dual-frequency SAR: deployable cylindrical reflector with two linear array feeds. The dimensions are 7.5-m in Y-direction, 4.5-m in x-direction*

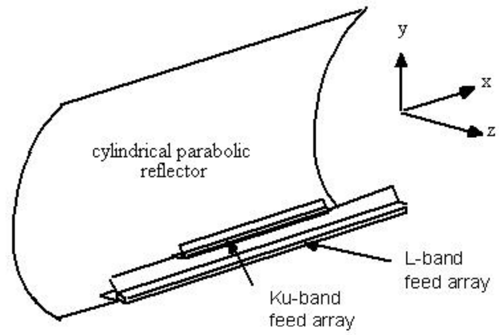
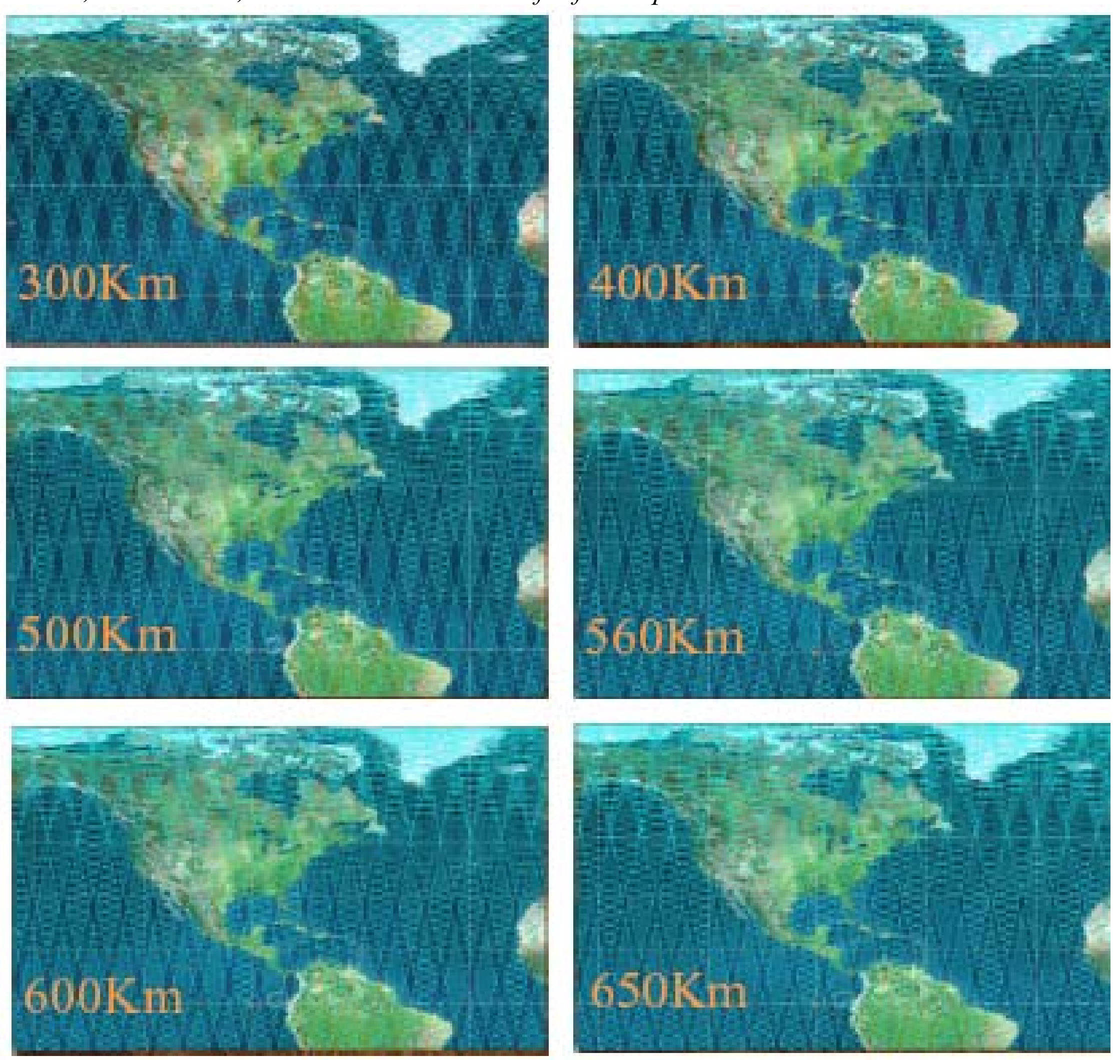


Figure 2.12. *Coverage of a side-looking synthetic aperture radar operating at sun-synchronous, polar-orbit, 98.6-degree inclination, 775-km orbit altitude with 3-day repeat. The six panels illustrate the coverage for swath widths of 300-km, 400-km, 500-km, 560-km, 600-km, and 650-km, indicated in the lower left of each panel.*

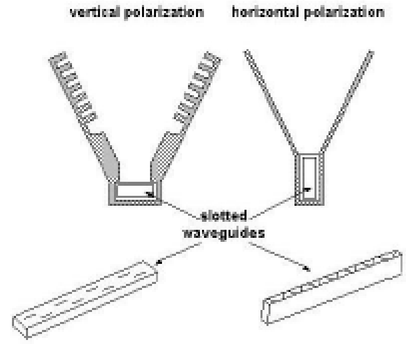


We conducted a trade-off study to determine the radar sensitivity as functions of transmit power and bandwidth for the Ku-band radar. The radar sensitivity is defined as the fractional error of the radar measurements. To be more precise, if the normalized radar cross-section of the target under illumination is denoted by σ_0 and the measurement error denoted by $\Delta\sigma_0$, the radar sensitivity is $\Delta\sigma_0/\sigma_0$. The radar sensitivity is a function of the signal to noise ratio (SNR) and the number of independent radar looks within a defined resolution.

The projected radar sensitivities are plotted in Figure 2.13 as a function of bandwidth for a range of transmit-power levels. Increasing the radar transmit bandwidth increases the number of looks, but will degrade the signal to noise ratio and hence the sensitivity. Offsetting the effects of noise will require increased transmit power level. However, increasing the transmit power further will have diminished return once the SNR is greater than 10. Based on the results indicated in Figure 2.13, we determined that the optimal bandwidth is between 20 and 40 MHz for peak transmit power of 7-kW. Higher transmit power will allow the use of larger bandwidth to improve the radar sensitivity.

For the dual-frequency SAR measurement scenario, the technology driver is the Ku-band antenna, radar transmit power level, and data rate. The overall data rate from the dual-frequency

Figure 2.14. *Slotted waveguide antenna concept for the InSAR measurement scenario.*



SAR approaches 500-Mbps level for 20-MHz chirp bandwidth. Should the bandwidth be increased to 40-MHz, the data rate will also double and reaches about 1-Gbps. The challenges are: How do we achieve 7-kW or more transmit power for the active array antenna? How do we achieve antenna flatness on the order of 1-mm (1/20 wavelength at KU-band)? How do we downlink the very large amount of data?

2.2. Antenna Technology Assessment

In this section, the focus is on the antenna technology for both measurement scenarios.

2.2.1. InSAR Antenna Technology

The InSAR antenna system illustrated in Figure 2.1 consists of eight identical Ku-band radiating units with each having a radiating aperture size of 10-m by 0.17-m. To perform interferometry, the 8 antenna units are separated into two identical groups with a physical separation or a baseline distance of about 40-m. The four units in each group are placed adjacent to each other (parallel along antenna's 10-m dimension) and are separated into two pairs with each pair physically oriented differently (along the 0.7-m dimension) to look at different spot in the cross-track direction on the Earth. One pair will have a look angle of 14.5^o from nadir, while the other pair will look at 23.0^o. Each rectangular aperture will radiate a direction-fixed beam.

The slotted waveguide is probably the most appropriate antenna type (Figure 2.14). The waveguide is slotted along the 10-m dimension and a pair of flairs in the direction of the 0.17-m dimension forms the required beamwidth. Along the 10-m dimension, the waveguide is broken into 40 sections with each section having its own transmit (T) and receive (R) amplifier module. In other words, each section is about 0.25-m long and has its own T/R module with a transmit power of 200 watts. This will yield the required total transmit radar power of 8-kW. Each T/R module will be equipped with a phase shifter (waveguide ferrite type). The phase shifters are used to perform real-time beam pointing correction due to possible antenna mechanical tilting from thermal and other error effects. A real-time metrology system is required for this beam correction function. This distributed array approach with T/R modules not only allows the 10-m long structure to be deployable/foldable, it also permit the generation of the total required 8-kW of power as well as beam pointing correcting function.

The 10-m long antenna structure must be made deployable in order for it to fit into a launch vehicle. The number of deployable sections will depend on the vertical space available in the launch vehicle. Let us assume there are a total of four deployable sections along the 10-m long direction and each deployable section has a length of 2.5-m with 10 T/R module sections. The RF signals of the 40 slotted waveguide sections, after T/R modules, can be combined by several possible methods. One straightforward approach would be to combine the signals by a set of corporate-feed waveguides and flexible coax cables. Coax cable could be used wherever there is a folding section. This approach would add significant amount of mass and volume to the antenna system due to many parallel-bundled waveguides. Another approach would be to modulate the RF signals, after T/R modules, onto optical signals and transmit and combined by optical fibers. This approach would be the low-mass approach, but with very high cost. A more advanced approach is the so-called "wireless" method. The Ku-band signal, after each T/R module, is down-converted to a lower frequency signal, say UHF, which is then radiated into space through a low-gain antenna and combined with similar UHF signals from other 39 sections. All these combining techniques require further detailed technical studies and traded for complexity, cost, mass, and performance.

Besides the antenna technology challenges associated with the InSAR, there are additional system challenges unique to this concept. The two antennas, separated by a long (30m-50m) baseline, must have aligned antenna beams. This places stringent requirements on antenna baseline dilation and tilt knowledge and radar phase stability. A metrology and calibration system will be required to accurately measure this baseline throughout the mission and correct for baseline tilt and radar phase changes. While this metrology/calibration technique has been successfully demonstrated on the Shuttle Radar Topography Mission (SRTM), the CLP accuracy requirement of a few centimeters is far more challenging than the SRTM requirements of a few meters. Furthermore, the high power and beam steering requirement for the CLP make this an even more challenging requirement since it would be necessary to achieve phase stability (<1deg) of two active arrays separated by 40 meters.

2.2.2. Dual-Frequency SAR Antenna Technology

There are three candidate antenna options proposed for the L-/Ku-band polarimetric SAR. One is an antenna system with an extremely long and narrow aperture (50-m x 1.08-m) having a single fixed beam at each frequency (Figure 2.9). Each beam has its broad beam oriented in the cross-track direction to provide wide coverage area and narrow beam in the along-track direction to provide the needed radar resolution. The second option is an antenna with a total aperture of 15-m by 2.5-m (Figure 2.10). For each frequency, there are 5 scanned beams generated along the cross-track direction (along 2.5-m dimension) to provide the necessary coverage area. The third concept uses a cylindrical reflector of 7.5-m x 4.5-m in aperture size and is fed by two linear phased arrays (L- and Ku-band) to achieve scanning beams (Figure 2.11). Antenna descriptions and technology drivers for both these options are discussed in more details as follows.

2.2.2.1. Option 1: 50-m x 1.08-m Antenna

The L-band antenna has an aperture of 50-m by 1.0-m, while the Ku-band has an aperture of 50-m by 0.08-m. The two apertures are placed adjacent to each other to form a total aperture of 50-m by 1.08-m. Since the Ku-band aperture is so narrow, a shared aperture approach is not justified. The radiating elements for both frequencies are microstrip patches. Since no scanning beam is needed, relatively large element spacing of 0.75-λ_0 is sufficient for both frequencies. With this element spacing, there will be 280 patch elements along the 50m dimension and 5 elements along the 1-m dimension with a total of 1400 elements for the L-band aperture. For the Ku-band aperture, there will be 3000 by 5 elements (or 15,000 total).

Because this aperture concept is extremely long and thin, the surface flatness will become a serious issue due to the effects of temperature gradient and structure resonance. Consequently, although no beam scanning is needed for the radar, controllable phase shifters, together with a metrology system for real-time surface deformation measurements, are needed to carry out the function of surface tolerance compensation. Transmit/Receive (T/R) amplifier modules are also needed to provide the needed high transmit power, as well as to mitigate the large insertion-loss problem associated with the beam former and phase shifters. For the L-band aperture, along the 50-m dimension, there will be 35 T/R modules with every eight elements fed by a T/R module and a phase shifter (4-bit) to form a sub-array. Along the 1-m dimension, there will be 5 T/R modules with every single subarray having a module and a phase shifter. This T/R module arrangement is illustrated in Fig. 2.9. Therefore, a total of 175 modules are needed with each one transmitting 24 watts of power, which translate to a total radiated power of 4.2-kW. The L-band antenna aperture will produce 3dB beam widths of about 0.35° and 16.5° with sidelobe level in the order of –20dB. For the Ku-band aperture shown in Fig.2.9, along the 50-m dimension, there will be a T/R module with a phase shifter for every 8-element subarray, which accounts to 375 T/R modules. Along the 0.08-m dimension, there will be 5 modules with every subarray having a module. As a result, there will be a total of 1,875 T/R modules and, with each one generating 4 watts of power, the Ku-band antenna will radiate a total power of 7.5-kW. If the each T/R module can generate 10 watts of radar power, there will be a total of about 18-kW radiated by the Ku-band array. This Ku-band aperture will radiate beam-widths in the order of 0.03° x 20° with a –20-dB sidelobe level design.

The complete L/Ku-band antenna aperture consists of 25 deployable panels, which can be folded for stowage. It is configured that the one center panel will be mounted onto the spacecraft while 12 panels will be deployed out to each side of the spacecraft. Each panel, 2-m by 1.08-m dimension, is a multi-layer thin-membrane low-mass design, which includes power divider transmission lines, T/R modules, phase shifters, patch elements, DC bias and control lines, etc. The 25 panels are deployed by space-rigidizable inflatable tubes placed along the edges of the panels in the 50-m dimension direction.

Option 1 Technology drivers: There are two major technology drivers for the above antenna system. One is the mechanical or inflatable deployment structure with adaptive metrology system. The structure must have high stiffness with low linear mass density and stow volume. The metrology system must include precision flatness measurements with active shape control and/or calibration to achieve the required electrical flatness. The antenna aperture is the second major technology driver. To achieve low mass and volume necessary to package this large antenna in low cost launch vehicles (such as Delta II), the antenna mass density should be less than 5 kg/m^2 (including deployment structure). Membrane antennas are currently the only technology that promises this performance. Thus membrane mounted T/R modules, phase shifters, d.c. bias and control circuits, and time-delay devices become critical technologies.

2.2.2.2. Option 2: 15-m x 2.25-m Antenna

For this design as shown in Fig. 2.10, the L-band antenna has an aperture of 15-m by 2.25-m, while the Ku-band has an aperture of 15-m by 0.25-m, which results a total aperture of 15-m by 2.5-m. For each frequency, five beam positions are needed along the cross track or the narrow aperture direction. All five beams, which can be scanned or switched, together cover the angular region of 20° to 45° from nadir. Several possible antenna options have been briefly studied and ruled out. The reflector antenna option (parabolic or cylindrical) is ruled out because the aperture's aspect ratio of the two dimensions is too large for the feed to effectively illuminate the reflector, in particular the ratio for the Ku-band aperture. Slotted-waveguide array approach is also ruled out since the waveguides will be too large and massive at the L-band frequency, and it would be very difficult to achieve dual-polarization by using the slotted-waveguide array. Microstrip array with T/R modules and phase shifters is proposed for both frequencies to perform the polarimetric functions. The 5 beam positions can be achieved either by switches using a Buttler Matrix approach or by electronic scanning using phase shifters. The phase shifter approach is selected since it also allows real-time fine beam correction due to surface deformation. The overall aperture of 15-m by 2.5-m can be broken into ten 1.5-m wide panels for mechanical deployment, which can be done by deployable rigid low-mass mechanical truss or by inflatable structures.

