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Concepts and Technologies for Synthetic Aperture Radar from MEO and Geosynchronous orbits

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ABSTRACT

The area accessible from a spaceborne imaging radar, e.g. a synthetic aperture radar (SAR), generally increases with the elevation of the satellite while the map coverage rate is a more complicated function of platform velocity and beam agility. The coverage of a low Earth orbit (LEO) satellite is basically given by the fast ground velocity times the relatively narrow swath width. The instantaneously accessible area will be limited to some hundreds of kilometers away from the sub-satellite point. In the other extreme, the sub-satellite point of a SAR in geosynchronous orbit will move relatively slowly, while the area which can be accessed at any given time is very large, reaching thousands of kilometers from the sub-satellite point. To effectively use the accessibility provided by a high vantage point, very large antennas with electronically steered beams are required. Interestingly, medium Earth orbits (MEO) will enable powerful observational systems which provide large instantaneous reach and high mapping rates, while pushing technology less than alternative systems at higher altitudes. Using interferometric SAR techniques which can reveal centimeter-level (potentially sub-centimeter) surface displacements, frequent and targeted observations might be key to developing such elusive applications as earthquake forecasting. This paper discusses the basic characteristics of a SAR observational system as a function of the platform altitude and the technologies being developed to make such systems feasible.

Keywords: SAR, InSAR, geosynchronous, MEO, SAR constellation

1. INTRODUCTION

For decades an earthquake forecasting capability has been a long sought-after goal, as the potential for overwhelming human and economic losses has grown with the populations in seismically active areas. Fortunately, recent measurements of solid-Earth surface deformation have enabled major advances in the current scientific understanding of crustal deformation associated with seismicity. Many of the recent insights in this field have been made possible by the advent of spaceborne interferomtric SAR (InSAR), a technique capable of providing centimeter-level surface displacement measurements at fine resolutions (tens of meters) over wide areas (hundreds of kilometers). As the value of the repeat-pass InSAR technique has been demonstrated by current instruments (SIR-C, ERS-1/2), next-generation InSAR systems hold the promise of providing data that could better the scientific understanding of global earthquake physics to the extent that they might ultimately lead to an earthquake forecasting capability. In order to do so, next-generation InSAR systems must provide fine temporal sampling (on the order of days) in order to capture the subtle effects associated with fault interactions and strain accumulation between earthquakes. Moreover, revisit times on the order of minutes can be used for disaster response scenarios. The optimal frequency of operation for these observational systems is L-band because the wavelength favors long-term temporal correlation since it is less sensitive to weather and vegetation.

In this paper we will summarize the results of an optimization study to evaluate L-band InSAR performance as a function of orbit altitude and will show that a medium Earth orbit (MEO) for InSAR systems may prove to be a good compromise between global accessibility and technology challenges. The technology challenges associated with advanced, higher-orbit InSAR systems are perhaps most demanding for the SAR antenna, which is the dominant component of the radar system. With the increasing demands for frequent temporal sampling, high sensitivity, flexible targetability, and extensive coverage, the antenna aperture necessarily becomes very large and complex. Therefore, we also provide a technology assessment and technology roadmap that could enable these future SAR missions at distant orbits.

2. ORBIT SELECTION TRADES

The scientific requirements for studying earthquakes drive two main components of the InSAR system design. Accurate, high-resolution surface deformation measurements must be resolved to an accuracy of 1mm/year over a decade. L-band repeat-pass InSAR techniques can provide these required high-resolution displacement maps. The second driving requirement is timely access and global coverage for earthquake research, disaster management and hazard monitoring, where the orbit selection is the primary factor in determining the overall accessibility of these InSAR systems. Greater coverage implies shorter revisit times and thus higher temporal resolution. Generally, increasing the satellite elevation enhances the instantaneous accessibility of the SAR sensor, since the area the satellite can view at any given time increases with orbit altitude. By increasing the satellite altitude, an enormous instantaneous field of regard can be achieved, reaching thousands of kilometers from the sub-satellite point (Fig. 1).

Interestingly, however, orbit optimization studies suggest that operation somewhere between the two extremes of low Earth orbit (LEO) and geosynchronous orbit (GEO) altitudes might be optimal for the goal of minimizing InSAR repeat periods, which does not necessarily coincide with minimizing the revisit time for a given ground location [1, 2]. This is because SAR interferograms may only be formed from identical viewing geometries, so the temporal sampling of an InSAR system is determined by the time required for the spacecraft to repeat its flight track. Wide *instantaneous* accessibility does not necessarily minimize the repeat time; rather, extensive *cumulative* (orbit-averaged) accessibility is desired to reduce the orbit repeat period required for global coverage.

