A Joint Space-Borne Radar Technology Demonstration Mission for NASA and the Air Force

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Abstract—NASA and the Air Force are currently studying joint technology demonstration concepts for large aperture space-borne radar systems. The mission focuses on elements of NASA's Earth Science Enterprise Strategic Plan and Air Force long term needs for Airborne moving target indication. The preliminary design for the system specifies a low center frequency such as L-band, a large physical aperture between 50 and 150 square meters, and on-board processing capability for SAR and MTI applications. The key technologies requiring demonstration are the aperture itself and the onboard processing. It is anticipated that this mission will provide technology validation and short term science return, and will lead to the next generation of Space-based Radar systems. The system incorporates active metrology for measurement of the shape of the aperture, and electronics and processing capability for active compensation of the aperture surface deformation. The goal of the mission is to demonstrate the ability to maintain coherence in a very large aperture in the space environment, to show scalability to larger apertures, and to demonstrate the ability to deliver fault-tolerant real-time products in space. The system will also permit characterization of spaceborne L-band AMTI phenomenology. This paper will describe the trades and technology risks addressed in this study. The work is being conducted jointly by Jet Propulsion Laboratory, California Institute of Technology, and the Air Force Research Laboratory, both under contract with NASA.

TABLE OF CONTENTS

1. INTRODUCTION 1
2. NASA SCIENCE REQUIREMENTS 1
3. AIR FORCE LONG TERM NEEDS 3
4. JOINT MISSION CONCEPT 4
5. SUMMARY AND FUTURE DIRECTIONS ... 6
REFERENCES 7

1. INTRODUCTION

The Air Force and NASA have long term needs for large aperture space-borne radar systems, each with their own unique technical capabilities, but with substantial commonality. The Air Force Research Laboratory (AFRL) and Jet Propulsion Laboratory (JPL) are collaborating in the area of space-based radar (SBR) technology development to promote dual use, light weight, space radar technology to be applied to a joint flight demonstration in this decade.

The Air Force has identified six fundamental technology areas that are independent of but critical to any SBR architecture concept. These are (1) Electronically Scanned Array (ESA) Technology; (2) On-board Processing; (3) Moving Target Indications Exploitation; (4) Radar Signal Processing Algorithms; (5) Information Management; and (6) Spacecraft Technology. NASA has similar needs. However, NASA requires more diverse antenna system architecture and alternate technology developments, and less emphasis on MTI exploitation in favor of general science algorithm technology.

This paper describes the plan for developing a joint flight demonstration, including scientific need, technical approach,

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management plan, cost and schedule, and required technology development. The Joint NASA-Air Force SBR program will address joint technology areas in terms of maturity and suitability of demonstration in a space mission. The current work at AFRL and JPL in the area of SBR can be considered "pre-Phase A" concept development and risk mitigation studies for the mission, and will be shown to fit into the bigger picture proposed here.

Developments in two technology areas are critical to Air Force and NASA flight goals: large aperture design and deployment, and on-board, high rate data processing. From the NASA perspective, the technology roadmap for 2010 and beyond includes constellations in low-earth, medium-earth, and geosynchronous orbits. The aperture sizes grow with the distance from the Earth, and with increased desires for targetability, area coverage, and rapid repeat capability. These large apertures will necessarily require polarization diversity and flexible pointing agility. With prodigious amounts of data, and the desire by NASA scientists to receive real-time science products from the spacecraft, a powerful, flexible, fault-tolerant onboard processing architecture must accompany these radar platforms. The Air Force has the same technology requirements with an emphasis on real time data transmitted from the satellite to the theater. Because of the narrowband datalinks used, a premium will be allowed for significant onboard processing.

Future refinement of the architecture and requirements for the flight demonstration will allow better understanding of those technology areas requiring additional emphasis.