For the L-band array, along the 15-m dimension, there are 88 patch elements with element spacing of 0.72-λ_0. There are a total of 11 T/R modules or subarrays in this dimension with each module exciting 8 series-fed patch elements. Along the 2.25-m dimension (beam scan direction), there are 18 subarrays and 18 T/R modules with 0.53-λ_0 element spacing. As a result, the entire array consists of 198 T/R modules with each module generating 20 watts of power, which yields a total L-band radiated power of about 4-kW. The overall L-band aperture will yield beamwidths of 1.1° x 7.5° with a peak sidelobe level of –20 dB. This L-band array can be implemented with conventional rigid panels and distributed T/R modules (10-15kg/m^2). However, by employing active-membrane antenna technology, a significant reduction of the antenna mass can be realized (2-5kg/m^2).

For the Ku-band array, there are 888 patch elements with element spacing of 0.75-λ_0 along the 15-m dimension. There are 111 T/R modules in this dimension with each module exciting 8 series-fed patch elements. Along the 0.25-m dimension, where beam is required to be scanned, there are 20 elements and 20 T/R modules with 0.56-λ_0 element spacing. The entire array has 2220 T/R modules with each module generating 3.3 watts of power and yielding a total antenna radiated power of 7.3-kW. If each T/R module output can be raised to 10-W, the total radar transmit power will approach 22-kW. Less number of T/R modules can also be implemented for the same array by using higher-power modules. However, it means one module needs to feed a large number of patch elements (currently 8), which will result in higher insertion loss with lower overall efficiency. The Ku-band aperture will radiate a main beam with beamwidths in the order of 0.1° x 6.3° and a peak sidelobe level of –20 dB.

Option 2 Technology drivers: This concept can be implemented using existing phased-array antenna technology (10-15kg/m^2). However, to make the system more affordable, then lightweight antenna technology is required. Membrane antennas are currently the only technology that promises this performance improvement (2-5kg/m^2). Thus membrane mounted T/R modules, phase shifters, d.c. bias and control circuits become critical technologies. The mechanical deployment of ten 1.5m x 2.5m panels is expected to be less complex than option 1 and not considered a technology driver.

2.2.2.3. Option 3: Cylindrical Reflector

This concept, shown in Fig. 2.11, uses an off-set-fed cylindrical reflector having a projected rectangular aperture of 7.5-m by 4.5-m and is fed by two linear phased arrays. The L-band feed array has a length of 4.5-m, while the Ku-band feed array has a length of 1.25-m. Since the required aperture for the Ku-band (3-m x 1.25-m) is smaller than that of the L-band, the Ku-band array will under-illuminate the reflector with an electrically wider feed in the y-direction and shorter feed in the x-direction. The cylindrical reflector can be deployed either by inflatable thin-membrane technology or by Astro-mesh approach to achieve low-mass and small stowed volume. This concept is similar to the reflector considered for the passive microwave 1D-STAR concept, but is substantially smaller.

Both the L-band and Ku-band feed arrays will employ low-mass microstrip radiators with T/R modules and phase shifters to achieve beam scan in the x-z plane (cross track direction). The L-band array has an element spacing of 0.55-λ_0 with 340 x 2 patch elements and 340 T/R modules. Each module will generate 12 watts of power with the total antenna radiated power equal to 4-kW. Ten scanned beams are needed in the angular region of 20° to 45° from the nadir. The –3dB beamwidths from the cylindrical reflector aperture (7.5-m x 4.5-m) will be about 2.2° x 3.7°. For the Ku-band feed array, there are 100 x 4 patch elements with 0.55-λ_0 element spacing and 400 T/R modules. Each module will provide 20 watts of power with a total antenna radiated power of 8-kW. The number of scanned beams is 25 between the same angular region of 20° to 45° from nadir. The beamwidths from this Ku-band reflector aperture are 0.52° x 1.25°.

Technology drivers: One technology driver will be the deployment of the cylindrical reflector to meet the required surface tolerance at Ku-band. The second one would be the development of a high-power phased-array feed with T/R modules for the reflector. The close element spacing (required for the beam steering) results in much denser distribution of T/R modules, requiring a very compact T/R module. Furthermore, this also adds additional thermal considerations where high transmit powers result in significant heat dissipation. Thus high efficiency T/R modules are particularly important for this application. Note: the deployment of a cylindrical reflector is also a technology driver for the 1D-STAR concept described in Section 3.3.2, which has even more stringent surface tolerance requirements due to the higher frequencies involved.

2.3. Further Trade Studies Analysis and Down-select Measurement Scenario

To facilitate the selection of a measurement scenario for further technology assessment, Table 2.4 summarizes the technical performance of the InSAR and dual-frequency SAR concepts. Both concepts share several similar technical challenges, including high radar power, high data rate and deployment of large structures.

Table 2.4. *Summary of performance and resource requirement trades*

Measurement Scenario	Accuracy	Resolution	Swath	Radar peak power	Data rate	Deployment
InSAR	Limited by very challenging baseline tilt knowledge (10-15 cm for 0.1 arcsec knowledge)	Limited to about 1 km	400km (limited by layover at near swath with shallow incidence angles)	~10 kW	250Mbps	Antenna panel and boom deployment
L/Ku-SAR	Limited by measurement	100m	>500km achievable	~10 kW	500Mbps	Antenna panel deployment

	sensitivity and algorithm					

The notable differences are the achievable accuracy, spatial resolution and swath coverage. Our analysis showed that the spatial resolution of the InSAR is limited to about 1-km for the desired centimeter SWE accuracy. The measurement accuracy cannot be improved by an increase in baseline length, which increases the height measurement sensitivity, but also increases the geometric de-correlation error. In addition, the accuracy of InSAR is primarily limited by the knowledge accuracy of baseline tilt. It is estimated that 1-arcsec accuracy for the knowledge of baseline-tilt (including the effects of spacecraft roll) will translate to about 1-m height error. The other discriminator is the swath coverage. InSAR concepts prefer to operate at near nadir look angles to take advantage of large radar backscatter. However, the effects of layover for SAR observation over land surfaces become severe for mountainous region at $<20^{o}$ incidence angle, resulting a significant constraint on the achievable swath width. Because of these two fundamental limitations of InSAR, we selected the dual-frequency SAR for further technology evaluation.

We summarize three antenna options and technology needs for the dual-Frequency SAR in Table 2.5. The technical descriptions of these options have been described in the previous section. Options 1 and 2 are planar active phased array antenna with distributed T/R modules, while option 3 is a passive reflector aperture. The advantage of option 3 is that it allows the combined use of active and passive microwave. However, the number of scan SAR beams for option 3 is >20. The large number of scanSAR beams makes it extremely difficult for radiometric calibration based on the experience of Radarsat SAR and SRTM. Therefore we proceed further to evaluate the resource requirements and technology needs for the planar phased-array antenna.

Table 2.5. *Summary of technology assessment for three antenna options for L-/Ku-band SAR.*

	L-band SAR			Ku-band SAR		
Option	**1**	**2**	**3**	**1**	**2**	**3**
Antenna aperture	Flat panel active phase array with membrane	Flat panel active phase array with membrane	Cylindrical mesh deployable reflector	Flat panel active phase array with membrane	Flat panel active phase array with membrane	Cylindrical mesh deployable reflector
Size	50mx1m	15mx2.25m	7.5mx4.5m	50mx0.08m	15mx0.25m	3mx1.25m
Feed	Microstrip line	Microstrip line	Microstrip array (4.5mx0.25m)	Microstrip line	Microstrip line	Microstrip array (1.25mx0.05 m)
Number of ScanSAR beams	1	5	10 (Very challenging for calibration)	1	5	25 (Very challenging for calibration)
Transmitter	175 T/R modules with 24 W output each	198 T/R modules with 20 W output each	340 T/R modules with 12 W output each	375 T/R modules with 30 W output each	2220 TR modules with 4W output each	400 TR modules with 20W output each
Technology needs for digital beam forming	Low loss delay line	Lightweight beam forming technology		Low loss delay line	Lightweight beam forming technology	
Beam control	DC-control and power distribution to reduce harness	DC-control and power distribution to reduce harness		DC-control and power distribution to reduce harness	DC-control and power distribution to reduce harness	
Aperture support structure	Deployable truss or inflatable tube	Deployable truss or inflatable tube		Deployable truss or inflatable tube	Deployable truss or inflatable tube	
Thermal			Thermal control for feed			Thermal control for feed
Synergism with passive microwave			Shared aperture			Shared aperture

2.4. Sensitivity Matrices

The technology development needs for the dual-frequency SAR measurement scenario was assessed through an end-to-end system evaluation environment using the JPL Team X and GSFC IMDC facilities. The study involved a cost analysis for the baseline dual-frequency SAR configuration and a delta impact on mission cost under the assumption of more advanced technologies.

The sensitivity and impact analysis assumes the following baseline instrument resource requirements on the spacecraft. The mass, power and data rate are current best estimates (CBE), which are illustrated in Table 2.6. An additional 30% contingency was added to the power and mass estimates for the Team X evaluation.

Table 2.6. *Instrument resource requirements on spacecraft.*

	Mass	**Power**	**Data Rate**
Instrument	500kg	4.7kW	500Mbps

To support this instrument for operating at a polar, sun-synchronous, 775km orbit, the spacecraft is 3-axis stabilized using star trackers and an Inertial Measurement Unit (IMU) for attitude determination, and large reaction wheels and magnetic torque rods for attitude control. A P-code capable GPS system is carried on-board to support co-pointing within 1-2 km for the formation flying option. In the baseline option, a spacecraft computer receives 500 Mbps of raw science data from the instrument over a FireWire interface, and stores it on a 2.4-Gbit disk drive array. The data is transmitted during one 34-min pass to the TDRSS System every other orbit, at a rate of 800 Mbps using a Ka-band 1.2-m diameter parabolic dish and a Ka-band 20-W output solid-state power amplifier. Commands are received from TDRSS at the same time using an S-band low-gain antenna and the next generation TDRSS transponder. Orbit injection error correction, ADCS back-up propulsion, orbital node maintenance and de-orbiting are carried out by one monopropellant propulsion system using twelve 4.5-N thrusters and two blow-down hydrazine tanks. For most of the time, the spacecraft is powered by two 11-m^2 solar array panels with GaAs Quad Rigid technology. The array is also used to recharge a 140 A-hr Ni-H_2 battery for continuous science operations even during the eclipse season over the Antarctic summer.

The Team-X study concluded that the dual-frequency SAR measurement scenario can be implemented with existing technologies for a space mission. However, the projected mission cost will be well over $600M, including about $200M for the instrument, $140M for the spacecraft, $70M for the Delta-2 launch vehicle, and $120M for reserve. To reduce the cost of this measurement concept, new technologies to reduce the mass, power and data rate of the instrument are crucial.

A sensitivity analysis was performed by the Team X to evaluate the potential benefits if the instrument mass, power, and data rate are reduced. Table 2.7 summarizes the results of the analysis.

Table 2.7. *Sensitivity matrix for key instrument resource requirements versus science performance impact and benefits.*

Sensitivity Matrix ID	Technology Element	Technology Development	Science Performance Impact	Benefits
1	Instrument power	Reduce the instrument power by 50% from 4.7KW to 2.3KW using more efficient Transmit/Receive modules	None	Savings of about 230kg in launch mass and reduction of at least $10M in mission cost
2	Instrument mass	Reduce the instrument mass by 50% from 500kg to 250kg using lightweight antenna and structure	None	Savings of about 520kg in launch mass. Reduction of $100M from Team X model estimates
3	Instrument mass and power	Combination of the above two	None	Savings of about $770kg in launch mass. Reduction of $120M-130M from Team X model estimates.
4	Instrument data rate	Reduce the data rate by a factor of 10 from 500Mbps to 50 Mbps using on-board processing	Loss of raw instrument data and single-look resolution	Enabling a much shorter TDRSS link for a total savings of about $10M

2.4.1. Instrument Power

The instrument power and the conditions in which it needs to operate drive the size of the solar array, battery and power electronics. If technology developments enabled a 50% reduction in instrument power for the same instrument configuration and mass, the reductions in the power subsystem would ripple through the system into savings of about 230 kg in launch mass and at least $10M in cost (this is a minimum, accounting only for the ripple effect on structure and propulsion; ACS would also change, although the benefits of a lighter spacecraft might be somewhat reduced by having smaller solar arrays to counteract the torque on the antenna).

2.4.2. Instrument mass

The mass of the instrument is the key driver for the total launch mass. If technology development efforts enabled a 50% reduction in instrument mass without any other change in power or configuration, the total savings would be of about 520 kg in launch mass. Using the Team X Instrument cost model, which is based solely on mass, would reduce the cost estimate by close to $100M. Most of the mass savings indeed correspond to structures and propellant. The mass savings could translate to more significant cost savings if a smaller launch vehicle could be used. Although a smaller Delta II might be possible, this reduction is not sufficient to fit on a current Taurus-class launch vehicle. More mass reduction is needed to launch it on a peacekeeper (Taurus-type with more lift capability).

2.4.3. Instrument mass and power

If the instrument mass and power were concurrently reduced by 50% without any change in configuration, the total mass savings would be of about 770 kg in launch mass, which in turn could be translated into launch vehicle cost savings. The total project cost reduction would be at least $110M with the Team X instrument model, or $20M with a fixed $100M instrument, taking into account ripple effects through the power, structure, thermal and propulsion subsystems only.

2.4.4. Data rate and coverage

The high data rate is driving not only the telecom and ground system design and cost, but also some spacecraft C&DH and software to some extent. An option to reduce the data rate from the radar is to use the pre-sum technique. This option does not require technology development, but will degrade the achievable SAR processing resolution. Pre-summing the data from two radar pulses will reduce the data rate by a factor of 2 from 500-Mbps to 250-Mbps and degrade the resolution by a factor of 2. Reducing the data rate to 250-Mbps would decrease the cost to TDRSS by $3.2M.

Another option to reduce the data rate is to use on-board SAR processing. On-board processing to perform SAR processing and multi-look averaging to 100-m spatial resolution will reduce the data rate to about 50Mbps. This ten-fold reduction from 500-Mbps to 50-Mbps would enable X-band downlink to the Earth as an alternative to Ka-band to TDRSS. As a rough cut: On-board processing would require an additional 7-kg, 75-W, $5M and at least $0.75M in additional software development. The savings would be at least $2M in spacecraft C&DH for smaller on-board memory and easier interfaces. The X-band-to-the-ground option would save 10-kg, 60-W and $5M in the spacecraft telecom subsystem, and reduce ground support costs by $2.1M and ground data processing costs by more than $10M. This would lead to overall savings of about 7-kg in launch mass and $10M in total project cost. Additional savings might be achieved at the program level by sharing the telecom system with another spacecraft. Alternatively, the same telecom system could be used with a much shorter TDRSS link. This would keep the spacecraft unchanged and save about $5.7M in TDRSS coverage, for total project cost savings of about $20M, including ground science data processing costs.