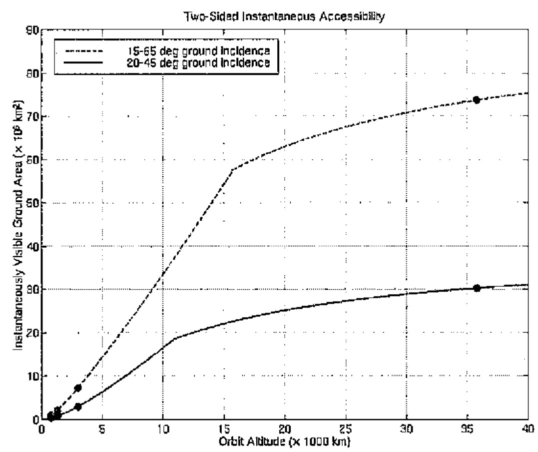

Figure 1. Two-side sensor visible footprint. Markers for LEO (800 km), LEO+ (1300 km), low MEO (3000 km), and GEO (35,800 km)

A first-order estimate of a SAR sensor's cumulative accessibility is given by its coverage rate, which can be modeled as the product of the platform velocity and the width of the SAR accessible swath. The coverage rate is shown as a function of platform altitude in Figure 2. Because the nadir velocity decreases with altitude while the swath width increases, these curves peak at the MEO altitudes. For any altitude, a constellation of nearly identical spacecraft could reduce the effective interferometric repeat period inversely with the number of satellites in the constellation.

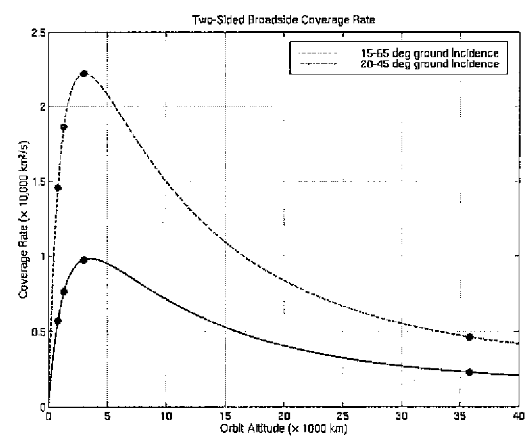

Figure 2. Coverage rates as a function of orbit altitude for swaths limited by ground incidence angle. Solid dots on these curves correspond to LEO, LEO+, low MEO, and geosynchronous orbit.

If continuous (non-interferometric) coverage is desired, higher orbits (10,000 to 40,000 km) would be more effective for providing instantaneous global accessibility because of their very large footprints (see Fig. 1). Since current requirements for solid-Earth science call mainly for short interferometric repeat periods rather than around-the-clock non-interferometric coverage, these requirements might be achieved most efficiently from orbits around 3000 km as indicated by the locations of the peaks in Fig. 2.

The decision to operate satellites in higher orbits does incur a penalty in increased instrument complexity. Higher altitude orbits place more demanding requirements on the radar instrument: a significantly larger antenna and more power is required in order to maintain acceptable performance. To effectively use the accessibility provided by a high vantage point, very large antennas with electronically steered beams are required. Generally, the relationship between the orbit and the antenna size can be described as

$$A \geq k \frac{4v\lambda R}{c \tan\theta}$$

where v is the velocity of the satellite relative to the Earth, λ is the wavelength, R is the range to the target, c is the speed of light, θ is the incidence angle and k is a weighting factor that depends on the specific sidelobe requirements and is generally on the order of 1.4 to 2.0. As the range R increases with platform altitude more quickly than the velocity v decreases, the antenna size must increase as the orbit gets higher. Figure 3 illustrates the ideal minimum antenna area as a function of platform altitude for various maximum ground incidence angles. The antenna size for a geosynchronous SAR is on the order of 700 m^2 for the lower incidence angles as compared to antenna areas of roughly 50 m^2 required for LEO systems. MEO SAR altitudes require antenna areas of roughly 400 m^2. Higher altitudes also require greater transmit power, while lower altitudes have more demanding antenna steering requirements.