The timeframe for development leads to launch in 2008 with one or two years of operations to characterize the performance of the system. Upon successful completion of this mission, NASA and the Air Force will be positioned to begin the development of their next generation flight systems beyond those scheduled to fly in the 2006-2015 period.

2. NASA Science Requirements

Table 1 summarizes those science/applications areas to which an L-band SAR would contribute in the future. The table shows the mapping from a particular science or applications objectives through the measurements to the specific objective mission. The rightmost column suggests a useful demonstration configuration. Note that with SAR there are many ways to design a mission to meet measurement requirements. It is clear that there is a common thread through many of the NASA science and Air Force applications involving a large aperture, steerable L-band radar with multiple phase centers and beamforming capability.

NASA's vision for Earth science in the coming decades incorporates numerous active microwave missions. For land processes and Solid Earth science, the primary *radar* tool for remote sensing will be synthetic aperture radar (SAR).

The SIR-C/X-SAR and SRTM SAR missions highlighted the unique capabilities and benefits of radar for terrain classification and mensuration. SIR-C/X-SAR (1994) was a three-frequency active-array radar, fully-polarimetric at two of the frequencies. With over 40 international science investigators, SIR-C demonstrated the ability to measure and classify biomass, perform topographic mapping using radar interferometry, and measure deformations of the Earth's surface to millimeter accuracy. SIR-C also showed that lower frequencies such as L-band (24 cm wavelength) are better suited to surface deformation measurements because they are less sensitive to small scale changes in the surface cover over time. SRTM was a milestone in mapping of the world, producing the first all digital, high resolution topographic map of land between –60 and +60 degrees of latitude. SRTM also demonstrated a clear cost benefit for topographic mapping relative to more conventional topographic mapping approaches.

The next generation of SAR missions for NASA will build on the successes of SIR-C and SRTM. The science community is calling for interferometric SAR measurements "everywhere, all the time" to properly measure surface deformations due to physical processes such as earthquakes, volcanoes and ice sheet movement (Solid Earth Science Working Group report to NASA). While existing international SAR sensors are capable of making some of these measurements some of the time, the science community is looking to NASA to provide a dedicated science tool for discovery in the short term, and a comprehensive plan for Earth system science in the long term. Long term needs require rapid repeat coverage of large areas with a targeting capability to track natural hazards as they evolve (e.g. erupting volcano or post-seismic deformation).

Other important science observations require low-frequency (L-band or lower) radar or quasi-scatterometric measurements. Daily synoptic measurements of the freeze-thaw transition in the spring and thaw-freeze transition in the fall are important control parameters of carbon sequestration in climate models. Soil moisture measurements with similar coverage and frequency also drive climate models, and require polarimetric low-frequency observations.

All these science observations eventually require very large apertures and efficient processing scenarios. With the abundance of planned sensors generating prodigious amounts of data, it may not be possible in the future to downlink all data for ground processing, pointing toward on-board processing. In the worst case, NASA might constrict its mission scenarios based on bandwidth availability rather than science need. Even if sufficient downlink bandwidth is made available, robust high-rate on-board processing can