2.5. Identification of Technology Needs

We have described a number of advanced mission concepts and have selected the dual-frequency SAR as the best candidate to achieve the science measurement goals with the least technical risk and cost. For the dual frequency SAR concept, three candidate approaches were then examined to assess technology requirements and challenges. For the 15-m L/Ku-band phased array (Option 2), the system could be implemented using conventional technologies (rigid panel phased array antennas). The 15m dual-frequency SAR option can be implemented without any significant technology development required. However, by incorporating advanced antenna technologies to reduce mass, power and complexity will help make Option 2 more affordable. The 50-meter long SAR concept (Option 1) will require new lightweight antenna technology. The array architecture presents many system level design and integration challenges. Since hundreds of T/R modules are required, reducing the mass, power and cost of these modules will be very beneficial. In addition, signal distribution (RF, control, power) is very complex and low cost interconnect technologies are required to interface with the modules. Also for the large array, advanced techniques such as digital beam-forming and true time delay (TTD) steering will be required. Adaptive methods to compensate for deformation in the array flatness will also need to be addressed. For such a large aperture to fit within existing launch vehicles, membrane antenna technology must be employed rather than conventional rigid panels. However, once these challenges are solved, lightweight membrane antennas would provide an order-of-magnitude reduction of antenna mass density (from 10-20kg/m^2 to <2kg/m^2). This technology would thus enable very large aperture antennas (such as Option 1), and could also be incorporated into smaller arrays make the mission more affordable (such as Option 2 or 3). Table 2.8 summarizes some of the key technologies that need to be further developed to achieve this goal.

2.5.1. Technology Options

Large Deployable Antennas Structures: Recent focus on inflatable structures has been to develop self-rigidizing technologies and methods to control deployment. Approaches to properly tension the membranes to maintain flatness and precise layer separation, is also an area of focus. Mechanically deployed structures are far more mature than inflatables and have the advantage of high stiffness and stability, however do not have the high packing efficiency of inflatable structures. Trade-off studies indicate that as the structure length grows beyond fifty meters, then inflatable technologies may be advantageous. For CLPM, both inflatable and deployable structures are candidates.

Membrane Apertures: Although inflatable membrane antennas have been successfully demonstrated, these antennas have not yet addressed the very complicated problem of integrating electronics within the aperture (reliably and cost effectively). Since the ultimate goal is to keep the weight and stowed volume of the antenna small, conventionally packaged T/R electronics are not appropriate. Furthermore, attaching a large packaged component to a thin-film membrane also presents reliability concerns. Therefore, we envision embedding or attaching unpackaged chips directly to the membrane aperture. New membrane materials with better heat conductivity are also needed for passive cooling of the electronics. At high RF powers, active cooling methods such as micro-machined heat pipes or similar technologies may be required. These difficulties are mitigated when very high-efficiency T/R modules are used.

T/R Modules: High-efficiency T/R modules are required for the CLPM mission due to the very high power requirement (>15KW for both arrays). High efficiency will reduce spacecraft cost as well as simplify the thermal management and improve reliability. Another goal of the T/R module is to reduce size and production cost since hundreds to thousands are required. The current state-of-the-art T/R modules typically use three or four chips in a packaged hybrid microcircuit. A fundamental goal is to integrate all the T/R electronics onto a single chip. This will minimize the total part count and will result in overall reductions in module cost, assembly cost and interconnect costs while increasing reliability. The same basic T/R module technology could be applied to all of the 3 concepts under consideration.

Radar Sensor Electronics: A number of emerging component technologies could also improve performance and reduce cost for all mission concepts. These include new wide band-gap semiconductors for higher power densities and efficiencies (such as SiC or GaN); low loss MEMS switches and phase shifters; or higher-speed digital components to enable direct signal generation at L-band and all digital receivers. As lower power devices become available, new architectures such as digital beam-forming techniques and digital true-time delay (TTD) steering could be more feasible and affordable.

Table 2.8 *Technology needs matrix for all antenna configuration options. Option 1: 50mx1m planar phased-array antenna. Option 2: 15mx2.25m planar phased-array antenna. Option 3: Cylindrical reflector antenna.* **CR** *– Cost-Reducing technology or technology which will provide increased performance/capability.* **E** *– Enabling technology (required for mission feasibility).* **NR** *– Not required for this option.*

	Option 1	**Option 2**	**Option 3**
Technology	**50m Long SAR**	**15m SAR**	**Cylindrical Reflector SAR**
Lightweight structures: High-stiffness deployment systems with high packing-efficiency; inflatable/rigidizable and mechanically deployable structures; membrane tensioning.	**E**	**CR**	E
Large membrane antennas materials: Durable, low loss thin-film membrane antenna materials; array feed technique compatible with the membrane electronics and array architecture.	**E**	**CR**	**NR**
High-efficiency L-band & Ku-band T/R modules: Class-E/F L-band and Ku-band SSPA; membrane compatible T/R modules.	**E**	**E**	**E**
High-power, high-efficiency Solid State devices: Explore emerging semiconductor device technologies: Si, GaAs, SiC and GaN power amplifiers at L-band and Ku-band. SiGe digital circuits.	**CR**	**CR**	**CR**
Integrated, rad-hard, low power components: Low power DCG ASIC; TTD devices; L-band digital receivers; digital filters; MEMS and BST phase-shifters.	**CR**	**CR**	**CR**
Membrane compatible electronics: Advanced packaging technologies including die thinning and attachment technologies to enable the reliable, direct attachment of thinned die onto membrane; embedded electronics (vs. attachment alone) to embed the die in the structure for added reliability.	**E**	**CR**	**NR**
Signal distribution: Technologies to simplify the interconnection of thousands of unit cells on the array; reliable RF, control, power and data distribution. Lightweight, low-loss, membrane-compatible interconnects for RF, data and power distribution	**E**	**CR**	**E**
Shielding for radiation tolerance: Since the conventional bulky package is not envisioned for the T/R module, the radiation protection of the device has to be accomplished through other methods of shielding and coatings. Die thinning for improved radiation tolerance.	**E**	**CR**	**NR**
Passive and active thermal management: Radar transparent thermal control coatings; variable emissivity surfaces/coatings; integrated micro heat pipes.	**E**	**CR**	**E**
Large-scale manufacturing: Low-cost methods of attaching thousands of components on the membrane in such a way that the antenna is manufacturable, testable and re-workable. New technologies, such as roll-to-roll manufacturing process, are a crucial step to enable a cost effective solution.	**CR**	**NR**	**NR**
System: Digital beamforming and digital TTD steering; calibration, metrology and phase-correction.	**E**	**NR**	**E**

2.6. Technology Development Roadmap

The technology development plan associated with this roadmap is provided in Table 2.9 Lightweight, high-power, deployable L-band and Ku-band phased arrays are the highest priority. This includes: high-efficiency T/R modules, membrane antennas and lightweight deployment structures. Membrane antennas could reduce the cost of near-term missions as well as enable more advanced large aperture systems envision for the next decade. NASA needs to push this technology development since research in this field is limited. Incremental improvements in conventional rigid panels (to reduce mass and cost) is also important, although slightly lower priority since industry leads this work. Metrology and calibration is critical for the large aperture array option. Less urgent objectives include research in new materials and devices since there is sufficient investment already in these areas. Our approach is to incorporate new and emerging component technologies as they mature.

Table 2.9. *Cold land processes mission technology development plan for dual-frequency (L/Ku-band) SAR with <100 m spatial resolution and >500 km swath width for snow water equivalent (SWE) and snow wetness with 10% relative accuracy over land above 50-deg latitude with 3 day repeat.*

Cold Land Process Mission (CLPM) Technology Development Plan

Dual-frequency (L/Ku-band) SAR with <100 m spatial resolution and >500 km swath width for snow water equivalent (SWE) and snow wetness with 10% relative accuracy over land above 50-deg latitude with 3 day repeat.

Estimate of Incremental Cost to Reach Indicated TRL — current TRL; TRL not applicable to this item

Technology Deliverable	Requirement Metric	Priority (1=highest 2=high 3=less urgent objective)	TRL 1 Basic principles observed and reported	TRL 2 Technology concept and/or application formulated	TRL 3 Analytical & experimental critical function and/or characteristic proof of concept	TRL 4 Component and/or breadboard validation in laboratory environment	TRL 5 Component and/or breadboard validation in relevant environment	TRL 6 System /subsystem model or prototype demonstration in a relevant environment
Lightweight Deployable Antennas								
Rigid Deployment Structures								
50m deployable truss	<1kg/m	1				$1.5M	$3M	$5M
50m inflatable/ridigizable booms	<1kg/m	1				$3M	$5M	$10M
15m deployable truss	<5kg/m	1						
15m deployable truss	<1kg/m	1				$1.5M	$3M	$5M
High strength, low-loss membrane materials		1				$500K	$1M	
Membrane tensioning and adaptive shape control		1			$300K	$500K	$1M	$5M
L-band & Ku-band Long SAR Array Aperture (50m antenna)								
50m active membrane phased-array aperture (L-band)	5KW, 2kg/m^2	1		$300K	$300K	$1M	$5M	$8M
50m active membrane phased-array aperture (Ku-band)	>8KW, 2kg/m^2	1		$300K	$300K	$1M	$6M	$10M
Membrane compatible electronics and interconnects		1			$300K	$500K	$1M	
Metrology/calibration for membrane antenna deformation	1mm for Ku-band	1			$300K	$500K	$1M	
Signal distribution (RF, control, power)		1			$500K	$500K	$2M	$5M
High power thermal management of membrane arrays		1			$300K	$500K	$1M	
Digital beamforming techniques		3			$500K	$500K	$1M	$5M
L-band & Ku-band Active Phased Array (15m antenna)								
15m lightweight rigid panel phased-array aperture (L-band)	5KW, 10kg/m^2	1					$2M	$5M
15m lightweight rigid panel phased-array aperture (Ku-band	>8KW, 10kg/m^2	1					$3M	$7M
15m active membrane phased-array aperture (L-band)	5KW, 2kg/m^2	2			$300K	$1M	$5M	$8M
15m active membrane phased-array aperture (Ku-band)	>8kw, 2kg/m^2	2			$300K	$1M	$6M	$10M
Membrane compatible electronics and interconnects		2			$300K	$500K	$1M	
Metrology/calibration system for membrane antennas	1mm for Ku-band	2			$300K	$500K	$1M	
Signal distribution (RF, control, power)		1			$500K	$500K	$2M	$5M
High power thermal management		1			$300K	$500K	$1M	
5-beam ScanSAR		1					$1M	$2M
L-band & Ku-band Cylindrical Reflector Antenna								
7.5mx4.5m cylindrical mesh reflector (L/Ku-band)		3			$300K	$1M	$5M	$8M
4.5m rigid panel phased-array feed (L-band)	5KW, 10-15kg/m^2	3					$2M	$5M
4.5m rigid panel phased-array feed (Ku-band)	>8KW, 10-15kg/m^2	3					$3M	$7M
10-beam ScanSAR (L-band)		3			$300K	$1M	$2M	$5M
25-beam ScanSAR (ku-band)		3		$200K	$300K	$1M	$2M	$5M
Active thermal control for feed		3			$300K	$500K	$1M	$5M
Radar Sensor Electronics								
RF Components & Devices								
Rad-hard L-band T/R modules	10-30W, 60% efficient	1				$500K	$500K	$2M
L-band Class-E/F power amplifiers	10-30W, 70-90% efficient	1				$300K	$300K	
SiC & GaN L-band power transistors	10-30W	2			$200K	$200K	$300K	
Low loss L-band RF switches and phase shifters	<0.5dB per switch/bit	2					$500K	
Low loss L-band TTD devices		2		$200K	$300K	$1M	$2M	
Rad-hard Ku-band T/R modules	5-20W, 60% efficient	1				$500K	$500K	$2M
Ku-band Class-E/F power amplifiers	5-20W, 60-80% efficient	1				$500K	$500K	
GaN Ku-band power transistors	5-20W	2		$200K	$300K	$500K	$500K	
Low loss Ku-band RF switches and phase shifters	<1dB per switch/bit	2			$300K	$500K	$500K	
Low loss Ku-band TTD devices		2		$200K	$300K	$1M	$2000K	
Low Power/Rad Hard Digital Electronics								
On-board SAR digital processors		3			$300K	$500K	$2M	$5M
High-speed, low power8 to12 bit A/D converters	>2Gsps, mw	3					$2M	
High-speed integrated (ASIC) low power waveform generat	>2GHz, 1MRad	3		$ 200 K	$300K	$500K	$2M	
L-band digital receivers and digital filters	1GHz, 1MRad	3			$300K	$500K	$2M	

3. RESULTS FOR THE PASSIVE MICROWAVE SCENARIOS

3.1. Measurement Concept Development

The basic requirements common for all three passive measurement concepts were: 5-km spatial resolution, 2-3 day revisit, global coverage, a polar sun-synchronous orbit, 19- and 37-GHz vertical and horizontal polarizations, and <0.5-K NEDT. Achieving the required spatial resolution is a fundamental technology challenge for all the passive microwave concepts. To achieve greater resolution, larger antenna apertures (either a single antenna or an array of smaller antennas yielding a larger effective aperture) are required, with associated increases in instrument size and mass.

For each of the three passive-microwave concepts, the key science parameter and its corresponding system parameter were identified (Table 3.1). For the real-aperture scenario, the science objective for spatial resolution drives a technology challenge for large aperture diameter. For the 1D-STAR scenario, resolution is more easily achievable, but obtaining the necessary coverage and swath width drives a technology challenge for larger array sizes. For the 2D-STAR scenario, the key science parameter is reducing NEDT (improving sensitivity) to acceptable levels, which drives a technology challenge involving array thinning and power. These science and system parameters represent the fundamental technology drivers for these three measurement concepts.

Table 3.1. *Key science and system parameters for the three passive microwave concepts.*

Concept	Key Remote Sensing Science Parameter	Key System Parameter
Real Aperture (RA)	Spatial resolution	Aperture Diameter
1D-STAR	Coverage/swath	Array Size
2D-STAR	NEDT	Thinning/power

The increase in mass associated with an increase in size lead us to investigate the mass of all three passive microwave measurement concepts to identify the scalability of each concept and whether mass alone presented significant technology drivers or limitations for the measurement (Table 3.2). The large total mass of the 2D-STAR concept for the resolution and frequencies of interest here emerged as a significant constraint limiting the scalability of this concept.

Table 3.2. *Summary of instrument mass analysis and scalability of the three passive microwave concepts.*

Items	Concept 1 – Real Aperture (RA) Umbrella Reflector			Concept 2 – 2D-STAR Y Arms			Concept 3 – Cylindrical (1D-STAR) Parabolic Reflector		
Size	*6 m*	*7 m*	*12 m*	*3m Arms*	*4m Arms*	*5m Arms*	*6x10m*	*6x12m*	*6x14m*
Type of Antenna	Flexible Mesh			Slotted Waveguide Panels			Flexible Mesh		
Concept Basis	Harris Deployable Antennas			SMOS			Astro-Aerospace Cylindrical Mesh		
Scalability	Yes			Limited			Yes		
Structural Mass (kg)	89.35	101.49	125	40.39	53.3	66.66	65.46	78.55	91.65
Electronics Mass (kg)	12	12	12	2955	3930	4935	100	115	130
Total Mass (kg)	**101**	**113**	**137**	**2995**	**3983**	**5002**	**165**	**194**	**222**

The large power and data handling requirements of this approach were also factors limiting the scalability. Scalability was also the rationale for making flexible mesh the baseline material for the real aperture and 1D-STAR hybrid approach. These issues will be discussed in greater detail in the technology roadmap section (Section 3.5).

3.1.1. Orbit Analysis

For the given set of microwave frequencies and spatial resolution requirements, the primary factor driving the overall size of each concept is the orbit. The analysis first considered polar sun-synchronous orbits with 1, 2, and 3-day revisits. Determination of the number of revolutions per revisit cycle and the orbital altitude identified the swath width necessary to provide full global coverage (no gaps even at the equator) and the associated sensor field of view (FOV). Combinations that led to extremely large FOVs or altitudes below 400 km were rejected, leaving the orbits listed in Table 3.3. Note that both the N=42 and N=45 orbits are also 1-day and 2-day repeat orbits.

Table 3.3. *Nominal orbits, swath widths, and FOVs for global coverage. The swath width is given in terms of degrees of longitude at the equator.*

Revs per Cycle (N)	Days in Cycle	Altitude above Equator (6378.166 km)	Sun Synch Inclination (deg)	Mean Ground Velocity (km/sec)	Swath Width (deg)	Minimum FOV (deg)
42	1,2,3	888	98.96	6.56	25.4	106.6
43	3	775	98.48	6.71	8.3	60.4
44	3	666	98.03	6.86	8.1	66.9
45	1,2,3	561	97.62	7.01	23.8	124.1
46	3	460	97.23	7.17	7.8	84.6

Wider swath widths and/or FOVs (N=42 and 45) generally complicate sensor designs and/or compromise science performance (e.g., due to the corresponding range of incidence angles for certain sensor configurations or retrieval algorithms). For these reasons, as well as for simplicity, only the N=44 (666-km, 3-day revisit) orbit was considered for the succeeding analyses. The 6am-6pm ascending-node time is nominal. A 1-day revisit was re-assessed near the end of the study in the context of a combined active/passive concept.

3.1.2. Reflector f/D Ratio

The orbit analysis indicated that a minimum aperture-size of 6-m may be necessary to achieve the science measurement objectives. A smaller aperture of 3.5 m can be used to provide three-day revisit for > 30^o latitude. However, an aperture size of 6-m is necessary to meet the full science requirement of global coverage (no gaps). For the relaxed science goal of coverage for > 30^o latitude, a 6-m aperture will provide 1-2 day revisit and 2-3 km resolution. The immediate implications of this are that a) a deployed design is necessary, b) the RA concept would need to use a reflector-based design, c) the 1D-STAR concept should also consider using a reflector, and d) the 2D-STAR would probably not involve a reflector. It was also assumed that a reflector-based aperture would be more amenable to combined operation with a radar. The f/D ratio (where f= focal length and D=antenna aperture size) of a reflector drives instrument size along the look direction. It was evident that f/D presented no technology challenges, so a reasonable value of 0.35 was chosen based on experience and used for both the real aperture and 1D-STAR concepts.

3.2. Real Aperture Scenario (RA)

The real aperture CLP passive measurement concept (Figure 3.1) is similar to concepts employed in a long heritage of satellite microwave conical scanners (e.g. TMI, AMSR, SSMI, etc.). The difference between the CLP concept and its predecessors is the larger reflector aperture (6-m or greater) necessary to achieve a spatial resolution of 5-km at 19 GHz (which automatically achieves better than 5-km resolution at 37 GHz.

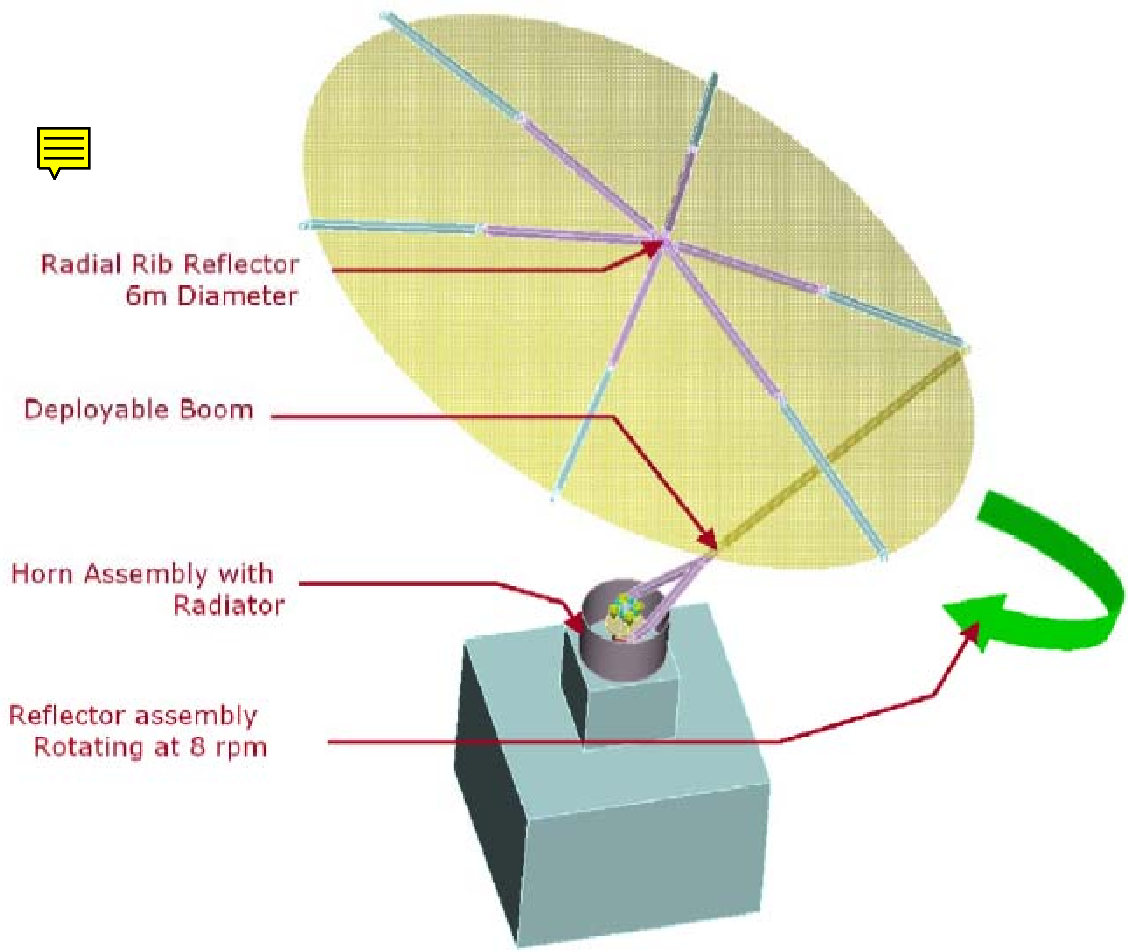


Figure 3.1. *Cartoon depicting deployed antenna configuration for the real aperture scenario.*

Nominal orbital characteristics unique to the real-aperture scenario (driven largely by the wide swath capabilities of this approach) were selected to meet science measurement objectives and to ensure a thermally stable (sun-synchronous) environment (Table 3.4). A 3-day repeat-interval was considered for this initial evaluation.

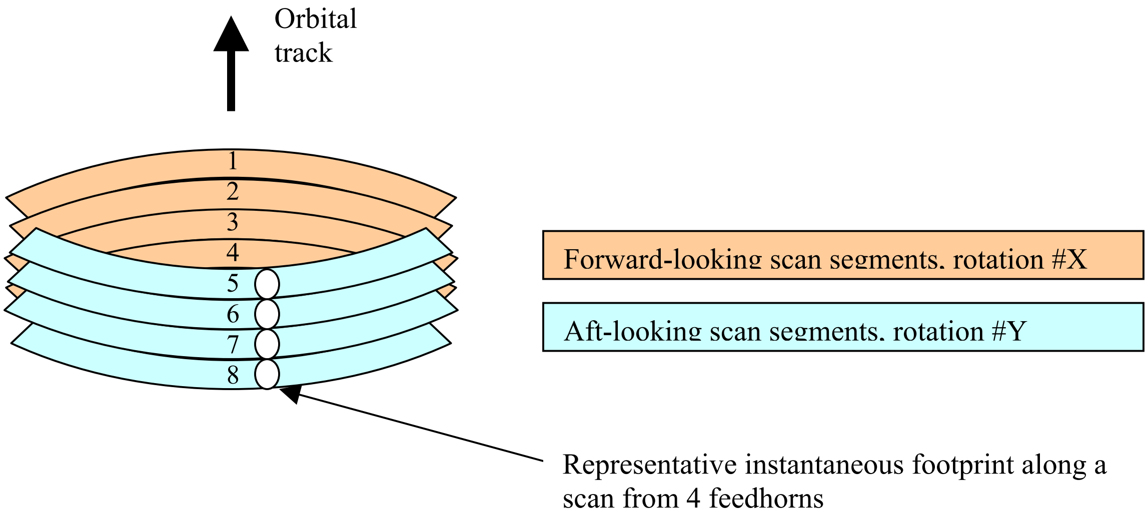
Table 3.4. *Orbit and scan parameters for the real-aperture passive microwave scenario.*

Parameter	**Value**	**Units**
Orbit Height	**670**	km
S/C Velocity (circular orbit)	7.52	km s^{-1}
Orbit Period	**98.0**	min
Ground Track velocity	**6.81**	km s^{-1}
Earth precession per day due to its orbit about sun	0.99	degrees
Precession distance on the Earth @ equator / day	109.60	km
Earth rotation during one orbit of satellite	24.50	degrees
Approx. Earth rotation at Equator during one orbit	2724.2	km
Approx. Number of orbits per day for satellite	14.7	orbits
Real Aperture conical scan angle @ S/C	45.0	degrees
Earth Incidence Angle	51.4	Degrees up from nadir
Swath width on the ground for real aperture	**1422.2**	km
Approx. Conical scan rpm	**8.0**	rpm
Conical scan half field of view for one feedhorn	**0.14**	degrees for circular FOV

To achieve gap-free global coverage at the CLP resolution (5-km footprints) using a conical scanner at a reasonable rotation rate, the RA concept must employ multiple feedhorns to generate multiple simultaneous beams per scan (e.g., 4 feedhorns per band and a spin rate of approximately 8-rpm). With four feedhorns, each 360-degree rotation would generate a total of eight scan segments - four along the forward-looking portion of the rotation, and four along the aft-looking portion of the rotation (Figure 3.2). By adjusting the number of feedhorns and the rotation rate for the footprint size, swath width, and orbital velocity, the no-gap imaging requirement can be met.

Slower rotation rates are desirable for both science and technology reasons. Slow rotation rates are scientifically advantageous because better radiometric sensitivity (NEDT) is achieved by longer dwell times per footprint. Thus there is a science requirement for NEDT, not for rotation rate. Slow rotation rates are technologically advantageous because spacecraft momentum compensation requirements are reduced and electrical and mechanical design requirements for the rotating interface are simplified.

Figure 3.2. *Imaging coverage for the rotating real-aperture concept using four feedhorns. Scan segments 1-4 are from the 4 feedhorns looking forward during conical scan #X in the track direction. Series 5-8, are from the same 4 feedhorns looking in the aft direction during a later scan #Y. The scan rate is about 8 rpm and the individual feedhorn footprint size is 5 x 7.8 km.*



The umbrella-shaped reflector of the RA approach is commonly used, and does not present a technology challenge until antenna diameters approach and exceed 6-m. At this size, the mass and inertia issues associated with rotating the antenna system present a technology challenge. For example, the moment of inertia for a 6-m RA concept about the rotation axis is 3.7E7 kg mm^{-2}. The coupling of power across a rotating interface is also a challenge. At antenna diameters greater than 6-m, the size of the reflector itself presents some technology challenges.

The coupling of power across a rotating interface becomes a more significant challenge with the consideration of an added radar component. IF high-power radar electronics are part of the rotating assembly, then the transfer of high-power (DC or RF) across a rotating interface while maintaining smooth continuous rotation or RF phase stability becomes a challenge. In this study, a non-rotating transmit antenna is considered for the RA approach to reduce complications of a high-power interface. This will require better understanding of the radar signal processing implications of a non-rotating transmit feedhorn with rotating (potentially) receive feedhorns. This issue is addressed in greater detail in Section 3.3.

3.3. Synthetic Thinned Aperture Radiometers (STAR)

Synthetic Thinned Aperture Radiometer (STAR) technology produces images by combining the outputs of multiple small antennae distributed across an aperture. The small antennae span the same area as the other passive approaches for a given spatial resolution, but its aperture is not filled by the small antennae. The STAR technique can be applied in one or two dimensions, potentially reducing instrument mass and simplifying packaging and deployment. The ESTAR imager at L-band and the Lightweight Rainfall Radiometer (LRR) at X-band are examples of successful airborne application of this technique. No STAR system has yet flown in space, but the

European Space Agency (ESA) is developing one for the Soil Moisture Ocean Salinity (SMOS) mission.

3.3.1. 2D-STAR (Y concept)

Although the mechanical deployment of a 2D-STAR concept is the simplest of the three passive microwave scenarios considered here (Figure 3.3), the 2D-STAR concept presents numerous technology challenges. As mentioned in Section 3.1, the large mass of the 2D-STAR concept, together with its high power (Figure 3.4) and data processing requirements, suggest this concept is not scalable to large apertures and shorter wavelengths relevant to this study

One challenge is to achieve adequate sensitivity (NEDT) at the 19- and 37-GHz frequencies. A minimum thinning approach considered for ESA's L-Band SMOS mission was considered, but did not meet the NEDT required for 19- and 37-GHz. Additional receiver strings along the Y-arms were used to improve the NEDT to less than 1-K, which may still be useful for CLP science but does not meet the 0.5K requirement identified in Section 3.1.

A second challenge is the high power requirement associated with this approach. Figure 3.4 details the power requirements for each receiver. Each receiver handles one polarization at one frequency. To achieve NEDT < 1K, 500 receivers are needed per arm per frequency, for a total of 1500 receivers per frequency per polarization. To measure both frequencies, 3000 receivers are needed (and this provides only one polarization at each frequency). Total power consumption for 3000 receivers is 1590W. To measure both polarizations at both frequencies, 6000 receivers would be needed. If a smaller aperture (e.g. < 3-m arms) could be used to achieve the necessary spatial resolution, the NEDT requirement might be met with fewer receivers, and power consumption might be reduced considerably.

A third challenge is the interconnectivity of 3000 receivers required for the 2D-STAR concept. The interconnectivity technology for such a large number of low voltage power supplies and local oscillator signal would be a highly relevant enabling technology for this concept and for the 1D-STAR concept described in the next section.

A fourth challenge is the large data-handling requirement of the 2D-STAR concept. With no on-board science processor, the receivers will generate 1.1E6 visibilities per band per polarization, for a net data rate of 170 Mb/s or about 2Tbyte/day (1 polarization at each frequency). Note that this is comparable to rates for the active microwave concepts considered earlier.

A fifth technology challenge is the mass of the feedhorns, which together comprise a large fraction of the total mass for this concept. It should be noted that the form factor of the receivers that we considered resulted in too many enclosures for the density of the elements. Repackaging multiple receivers into a single enclosure is a technology development that would make the "Y" a more viable concept for CLP applications.