Table 1. Requirements Flow for Joint NASA–Air Force Technology Mission

Science/ Applications Needs	Measurement Characteristics	Anticipated Mission Requirements	Demonstration Mission Requirements
Wide Area Crustal Deformation	• 100 m resolution @ 10 looks • -30 dB noise-equivalent sigma0 • Interferometric coherence over long time periods • Rapid repeat observations • Global coverage	• 1-day repeat period • 50-100 m aperture • 500-1000 km swath • L-band • LEO / MEO constellation • Electronic steering (desired)	• 600 km orbit / 3-day repeat period • 0.72 m x 50 m aperture • 500 km swath • L-band • Electronic steering (desired)
Targeted Hazard Assessment and Monitoring	• 25 m at 10 looks • -30 dB Nesigma0 • Interferometric coherence over short time periods • Very rapid repeat • Global access	• < 1-day repeat • 10-50 m aperture • 1000 kmtargetable swath • L-band • LEO / MEO / GEO constellation • Electronic steering	Same as above
Global Soil Moisture	• Rapid Repeat observations • 1000m resolution @ 100 looks	• 1-day repeat • 0.72 m x 100 m aperture or short apertureScanSAR • 1000 km swath • L-band • On-board processing	• 600 km orbit / 3-day repeat • 0.72 m x 50 m aperture or short apertureScanSAR • 500 km swath • L-band • On-board processing
Boreal Freeze-Thaw	• Rapid Repeat observations • 1000m res. @ 100 looks	Same as above	Same as above
Ocean Currents	Vector ATI capability 500 m resolution at 10 looks	C- to L-band 50-m separated sub-aperture illumination ScanSAR operations On-board processing	C- to L-band 50-m separated sub-aperture illumination ScanSAR operations On-board processing
Air Moving Target Indicator	Detection and Track fighter targets to Mach 2 Low altitude target detection of slow movers	Wide Area Surveillance (500 km x 500 km) Target track to airfield Bistatic space-air ops for difficult targets	3 m x 50 m aperture UHF- or L-band Digital Beam Form Bistaticoperatons On-board processing
SAR Imaging	Fine Resolution on demand	Detect slow moving targets under CC&D	Along Track IFSAR
DTED	Terrain height under trees	Targeted DTED-3	

have significant advantages. It can allow scientists to think beyond individual measurements or data reductions and think of synergistic science platform fusions on orbit. Furthermore, a degree of autonomy may be introduced if there is on-board processing.

3. AIR FORCE NEEDS

SBR is a Reconnaissance, Surveillance, and Target Acquisition (RSTA) system capable of supporting a wide variety of joint missions and tasks simultaneously, including battle management/command and control (BM/C2), target detection and tracking, wide area surveillance and attack operations. SBR also supports traditional Intelligence, Surveillance and Reconnaissance (ISR) missions such as indications and warning (I&W), intelligence and assessment. These mission areas cover the strategic, operational, and tactical levels of operations and interest.

A baseline SBR system will encompass real time radar modes of Ground Moving Target Indication (GMTI), stripmap Synthetic Aperture Radar (SAR) and spotlight SAR, along with the ability to produce Digital Terrain Elevation Data (DTED). Projected SBR system architectures are at X-Band frequency, due to the requirements on tracking accuracy and minimum detectable velocity of ground targets. It is not expected that this design

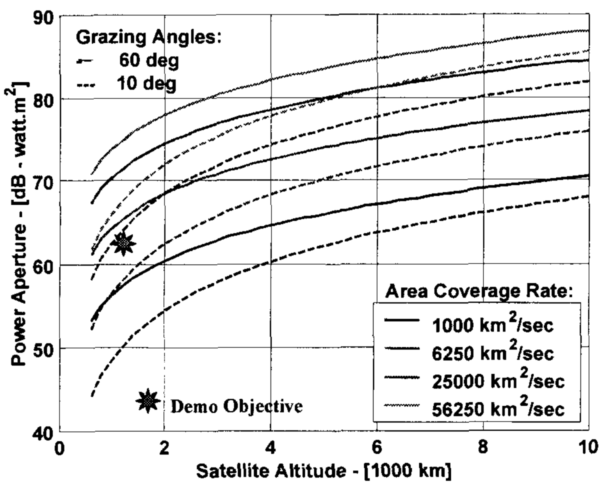
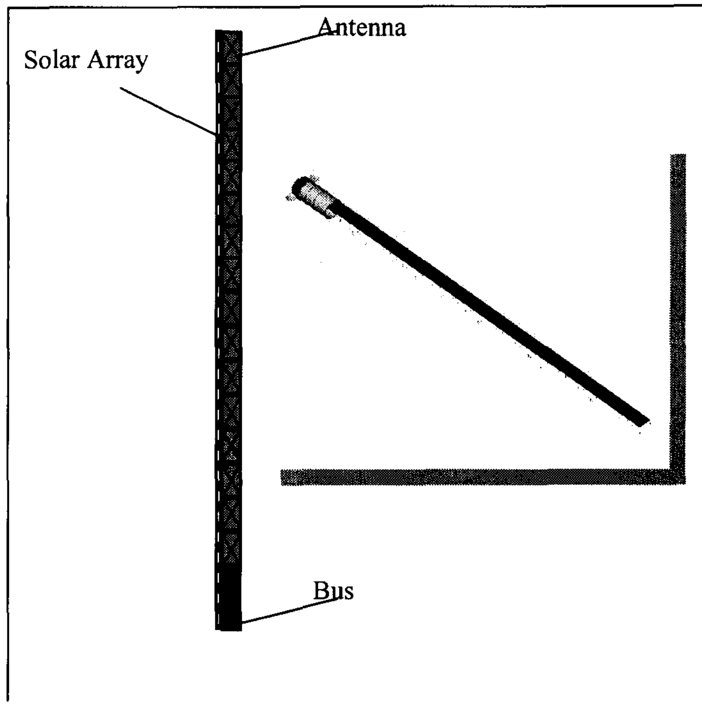