Figure 3.3. *Cartoon depicting the deployed configuration of the 2D-STAR concept, showing three 3-m long arms with 500 feedhorns/channel along each arm. Two polarizations at two frequencies equals 4 channels.*

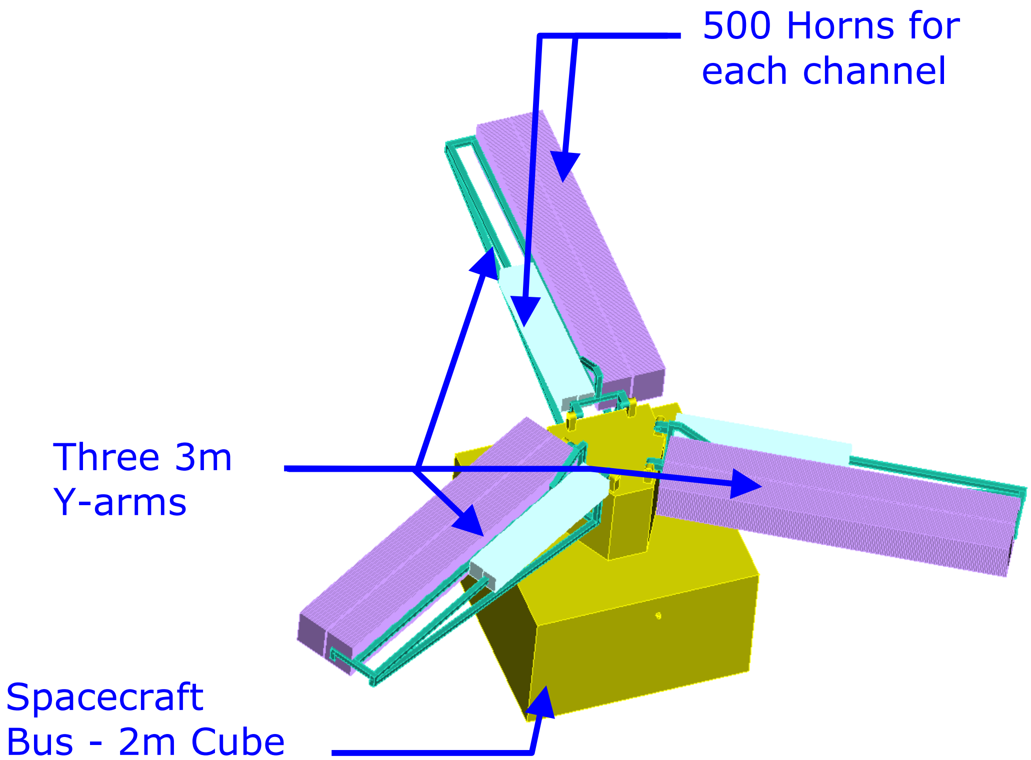
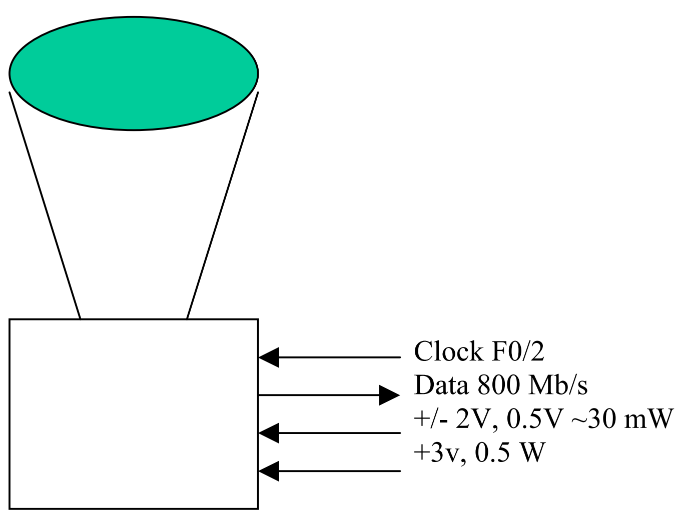


Figure 3.4. *Summary of the derived power requirements for each receiver in the 2D-STAR scenario (1590 W total), based on:[(3v @ 0.5 W * 3000) + (+/-2V, 0.5V @ 30mW * 3000) = 1590W].*

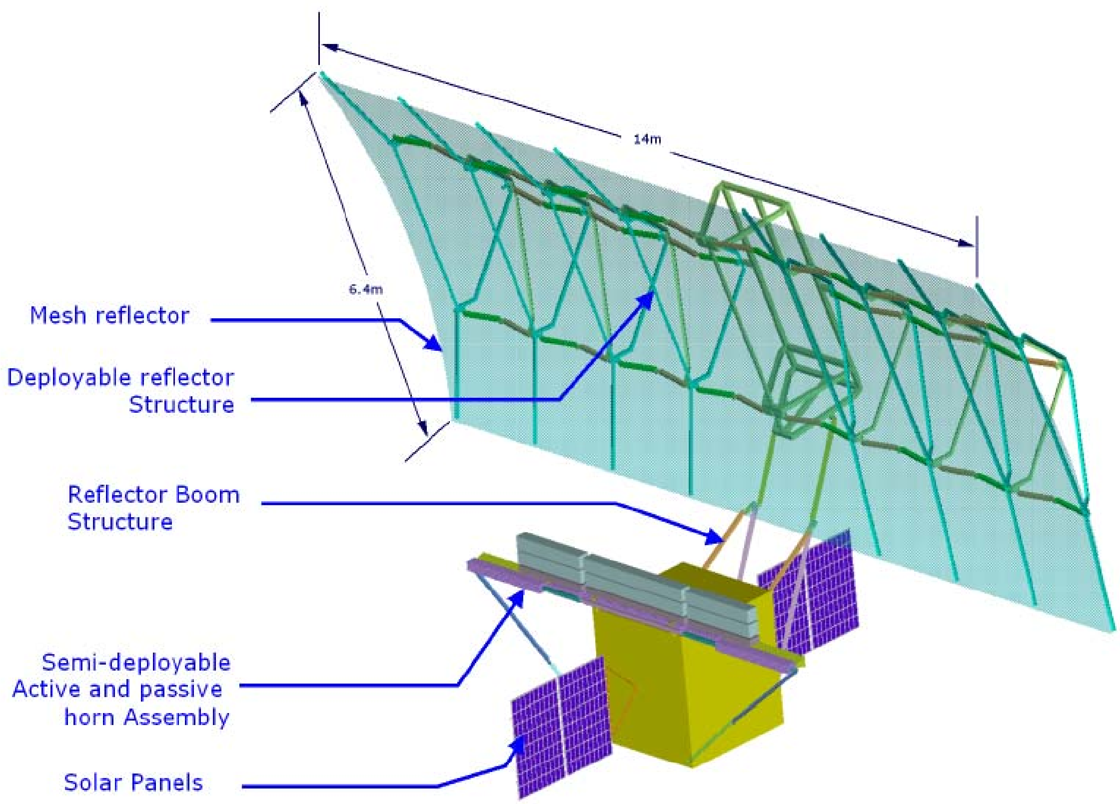


3.3.2. 1D-STAR (Hybrid Real aperture and STAR Concept)

The third measurement scenario is actually a hybrid concept that uses 1D-STAR approach in the cross-track dimension and a real-aperture approach in the along-track dimension. The antenna configuration consists of a large 14-m x 6.4-m parabolic cylindrical mesh reflector that has a +/- 50^{o} FOV relative to nadir in the cross-track dimension (Figure 3.5). The surface control requirement along the parabolic dimension (6.4-m) is 0.32-mm. The reflector deployment concept is based on a single axis deployment along the longer 14-m length. The shorter length would not deployed, keeping the structure inherently rigid to achieve high surface accuracies in the range of 0.3-mm.

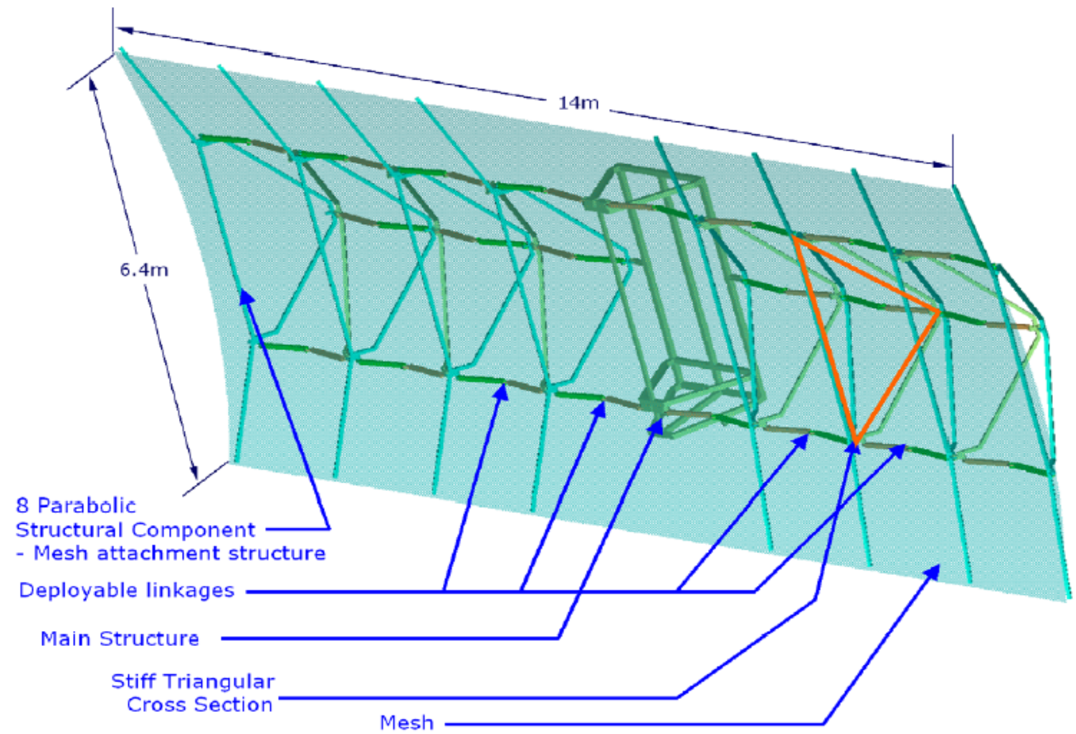
This concept was considered to be the most scalable in terms of meeting measurement accuracy and resolution requirements. Although undesirable for SAR operation because of the large number of ScanSAR beams required for wide-swath operation (see section 2), it is possible to use this approach in a shared-aperture, combined active/passive system. Therefore, this concept was selected from the three passive concepts for further evaluation.

Figure 3.5. *Cartoon showing deployed configuration of the 1D-STAR concept.*



The principal technology issue associated with the parabolic cylindrical mesh reflector are a) packaging to fit inside the smallest possible launch vehicle shroud, b) achieving the required deployed figure and maintaining this shape to within a surface accuracy of 0.3-mm, and c) achieving higher reflectivities at 19- and 37-GHz. The Integrated Sensor Analysis Laboratory (ISAL) at GSFC currently rates this mesh reflector at TRL 1-2, so these should be considered enabling technologies.

Figure 3.6. *Details of the reflector structure.*

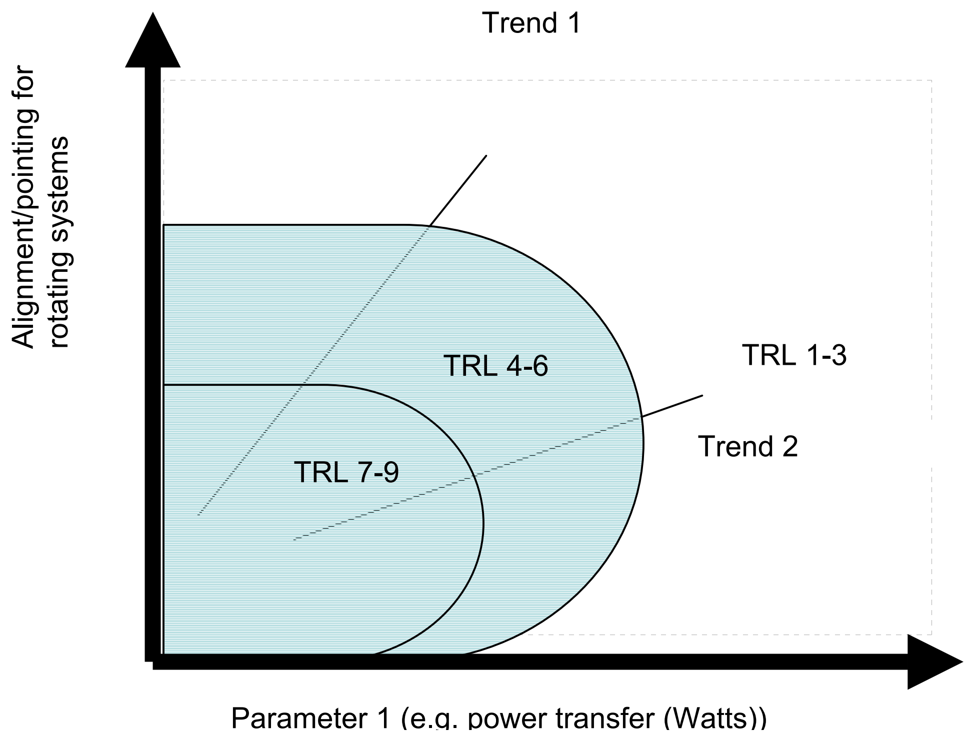


This 1D-STAR conceptual design includes a 7-m linear array of feed horns mounted on the spacecraft bus. The bus is depicted generically as a cubical shape in Figure 3.6. Keeping the feedhorns as close as possible to the bus would simplify the transfer of heat, power and data between the feed electronics and the spacecraft bus. To maintain the separation of 4.35-m (for a f/D ratio of 0.35) between the reflector and the feed horns, the reflector is deployed away from the spacecraft in the deployed configuration. Deployment of the feed horns away from the spacecraft would pose unnecessary subsystem design problems.

3.4. Assessment of Technology Challenges for Passive Microwave Scenarios

In the following sections we review technology challenges for the three passive microwave scenarios by category (e.g. component technologies, systems, etc). For areas where enabling technology investment is necessary, we employ a graphical format to illustrate the relationships between technology readiness levels (TRLs) and technology investment (Figure 3.7). The diagrams place a TRL backdrop behind the current technology maturity for a given set of parameters. Close to the origin, there is mature evidence that requirements are being met. This space is given a TRL range of 7-9. In the next region, assigned TRL 4-6, industry investment is occurring, but some investment by NASA may be necessary to guide the current trend towards technology development that will more directly address cold-land processes measurement requirements. The final region, assigned TRL 1-3, represents an area where industry development is not occurring but enabling technology is required to support cold-land process measurement objectives. Trend lines are shown to illustrate the direction that technology investment has taken to date, and the direction that s necessary to support cold-land processes measurements while still taking advantage of previous investments.

Figure 3.7. *Cartoon showing a hypothetical example of the graphical format used to assess technology development and investment in Section 3.3.*



3.4.1. Component Technologies

Technology development needs were identified for three components: 1) meshes and flexible reflector material (relevant to the RA and 1D-STAR concepts), 2) heat dissipation for balance and power transfer assemblies (relevant to the RA concept), and 3) increasing receiver power efficiency relevant to the 2D-STAR and 1D-STAR concepts).

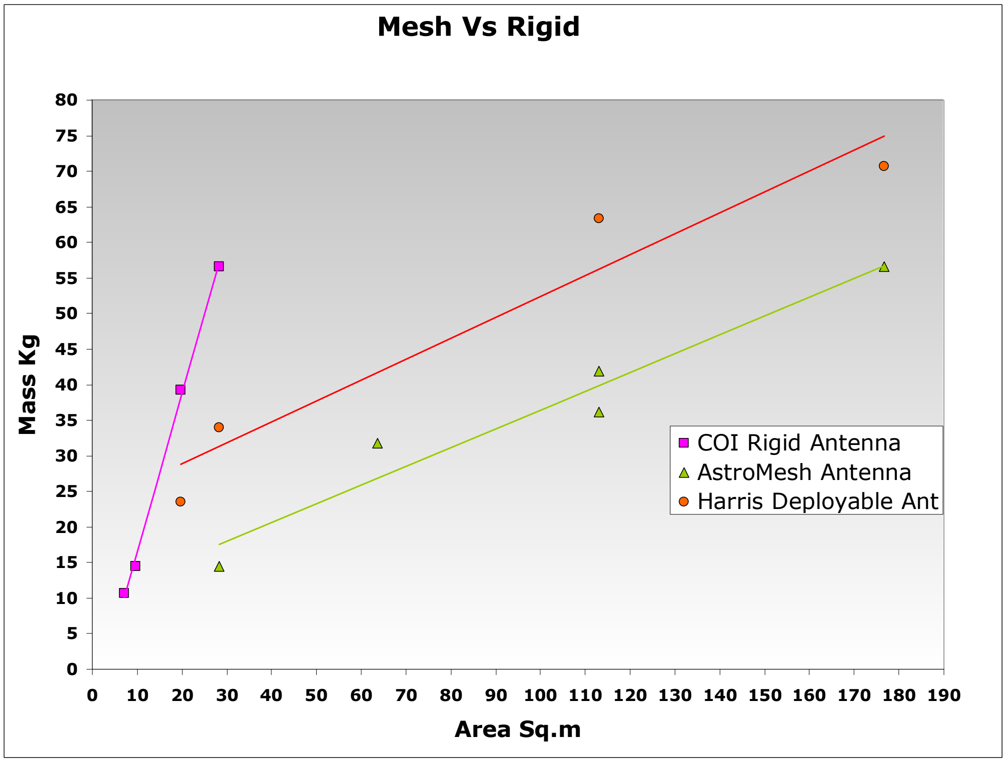
3.4.1.1. Meshes and Flexible Reflector Material

The science measurement goal for 5-km spatial resolution results in a key mechanical trade-off between varying the collecting aperture size above 6-m, and keeping surface control to 0.3-mm (1/20 wavelength at 37 GHz). Industry has not yet accomplished high surface accuracies with mesh reflectors but there is already considerable energy and investment to do so. Surface accuracies of 0.62-mm have been achieved. Better surface accuracy would require considerable engineering effort. The reflector size and higher surface accuracy requirement thus drive the mechanical design of the reflector.