Figure 1. Power Aperture Design Requirements of GMTI systems at several area coverage rates and grazing angle limits.



will address the GMTI capabilities of an operational AF system.

Longer-term Air Force plans indicate a desire to operate at lower frequencies than X-band: at a frequency between UHF-Band and S-Band, primarily to support Air Moving Target Indication (AMTI) capabilities. L-Band operation is attractive due to common missions with NASA in Solid Earth Science, and reduced ionospheric dispersion over UHF. The primary mission of the experimental system will be to demonstrate SAR and AMTI modes. The challenge at lower frequencies will be to obtain adequate angular accuracy for tracking and low sidelobes to reduce range and Doppler foldover interference.

The Defense Department's long-term technical plan is to investigate the ability for operation at Mid Earth Orbit (MEO), to provide long dwell operation and reduce the total number of satellites. However the size of the system grows significantly as a function of area coverage rate (ACR) as shown in Figure 1. This first order analysis demonstrates several issues in SBR design:

- Area Coverage Rate directly determines the Radar power aperture
- High grazing angle operation demands more ACR due to the smaller footprint of the radar on the Earth
- MEO operation requires significantly larger power aperture than LEO

The ability to design and deploy a large antenna system on orbit will greatly reduce the risk of future missions. The preliminary power aperture and altitude objective of the Joint experiment is shown in the figure, at the mid point of potential DoD mission requirements. Note that the ACR of a system is independent of frequency. However, the target and clutter characteristics are not independent of frequency. For airborne targets, a reasonable objective for the experiment operating frequency is L-Band, providing experimental evidence for determining the technical risks and techniques needed for operating in the ionosphere and at higher altitudes.

4. Joint Mission Concept

It is important to demonstrate a capability that stretches beyond what has been previously flown, and that will provide insight into the potential technology paths for future scientific/operational missions. A full mission demonstration is needed to test the technology as a system, including understanding the dynamics of a large system through metrology.

Spacecraft Bus

The anticipated bus design will be conventional (not distributed with the structure) and most likely will be a catalog bus structurally modified to support the aperture and structure.

Affordable Phased Array Antennas

Large power aperture designs as depicted in Figure 2 must be developed for instantaneous field of view to meet expected operational needs for detection, identification and tracking within a single satellite pass, or to enhance the capability of airborne radar systems.

On-Board Processing

The benefits of on-board processing include rapid and efficient processing for time-critical operations and reducing the requirements for communications bandwidth. Areas of focus include developing processing algorithms and implementation in massively parallel architectures.

Applications of on-board processing include space-time adaptive processing (STAP), improved electronic protection, clutter cancellation, and MTI track formation.