Six-meters may be approaching the maximum diameter limit of solid reflectors, due to their inherent high density per unit area (above 2-kg m^{-2}) that results from rigid panels. Packaging of the solid reflectors in small volume is also challenging because of the inherent nature of the design. The introduction of too many folds to improve packaging could result in decreased reliability, increased risk and complicated deployment. Mechanical design complications with solid reflectors include more hinges, stowage issues, supporting the structure in the launch vehicle configuration etc. Re-use of the reflector for a shared-aperture active system affects the Earth Incidence Angle (EIA) and complicates retrievals, however active/passive retrievals will be easier using a common aperture.

Our assessment of the technology development of mesh versus rigid reflectors indicates that two of the passive CLP measurement scenarios (RA and 1D-STAR) would benefit from investments to increase reflector area without significant increases in mass, i.e. large lightweight antennae (Figure 3.8). The purple trend line represents previous work done on large spaceborne apertures using rigid aperture material and backing structures. It has met the CLP surface control requirements, but the largest rigid antenna just meets the CLP *minimum* collecting aperture requirement. The red line and green lines represent industry trends with systems that are consistent approaches for satisfying the RA concept and the 1D-STAR concept respectively. However there is not much current investment for instrument applications that require surface control better than what is needed for communication applications. In other words, mesh-based reflectors of sufficient size are being developed in industry, but not with adequate surface accuracy for CLP requirements.

Figure 3.8. *Assessment of mesh versus rigid antenna reflector technology development investments (TRL/Cost).*



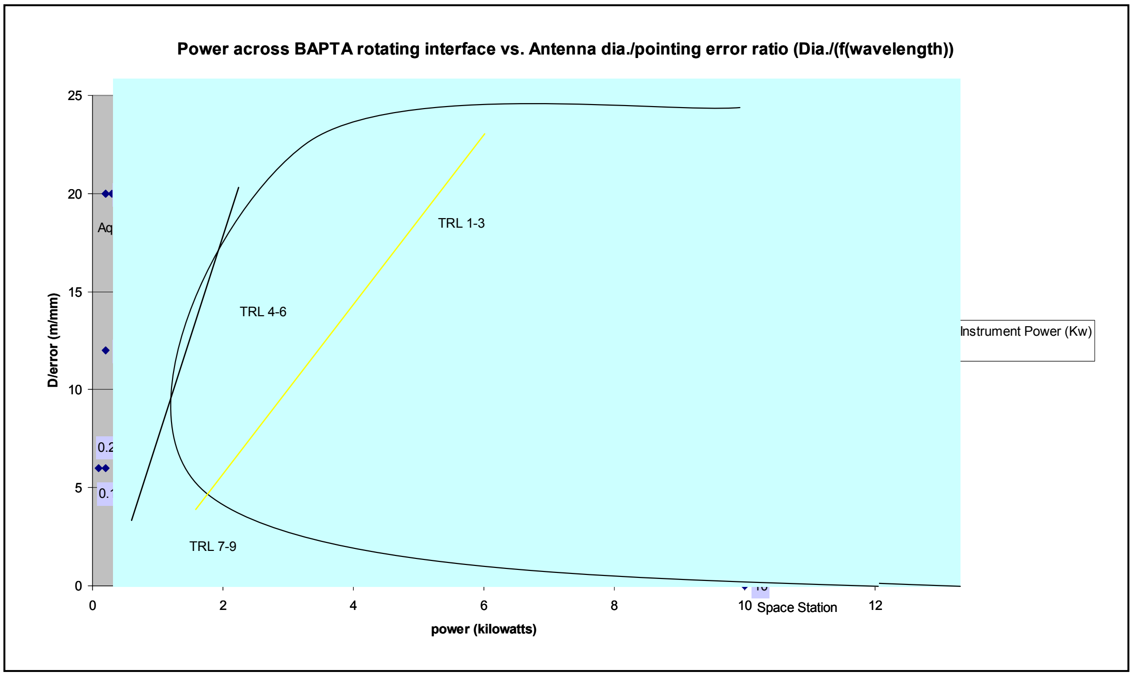
An assessment of mesh technology development indicates that the loss mechanisms of meshes need to be better understood (Appendix 1). Passive microwave applications at any frequency require low loss (i.e. high reflectivity) reflectors. The reflectivity of existing 10- and 20-opi gold-plated wire mesh was measured both at L-band and 37-GHz to bound the performance of these meshes for 37-GHz radiometric applications. The loss mechanism within the weave structure of gold plated wire appears to be frequency-dependent. The impact of the large reduction in mesh wires/wavelength of the samples at 37-GHz compared to 1.4-GHz (factor of 26.4) is not well understood relative to the small losses of interest here. Our assessment also indicates that investment is needed to improve the surface control using low-density materials. Molybdenum gold meshes are the current industry standard, but additional materials research will be important to CLP applications.

3.4.1.2. Balance and Power Transfer Assembly (BAPTA) Technology

The science measurement goals for high spatial resolution present additional technology challenges for the RA concept. No reflector of this size and required surface control has been flown. The impact of the increased mass and resultant moments of inertia (MOI) on the pointing tolerance of a traditional Balance and Power Transfer Assembly (BAPTA) is unknown. For a SAR system combined with the RA approach, design options exist that include rotation of the transmitter horn and electronics, the receiver horn and electronics, or both. If the transmit electronics are part of the rotating assembly, assessment of this component technology indicates that heat removal is the major issue. Several kilowatts of heat must be removed from the rotating transmit electronics, which has not been done before on systems with precision pointing requirements (Figure 3.9).

The current trend in BAPTA development (black trend line) is towards low-power passive-only applications with no current emphasis on the alignment and spatial resolution (i.e. aperture size) required for 19- and 37-GHz cold-land processes measurements, and no emphasis on large heat-removal requirements. If high power must be provided over a rotating interface, a new approach (yellow trend line) may be needed. This approach requires enabling BAPTA technology development to develop appropriate heat dissipation methods. The only data found for systems that could handle the heat dissipation in the rotating interface was for Space Station Freedom, however that system had no precision pointing requirements and the heritage cannot be used for the CLP application. System studies are also needed to understand disturbance torque and momentum compensation requirements associated with rotating a large system. Calculations of MOIs need to be considered with antenna size decisions to gauge current technology readiness levels.

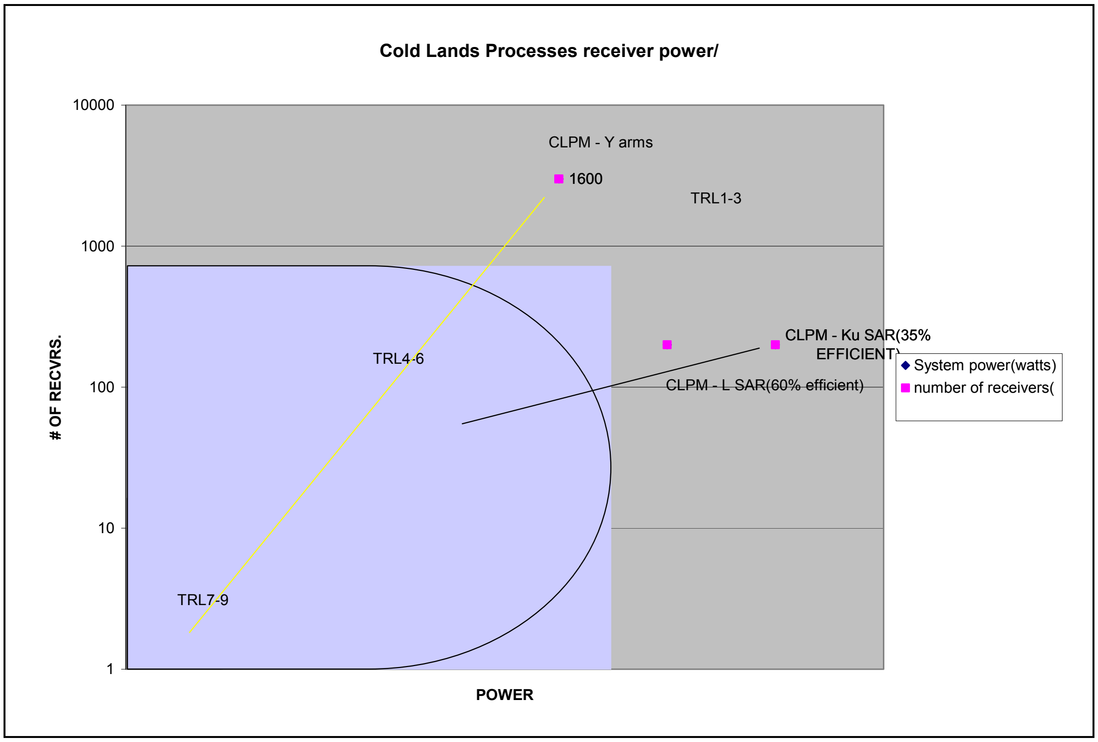
Figure 3.9. *Assessment of power across BAPTA rotating interface and antenna diameter/pointing area ratio.*



3.4.1.3. Low Power Receiver Technology

A fundamental technology challenge for the 2D-STAR concept and (to as lesser extent) the 1D-STAR concept is to increase receiver power efficiency. Two distinct technology development trends are evident in this area (Figure 3.10). First, there has been considerable effort to improve the power efficiency of high-power systems (black trend line). The second trend is directed towards using multiple receiver-channels in an electronically scanned array and improving power efficiency on a per-receiver basis (yellow trend line). Research now underway on reduced power RF design has demonstrated significant progress towards more efficient RF receivers at 19- and 37 GHz. However, the number of receivers is large for the STAR concepts, and there is little that can be done to further reduce the number of receivers in the STAR designs. Therefore the cumulative power-requirements of a large number of moderately efficient receivers remains problematic. Further progress towards improving receiver power efficiency is necessary to enable the 2D-STAR concept (TRL 1-3) and will enhance the 1D-STAR concept (TRL 4-6).

Figure 3.10. *Assessment of low-power receiver technology development indicates that current "low power" receivers must be made even more efficient to support multiple receiver STAR concepts (TRL/Cost).*



3.4.1.4. Packaging/Launch Vehicle Technology

All three of the passive microwave concepts involve relatively large antenna structures that present packaging challenges for the current fleet of launch vehicles. Both the RA and 1D-STAR reflector concepts show promise as the supporting framework for "sensorcraft" packaging that would wrap around functional components and give the reflector the prime position in the fairing for launch. The mass/stowed-volume ratios of these concepts are relatively low, meaning launch vehicles with fairing capacities large enough to hold a stowed instrument tend to have far greater mass-lift capability than necessary to lift the instrument to orbit (Figure 3.11). Although the TRL assessment for low-volume packaging solutions is very mission-specific, Figure 3.11 illustrates that current trends (black trend line) provide more than enough mass-to-orbit capability but insufficient fairing volume for CLP concepts (yellow trend line). High volume capabilities are currently only served by the Delta-IV series (Figure 3.12). A breakthrough in innovative packaging techniques like sensorcraft technology will be necessary to enable use of one of the less expensive Delta-II launch vehicle series ($25M cost savings).

Figure 3.11. *Assessment of low volume packaging (TRL/cost) for sensorcraft. A sensorcraft configuration or new fairing option is needed that better matches cold land process instrument volume and mass-orbit requirements.*

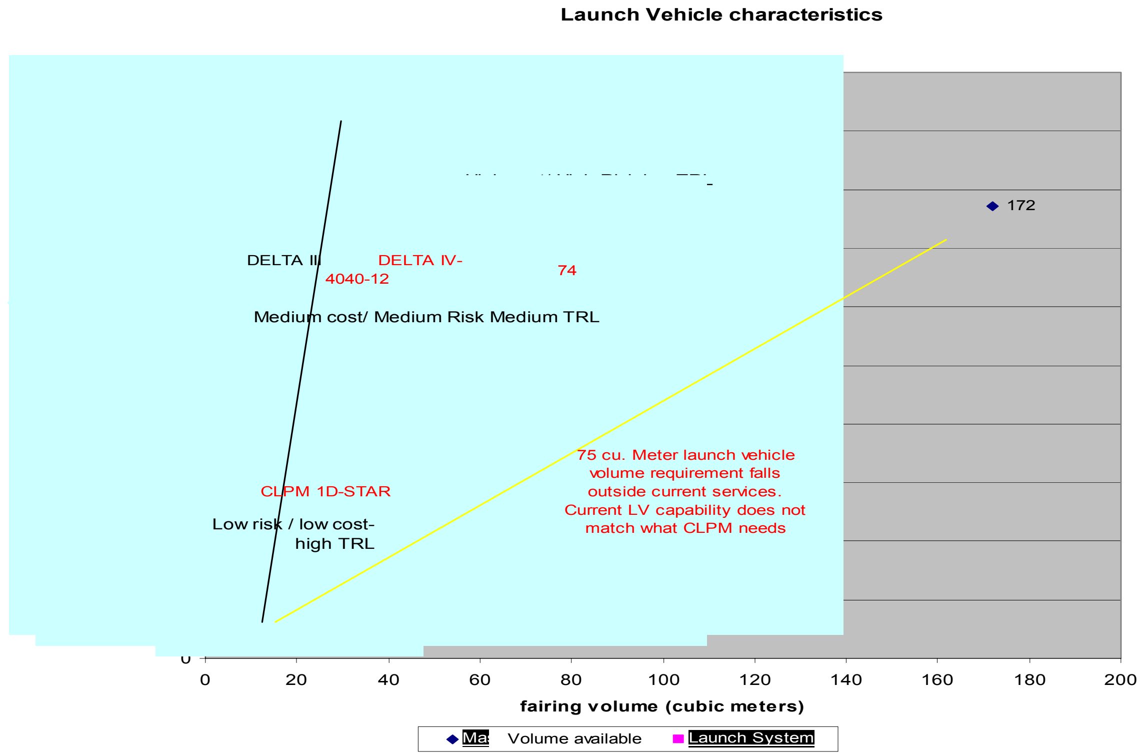
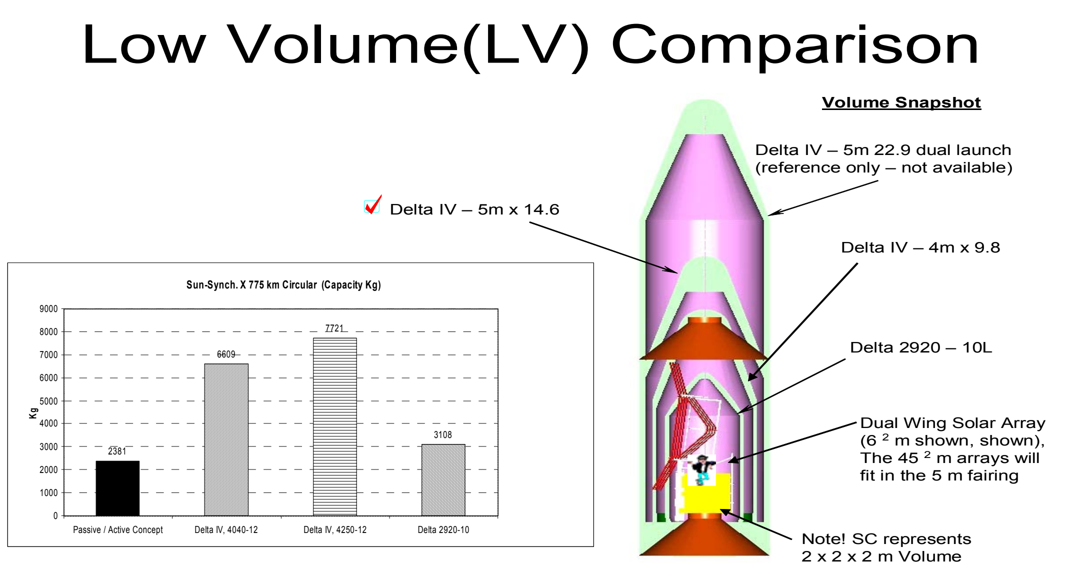