Spacecraft Payload Design

The need for very large Space antenna structures is changing the way aerospace engineers must specify, design, develop and deploy these future systems. Space payloads have evolved from the heritage of electronics and antennas primarily located in a centralized box with a reasonably controlled environment (Temperature and Radiation shielding). This centralized payload logically leads to a centralized bus with solar collection of power to a centralized point source.

Very large antenna structures have opened the trade space. The antennas will now have significantly larger area than the solar collection area. The electronics will be distributed over large areas and not located in a small environmentally controlled volume. Designers must determine which departures from the conventional thinking make sense.

The goal of this mission is to collect experimental data on key methodology changes that should be incorporated into the design of spacecraft using very large antennas. Key objectives are to:

- Demonstrate the ability to deploy large antenna structures in space
- Demonstrate the ability to maintain antenna calibration of large antenna structures with the additional constraints of: less rigid structures, more extreme temperature variations on structure and electronics, and significantly tighter mechanical tolerances due to antenna size.
- Demonstrate the ability to perform accurate / stable roll of very large antenna structures.
- Demonstrate the ability of distributed electronics/panels to meet performance requirements in the extreme temperature swings to be encountered in very large apertures. This includes gathering data on the materials and processes used to fabricate panels for large antennas (panel processes must be different than past approaches due to significantly more stringent cost, mass, and volume constraints required by large antennas)
- Gather data to aid in the decision for centralized vs distributed bus.
- Gather data to aid in the decision for centralized vs distributed processing and demonstrate fault-tolerant on-board processing.
- Demonstrate critical pieces of advanced algorithms under development that will utilize the large antennas with their enhanced number of phase centers. Ground based modeling is not accurate enough to model all the variables.
- Gather data to aid in the decision for centralized station keeping vs. distributed control of large structures.
- Design a series of experiments that will provide real data that can be extrapolated to larger structures with a fair level of confidence.
- Gather data to aid in the design of beamforming architectures for large antennas. Key decisions are required in the approaches. Analog vs digital, digital vs photonics. Approach for routing of large volumes of data over large aperture distances. This approach must be integrated with the metrology/calibration system.

Design Parameters for an Air Force and NASA demonstration system

A first order sizing of a suitable radar system has been carried out. to meet the area coverage rate in MTI and the image quality parameters for DoD-relevant SAR. A similar sizing of a suitable NASA radar system has been carried out. Note that the success criteria of a demonstration system are more flexible that for operational systems, so area coverage rate and other design goals can be traded against mission cost and complexity. One of the goals of the present research is to find the right balance between objectives, design and cost.

Table 3 summarizes the critical parameters needed to meet the area coverage rate in low and high resolution SAR modes and MTI modes.

The L-stripmap low res mode uses strip mapping with the 50m x 2m antenna and has a 528 kmm swath width. The antenna T/Rs are beam spoiled in range to broaden the beam. The number of powered T/Rs in range x azimuth are 12 x 384. The 12 T/Rs in range allows steering +/- 20 deg. The mode has 5 looks in range for 25m resolution; over the range of look angles of 15-55 deg for this mode, the data rate is 610 Mbits/sec. The mode can be operated as a single polarization to achieve the full swath, or in dual-pol (HH,HV or VV, VH) mode at half swath, or in quad pol (HH, HV, VV, VH) at quarter swath. The polarization diversity is achieved with a single receive network to reduce instrument data path complexity, and mass and power requirements, albeit with higher PRFs. In single pol mode, the system is operated at a 350 Hz PRF. In dual-pol mode, the PRF is doubled, and alternate pulses first transmit H and receive H polarization then transmit H and receive V polarization. By doubling the PRF, the swath must be reduced (and beam reshaped) to minimize range ambiguities. For quad-pol mode, the PRF is increased by 2 again, and the four possible combinations of H and V transmit/receive polarizations are cycled.