Figure 3.12. *Comparison of low volume packaging needs for selected 1D-STAR concept. A Delta-IV 5-m diameter launch vehicle is currently required to contain the large volume of this stowed reflector, however the overall mass is much lower than the Delta-IV is capable of lifting to orbit. More efficient low-volume stowage technology is needed.*

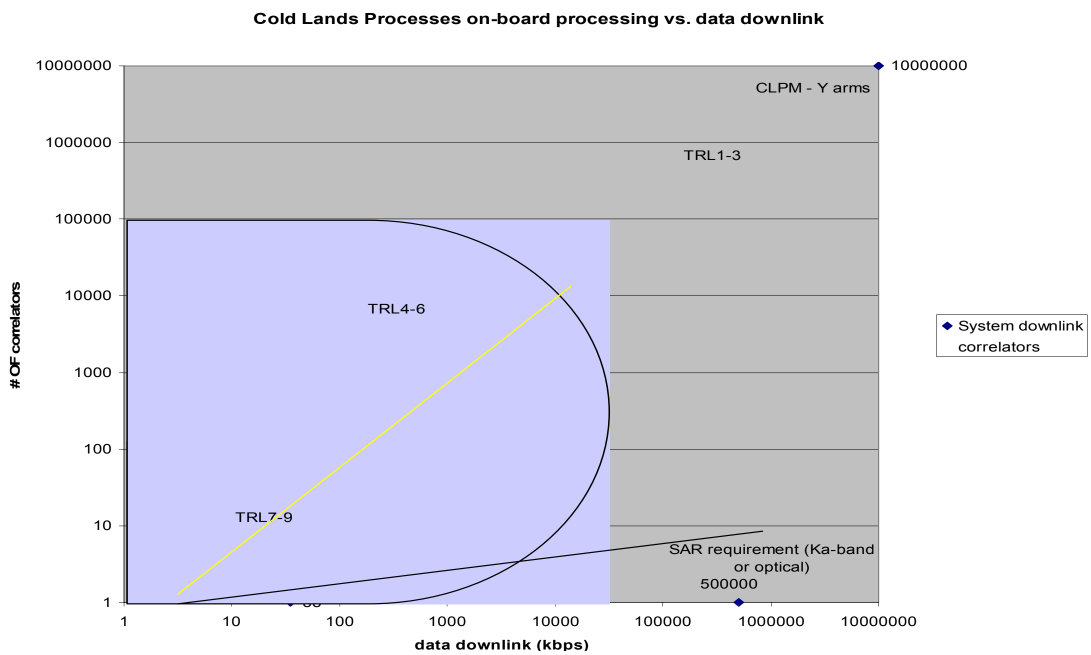


3.4.1.5. High speed Data-downlink and On-board Processing Technologies

The 2D-STAR concept presents a very large data-rate relative to the other passive microwave scenarios (Figure 3.16), but would be reduced if smaller apertures were possible. Data rates from this concept are similar in magnitude to active-radar instruments. The resulting technology challenges involve downlink capacities ("pure" downlink technology solutions) and a combination of on-board data processing and downlink technology solutions. The yellow trend line in Figure 3.13 shows that the 2D-STAR concept is the greatest driver (TRL-1) for this technology need, while the other passive concepts fall into the TRL 4-6 range. For comparison, the black trend line shows the relationship for active radar concepts.

A combined active/passive approach compounds the problem. In our integrated mission analysis, both the GSFC Integrated Mission Design Center and JPL Team X recommended the development of optical and Ku-band downlinks to take advantage of their large bandwidths, and to avoid dependence on already-tight TDRSS schedules. We do not recommend a specific technology approach here, however. The current state of on-board processing and downlink advances needs to be assessed before specific technologies can be identified to support cold-land process measurements.

Figure 3.13. *Assessment of on-board processing benefit relative to a pure downlink technology solution.*



3.4.2. Systems Technology

Only systems level technology demonstrations and trades can infuse new technology and advance maturity up to TRL 6. A plan to demonstrate Integration, Alignment, Calibration and Test in thermal vacuum is envisioned, with the inclusion of active measurement components as they become available.

3.4.2.1. Integration and Test of a 1D-STAR system

The integration and testing of the 1D-STAR concept (TRL 2) is recognized as a top priority and is synergistic with the development of the mesh reflector material technology. The important components need to be brought together into a system demonstration in a relevant environment.

3.4.2.2. On-board data processing

The system demonstration will give the CLP team an opportunity to trade different levels of on-board processing and the associated scientific uncertainty against the downlink requirements that will drive mission hardware, ground operations, and personnel costs.

3.4.2.3. Instrument-Algorithm Complexity Tradeoffs

In this section, we consider high-level tradeoffs with respect to the maturity of the measurement approach options vs. retrieval algorithm options that are fundamentally tied to those options. The algorithm issues have the potential to change or impose new requirements on various CLP measurement technologies. This is particularly true for combined active/passive retrievals due to their relatively lower maturity vs. passive-only or active-only legacy algorithms.

A combined passive/active approach is scientifically attractive because the two types of sensors provide complementary information, which can lead to more robust retrievals of cold lands parameters. The results of the current study indicate that several candidate approaches exist that are technologically feasible (in order of increasing system-level complexity):

1) A rotating real aperture passive instrument plus a SAR using a separate 2nd antenna on the same platform.
2) A STAR-type passive instrument plus a SAR using a separate 2nd antenna on the same platform.

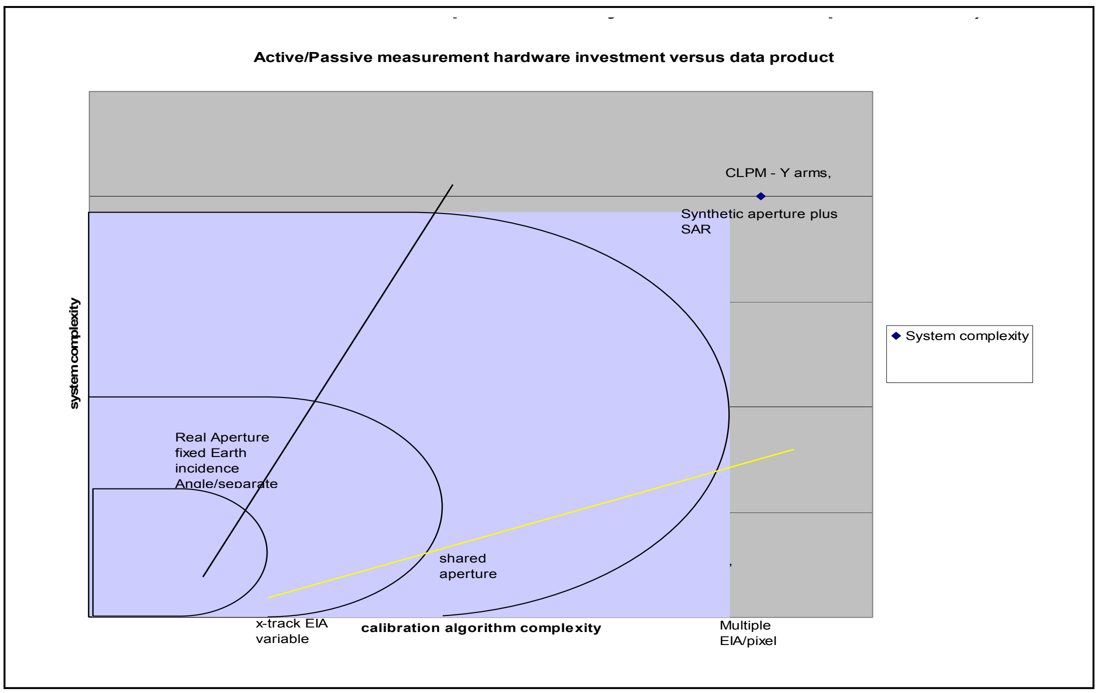
Each of these technological approaches has unique implications for science objectives, especially for the characteristics and complexity of passive-only and combined active/passive retrieval algorithms and their accuracy:

a) A rotating real aperture approach yields observations with a constant earth incidence angle (EIA). This is the legacy approach (SSM/I, AMSR, CMIS), so we would expect retrieval algorithms to be the simplest and to differ the least vs. legacy-style algorithms.
b) A 1D-STAR instrument would yield observations with a varying EIA along the cross-track direction. Retrievals must take the varying EIA into consideration and therefore involve greater complexity. There is aircraft heritage with the 1D ESTAR instrument and now also the LRR IIP aircraft instrument.
c) A 2D-STAR instrument would yield observations with a varying EIA along both the cross-track and along-track directions. Each pixel on the surface would be observed multiple times per pass with multiple EIAs. Retrievals must take the varying EIA and multiple looks into consideration and therefore involve greater complexity. There are presently several 2D-STAR instruments under development (including the 2D-ESTAR IIP aircraft instrument at GSFC and the ESA's SMOS space mission), but end-to-end calibrations and image generation are the subjects of current research. Importantly, all of these 2D-STAR efforts are at a much lower frequency (1.4 GHz), and involve coarser spatial resolution requirements than are required for cold land processes measurements.

Science studies are needed to quantitatively evaluate these algorithm issues with respect to the three combined active/passive technology approaches defined above. A conceptual trade-space illustrates the relationship between retrieval-algorithm complexity (including instrument-level calibration) and system technological-complexity (Figure 3.14). In this trade-space, the complexity of retrieval algorithms increases towards the right and system complexity increases in the upward direction. High flight-readiness levels are located near the origin. Approach #1 (1D-STAR + shared-aperture SAR) involves the least technology complexity, but complex algorithm for SAR calibration. Approach #2 (rotating RA + SAR, with separate apertures) involves the least algorithm complexity and moderate technology complexity. Approach #3 (STAR + SAR with separate apertures) involves the least algorithm and technology complexity. The following assumptions are implicit in Figure 3.14:

- flying both the passive and active instruments on the same platform is more desirable, in order to minimize overall mission cost (one bus instead of two, etc).
- a combined a/p approach using a shared aperture simplifies retrievals and leads to more accurate science (all other things being equal) because geolocation issues will be simpler
- a combined a/p approach involving co-located a & p footprints simplifies retrievals because the incidence angle, look direction, and observation times will match

Figure 3.14. *Tradeoff space for complexity of combined active/passive instrument approaches vs. corresponding retrieval algorithm complexity. The latter implicitly includes calibration issues.*



3.5. Identification of Technology Needs

The next sections summarize the technology needs of the passive-only and the combined active/passive CLP measurement concepts, describe a roadmap for addressing these needs within the next several years, and the benefits expected from addressing these needs.

Technology Needs Matrix

The following work-breakdown structure (WBS) summarizes the technology development required for CLP measurement concepts (Table 3.5). Ranked in order of priority, these technology needs are either a) *enabling* (necessary to make a measurement), b) *cost reduction* (necessary to lower the cost of making a measurement), c) *enhancing* (development will improve the measurement, but lack of development will not prevent the measurement), or d) *infeasible* (further technology development appears impractical, based on today's technology).

Table 3.5. *CLP technology development requirements and associated priority for component technologies (upper panel) and system technologies (lower panel).*

Section in Text	WBS.items for Component Technologies	Real Aperture	Y-STAR	Cylindrical	Cylindrical plus radar	Real Aperture plus radar
3.4.1.1	1C.Meshes	Enabling		Enabling	Enabling	Enabling
3.4.1.3	2C.Low power receivers	Enhancing	Infeasible	Cost reduction	Cost reduction	Cost reduction
3.4.1.2	3C.BAPTA	Cost reduction				
3.4.1.4	4C.Sensorcraft vs. fairing			Cost reduction	Cost reduction	
3.4.1.5	5C. downlink		Cost reduction		Cost reduction	Cost reduction
Section in Text	**WBS items for System Technology Trades**	**Real Aperture**	**Y-STAR**	**Cylindrical**	**Cylindrical plus radar**	**Real Aperture plus radar**
3.4.2.1	1S.STAR integration	Enhancing	Enabling	Enabling	Enabling	
3.4.2.2	2S.On-board data processing	Enhancing	Infeasible	Cost reduction	Cost reduction	Cost reduction
3.4.2.3	3S. instrument calibration/algorithm complexity	Enhancing	Enabling	Enabling	Enabling	

There are two "infeasible" technology areas where further development seems impractical or it seems unlikely that further development will yield significant improvements. Both of these (low power receivers and on-board data processing) involve the 2D-STAR concept, so it is appropriate to not pursue this concept. If a smaller aperture (e.g. 3-m) proves feasible to achieve the required spatial resolution, both of these technology constraints are relaxed and the 2D-STAR concept would remain viable.

Emerging as the most critical component technology was the development of lightweight flexible reflector material suitable for use at 19 and 37 GHz (the "meshes" row). The system demonstration of integration and calibration of a chosen measurement method was the most important of the system technology needs. It was viewed as enabling for the STAR concepts and enhancing for the real aperture concept..

3.6. Technology Roadmap

The Passive CLP Technology Roadmap (Table 3.6) assumes the 2010-2013 timeframe as the goal for deployment of advanced cold land process measurements, with five windows of opportunity for technology development necessary to meet that goal. The two-year component-technology windows are consistent with the ACT and AIST programs and the 3-year IIP window was assumed because that was a practical overlay for the systems work to be infused with the component technologies. The work-breakdown structure is evolved from the eight major technology challenges already identified.

The mesh technology and receiver power technology are all needed immediately and will have important applications outside of CLP. Development of the platform, packaging/sensorcraft, and downlink technologies is also important, but must remain flexible to be responsive to both an evolving CLP measurement concept and emerging industry technology developments..

The most important technology investment for the passive-microwave and combined active/passive approaches discussed in this section is a tradeoff study of instrument-algorithm complexity relationships. It has the potential to guide all the other technology development efforts identified. And conversely, the outcomes of the component and systems technology efforts, as they become available, will likely influence the instrument-algorithm tradeoff. This study will have the largest and most global payoff with respect to reducing CLP measurement risk and cost. Yet because it must consider both technology and science issues together, it must be protected from "falling through the cracks" between traditional programmatic boundaries at NASA.

3.7. Technology Investment and Benefit

Whereas the roadmap (Table 3.6) presents a technology development schedule, the technology investment and benefit table (Table 3.7) is organized along major instrument systems and mission discipline areas (the same areas as in the rightmost column of the roadmap), summarizing current TRLs for the CLP application, the recommended TRL advancement strategy to TRL 6, and the expected benefit in reduction of risk and cost.