Table 3. L-band Performance for SAR modes

Mode of Operation	L-stripmap low res	L-stripmap high res
Range Resolution- single look (m)	5	5 – 2.5
Azimuth Resolution- single look (m)	25	5
Resolution- multilook (m)	25	5
Ground Swath (km)	528	20
Number of Looks	5	1-2
Field of View from Nadir (Inc. Angle)	15-55°	25-55°
Number of Beams for Global Coverage	1	15
Polarizations (dual and quad pol have narrower swath	HH, HH,HV or VV,VH or Quad	HH, HH,HV or VV,VH or Quad
Noise Equivalent σ_0 (dB)	-25	-30
Frequency Range (MHz)	1252.5-1297.5	1232.5-1297.5
Bandwidth (MHz)	45	65
Pulse Repetition Frequency (Hz)	350	1780-1765
Pulsewidth (microsec)	100	10-50
Range/Azimuth Ambiguities (dB)	-20/-20	-20/-20
DC Power Draw (W)	6275	1230-2330
Data rate (Mbps)	610	150-340

*Note: assumes 25kW peak power for full L-band array 3 m x 50m

Table 2: Joint Mission Characteristics

Modes	SAR and MTI, exclusively operated
Aperture size	2 m x 50 m
Aperture Type	Phased-array
Aperture form	Z-fold rectangular
Structure Type	Triagonal Truss
Structure Composition	inflatable-rigidizable if ready
Frequency	L-band
Polarization	Single, Dual, Quad with PRF cycling
Electronic steering	+/- 20 deg el. by +/- 45 deg az.
Bandwidth	80 MHz, 1220 – 1300 MHz
On-board Processor Architecture	FPGA/ General Purpose Processor
On-board Processing Algorithms	SAR, MTI
Metrology	Array shape measurement and phase compensation
Orbit	500 km Polar Sun-Synchronous
Power	4 KW orbit average
Mass	4000 kg

Note that to retrieve the full 528 km swath coverage in multi-pol mode, a scansar system similar to that employed in the Shuttle Radar Topography Mission could be employed, giving very wide swath scansar polarimetry.

The L-stripmap high res dual pol (HH,HV or VV,VH) uses strip mapping with the 50m x 2m antenna and has a 20 km swath width. All antenna T/Rs are turned on in range with an effective width of 2 m. The antenna T/Rs in azimuth are turned off to broaden the beam with an effective length of 10m. The 18 T/Rs in range allows steering +/- 20.

Note that the high-resolution mode potentially can be configured for along-track interferometry observations by splitting the 50 m aperture into two separated 10 m apertures.

5. SUMMARY AND FUTURE DIRECTIONS

The joint mission concept presented here is designed to satisfy a number of important multi-agency objectives in spaceborne radar observations. In particular the mission is scoped to address issues in two critical areas of future missions: large power apertures in space, and on board processing.

AFRL and JPL will produce a report describing the implementation, risks, schedule, and costs of such a mission, delivered to NASA and the Air Force in the April 2003 time period. It is our intent for this report will form the basis of a joint development path for the rest of this decade.

The near-term objectives of the Air Force for SBR are not focused on this specific mission, however many of the issues posed here – large power apertures, metrology, distributed power systems, on-board processing – have considerable overlap with other SBR programs. It is hoped that the work reported here will be of use to these programs as well.

REFERENCES

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Dr. Paul Rosen is a principal engineer in the Radar Science and Engineering Section at Jet Propulsion Laboratory, where he focuses on interferometric radar system design, algorithm development and applications science. He is a NASA investigator in the area of Solid Earth and Natural Hazards, and led the Algorithm Development and Calibration Team for the Shuttle Radar Topography Mission. He presently holds an interest in developing dual use capabilities in radar for NASA and the DoD. Dr. Rosen is a visiting faculty member at Caltech. He has a BSEE and MSEE from University of Pennsylvania and a PhD in EE from Stanford University.

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