Table 3.6. *Technology Development Roadmap.*

WBS.Component Technologies	2003-2004 Component Technology opportunity (e.g. ACT)	2005-2006 Component Technology opportunity (e.g. ACT)	2007-2008 Component Technology opportunity (e.g. ACT)	Major Instrument System and Mission Discipline Categories
1C.Meshes	Characterize new materials and test emissivity__(37 Ghz)(TRL1)	Build reflector w/ new materials (37 GHz)		Antenna
2C.Low power receivers	Develop LP receivers 0.3 watts DC power (TRL3)________________	Repackage receivers as sensorcraft components discrete front ends/FPGAs to LP Designs to MMIC/ASIC	Convert to rad-tolerant low power designs	Receivers
3C.BAPTA	Develop slip rings, roll rings w/ KW power handling,(TRL2)	Trade despun xmit horn vs. rotating w/ new KW BAPTA data.	Demo BAPTA in 1G for RA reflector ≥ 6m dia., MOIs , 8 rpm	Mechanisms
4C.Sensorcraft vs. fairing	Design wraparound structure and components for reflectors Trade against larger fairings(TRL2)	Fit check by analysis in Delta II / Demonstrate surface figure w/ sensorcraft components		Platform Mech/Thermal
5C. downlink	K-band (TRL 6) optical (TRL 4)	Trade STAR/SAR imaging / vs. cost of downlink components	Reassess CLP downlink reqmt. Invest based on current on-bd. Processing/downlink trade	Platform Communication and mission operations
Technology Trades	**2003-2005 System Technology Analysis and/or demonstration opportunity (e.g. IIP)**		**2006-2008 System Technology Analysis and/or demonstration opportunity (e.g. IIP)**	**Instrument Systems**
1S.STAR integration	Model and build facets prototype to required surface figure (0.3 mm @ 19 GHz)	Insert 1C, 2C	Demo STAR deployment / , Insert new components from 1C, 2C	Mech/Thermal/Electrical Systems , I & T
2S.On-board data processing	Trade Image return vs. correlations Revisit TRLs of separate RA, SAR approach vs. combined STAR/SAR instrument approach		Insert 3C and/or Insert 4C based on 3S pick / Insert 5C based on d/l requirement	C & DH
3S. Instrument-algorithm complexity	Study system stability of STAR	Compare CLP approaches – pick concept	Using CLP concept Calibrate and Generate performance data in thermal vacuum	Science and Calibration

Table 3.7. *Technology Investment and Benefit.*

2009-2013/ Flight opportunity (e.g. ESSP)	Technology Investment (Measurement Concepts Current TRL),	Path to TRL 6	Flight Project Benefit ($ and /or risk saved)
Antenna	RA(4), Cylindrical (2), Y(4)	Develop high frequency Meshes, integrate and test demo cylindrical	No development time required, build to print
Receivers	RA(6), Cylindrical (4), Y(1), big power requirement	Demo LP, RT designs in system	Recurring cost only, system power known
Mechanisms	RA-passive only (6), RA-Act/Pass(1)-heat dissipation issues, Cylindrical (4), Y(5)	BAPTA life test, 1G TV test w/reflector mass model, slip rings or roll rings with CLP power dissipation in TV, Demo STAR deployment in TV	Begin BAPTA accelerated life test early, root out deploy mechanism problems on STARs
Platform Mech/Thermal	RA-passive (6), RA-Act/Pass(4), Passive only Cylindrical -(4), A/P Cylindrical (3)-big radiators and solar array and reflector, Y (5)	Sensorcraft	Fit in Lower Volume ($25M in launch costs)
Platform Communication and mission operations	RA-passive only (9), RA-Act/Pass(3), A/P Cylindrical (3), Cylindrical (4), Y(1), big data requirement	Except for Y , this may advance/w/o specific CLP investment	Preparation to use High speed downlinks will streamline Mission ops
Instrument Systems			
Mech/Thermal/Electrical Systems , I & T	RA-passive only (6), RA-Act/Pass(1)-heat dissipation issues, Cylindrical (4), Y(3)	Recommend Cylindrical only as testbed for component technology infusion	System demonstration will prove STAR calibration and develop confidence in active/passive retrievals
C & DH			
Science and Calibration	RA-passive only (9), RA-Act/Pass(3), A/P Cylindrical (3), Cylindrical (4), Y(1), big correlation requirement		

Appendix 1. Motivation for development of 37 GHz mesh
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August, 2003

The Cold Land Processes Working Group identified several technology scenarios that included passive microwave measurements at a minimum of 19 & 37 GHz and a 6-meter class deployable reflector. There are several well-developed deployable antenna concepts that could be considered candidates for such an instrument using a scanning reflector (option 4), or with modification may be applicable to a 1-d STAR concepts (option 6). These concepts may provide unprecedented temporal and spatial resolution and may enable substantial improvement in our understanding of the terrestrial cryosphere. A critical portion of this improvement is the ability to enable a ~6 meter deployable reflector that is suitable for radiometric applications through 37 GHz.

Deployable mesh antennas technology has been in use successfully for some time for space borne communication applications and antennas as large as 12 meters have been developed and successfully launched [Miller,1998]. However, these antennas utilize a gold plated molybdenum wire mesh for the reflector surface and while this technology has been used for some time in communications applications it is not clear that the mesh will meet the more stringent requirements for radiometric applications. The effect of the emissivity of the reflector surface on the system radiometric error budget can be illustrated by examining the contribution of the radiometric properties of the reflector on the received brightness temperature. The measured antenna temperature can be considered as three terms: the received power from the footprint of the antenna on the earth's surface reduced by the reflectivity of the reflector surface; the power radiated from the reflector surface and received by the feed; and a very small term due to the cosmic background radiation transmitted through the mesh and received by the feed. These terms ca be written as shown below.

$$T_{ant} = \Gamma_{mesh} T_{scene} + \varepsilon_{mesh} T_{mesh}^{phy} + \mathrm{T}_{mesh} T_{\cos mic}$$

The sensitivity of the measured brightness temperature to variations in these parameters can be approximated as [Lawrence & Campbell, 2000]

$$\Delta T_{ant} = (T_{scene} - T_{\cos mic})\Delta\Gamma_{mesh} + (T_{mesh}^{phy} - T_{\cos mic})\Delta\varepsilon_{mesh} + \varepsilon_{mesh}\Delta T_{mesh}^{phy}$$

Keeping in mind that an important design goal for these large deployable antennas is light weight, reflector surfaces of interest will be inherently low mass. Thus, for typical orbits the reflector physical temperature changes will result in error contribution due to the reflector surfaces to be dominated by the third term, emissivity of the material.
Thus, the emissivity of the material used for the reflector surface as well as its stability is extremely important.

The many studies have recognized the potential advantages of mesh reflectors for radiometric applications and have analyzed sensor concepts which include the use of deployable mesh reflectors [NASA, 1984], [Schroeder et al., 1994]. These studies have identified the mesh as a key technology and researchers have evaluated the emissivity and reflectivity of gold plated molybdenum mesh materials albeit for lower frequency applications [Harrington & Blume, 1984], [Lawrence & Campbell, 2000]. Further, a recent study also included a thermal study of a deployable mesh concept to estimate the temporal variation of the expected radiometric error [Njoku et al., 2001]. This study, while for 1.4 GHz, was for a 6 meter mesh antenna and provides

a rough order of magnitude of the potential impact of thermal variations and the emissivity of the mesh reflector and compared the performance at 1.4 GHz of 20, 18 and 10 openings per inch (opi) material [Njoku et al., 2001]. However, it not clear that the mesh performance at 19 & 37 GHz can be estimated using these results.
While it appears that the emissivity has decreased by a factor of two as the mesh density doubled from 10 to 20 opi, it is not likely that the mesh properties will scale in such a straightforward way. The loss mechanism within the weave structure of gold plated wire may well be frequency

Sample opi	Emissivity	
10	0.0094	+/- 0.0002
18	0.0056	+/- 0.0002
18	0.0053	+/- 0.00025
20	0.0053	+/- 0.0003
20	0.0051	+/- 0.0002
20	0.005	+/- 0.00035

Emissivity at 1.4 GHz

dependent. The impact of the large reduction in mesh wires/wavelength of the samples at 37 GHz compared to 1.4 GHz (factor of 26.4) is not well understood relative to the small losses of interest here. Finally, other measurements have demonstrated difficulty comparing over wavelength differences far less than required here [Harrington & Blume,1984].

In an attempt to characterize the technology issues related to extending mesh performance to the frequencies of interest for Options 4 & 6 identified by the Cold Land Process Working Group the reflectivity was measured both at L-band and 37 GHz to bound the performance of existing 10 and 20 opi mesh for 37 GHz radiometric applications. The Reflectivity for the 10 and 20 opi samples (similar to those used in [Njoku et al., 2001]) are shown below.

Additional characterization of these samples at 37 GHz was also attempted using a free space scattering transmission measurement. These 26 to 37 GHz measurements are only intended to help evaluate the need for a more comprehensive evaluation program. The measurement technique did not include an evaluation to study error mechanisms or to evaluate the calibration approach. Finally, the difficulty inherent in performing high fidelity measurements of highly reflective targets required a hybrid approach mixing far field and nears field measurements. However, even with these limitations, it would appear that the performance of the mesh at 37 GHz is clearly an issue.

The reflectivity estimated from the free space measurement for the 20 opi sample was on the order of 0.5 and the estimated emissivity was approximately 0.25 to 0.4. The emissivity appears higher (worse) than would be predicted by linear scaling the L-band data. Even given the uncertainty of the somewhat crude free space measurements, it is clear that improved mesh will be required to enable the reflector performance required for the CLP missions described by the CLP Working Group. Further developing the gold plated molybdenum wire technology may be limited by the wire gage and the strength of the resulting wire/weave. While industry is working to extend the mesh materials to 40 opi, this alone may not provide a mesh that will enable the important passive measurements of interest to the CLP Working Group and NASA.

New material concepts that provide low emissivity and retain the mechanical properties to leverage existing antenna deployment concepts are needed. NASA should invest in the development of low TRL material concepts to develop these materials. The antenna deployment concepts that have been developed for the existing mesh represent years of technology investment and have significant space flight heritage. The development of the next generation surface material will leverage this investment and extend the capability of these antennas to enable new measurement capability. This NASA technology investment is critical since it is not an technology that will be driven by commercial communications applications. It also it provides substantial technology leveraging. That is, a relatively small investment in material development to advance the TRL of the reflector surface will result in a high TRL sensor concept.

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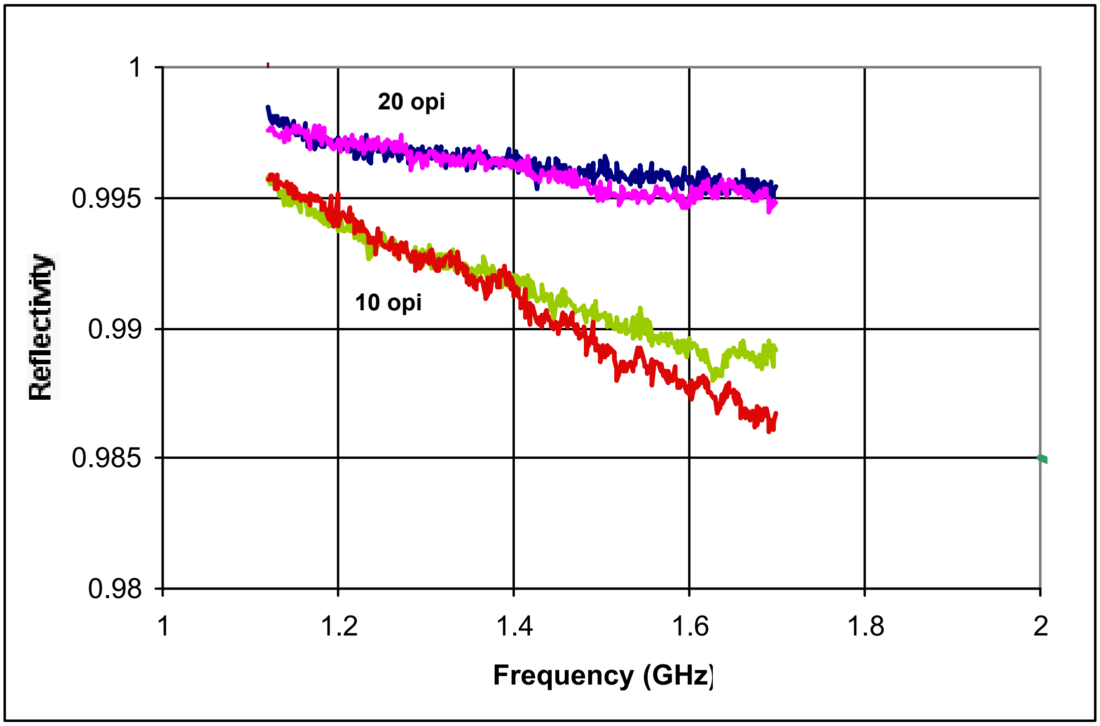
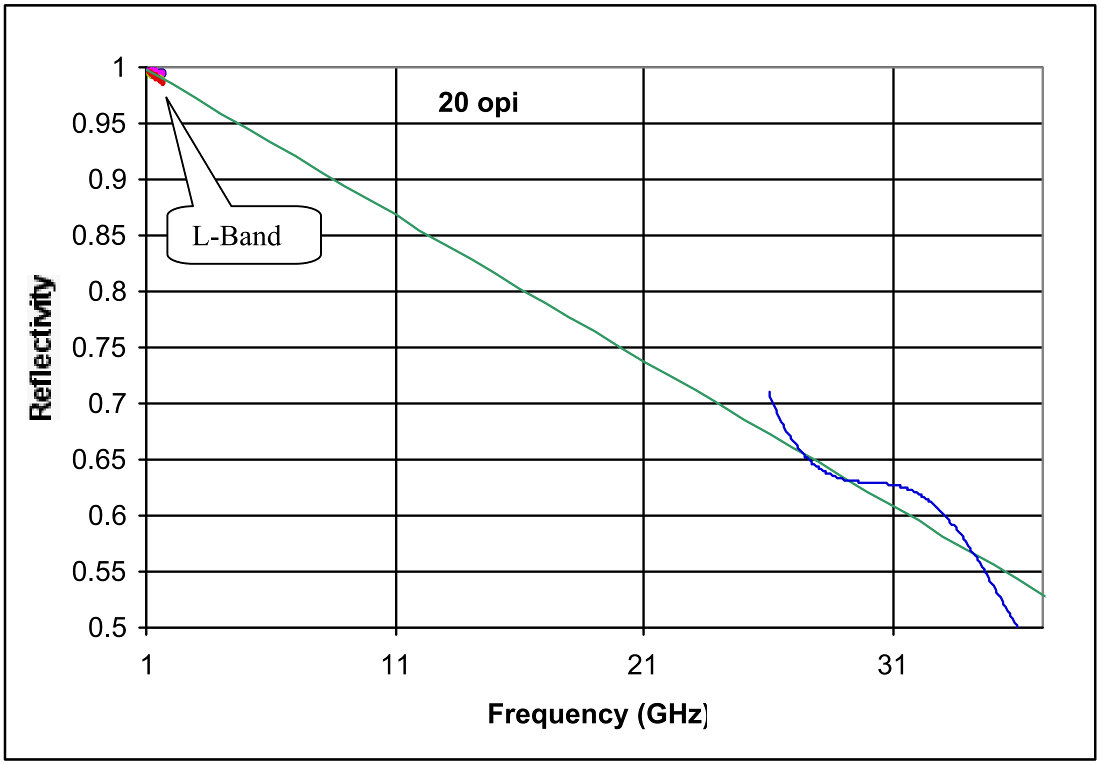


20 opi
10 opi
Reflectivity
Frequency (GHz)
1
0.995
0.99
0.985
0.98
1
1.2
1.4
1.6
1.8
2



20 opi
L-Band
Reflectivity
Frequency (GHz)
1
0.95
0.9
0.85
0.8
0.75
0.7
0.65
0.6
0.55
0.5
1
11
21
31