Another important consideration in selecting the orbit is the radiation environment. The radiation environment is particularly of concern when using lightweight active antenna technologies since heavy shielding is impractical, and therefore rad-hard electronics are needed. The multiple radiation effects include total ionizing dose (TID), displacement damage, charging/electrostatic discharge (ESD) and single event upset (SEU). The radiation environment varies significantly for different orbit altitudes and inclinations and the radiation environment is known to be particularly severe at high MEO altitudes. Undoubtedly, the radiation effects will drive the design and technology selection.

Table 1 summarizes the characteristics of the InSAR system as a function of orbit altitude, illustrating that perhaps a MEO orbit is the best overall compromise between performance and instrument complexity.

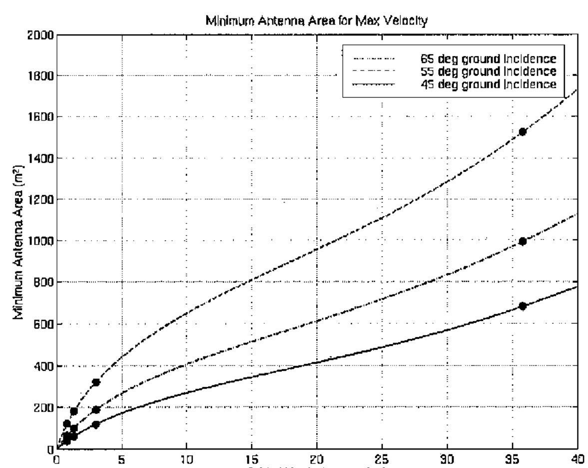

Figure 3. Required L-band antenna area vs. orbit altitude for assumed far-range ground incidence angles (markers for LEO, MEO and GEO orbits).

Table 1. Summary of InSAR characteristics for LEO, MEO and Geosynchronous orbit vantage points.

	LEO	Low MEO	High MEO	GEO
Altitude	800 km	3000 km	14,000 km	35,800 km
Capability Enabled	• Improved modeling of fault dynamics	• Local earthquake forecasting • Limited disaster response	• Earthquake forecasting • Disaster response	• Earthquake forecasting • Disaster response
Usable swath	350 km	3900 km	6200 km	7000 km
Repeat time	8 day	2 day	1 day	1 day
Spatial resolution	30 m	30 m	30 m	30 m
3-D displacement acc	Good	Very good	Excellent	Excellent
Radiation environment	moderate	high	severe	high to severe
Antenna area	50 m^2	400 m^2	500 m^2	700 m^2
Transmit power	5 KW	30 KW	45 KW	60 KW
Beam scan	+/- 30-deg (elev)	+/- 15-deg (az/elev)	+/- 8-deg (az/elev)	+/-- 6-deg (az/elev)
# T/R modules	400	14,000	17,000	24,000
T/R module efficiency	30%	40%	50%	60%
DC power	1667 W	7500 W	9000 W	10,000 W

3. LEO SAR ARCHITECTURE

There have been many past SAR system studies focusing on the Low Earth Orbits (LEO) elevations in the range of 560-1330 km, and the performance of such systems is fairly well understood [1, 3]. These systems are typically launched into a nearly circular, sun-synchronous terminator orbit. These systems require antenna apertures on the order of 30 to 50 square meters (i.e., 3m x 15m) for L band and must transmit 5-10 KW of peak RF power and typically have swath widths of around 100 km. With the use of ScanSAR techniques [4], the swath can be extended up to several hundred kilometers at the expense of image resolution. These systems require active phased array antennas to electronically steer multiple beams. One-dimensional electronic beam steering is needed in elevation for both ScanSAR operation or for targeting the subswath within the accessible field of view to provide greater beam agility.

Technology requirements for LEO SAR antennas need to be lightweight to make these missions affordable. Current antenna technologies consisting of lightweight rigid panel architectures deployed with a precision deployment structure to achieve the required aperture flatness of roughly 1 cm are available for these systems. The implementation of repeat-pass interferometry using a ScanSAR system, where the bursts would have to be precisely aligned between orbits, while it appears feasible, has not been done before.

4. SYSTEM ARCHITECTURES AT HIGHER ORBITS

Future advanced SAR concepts conceived for higher orbits, such as those being studied for a MEO SAR or Geosynchronous SAR mission, require very large antenna apertures with full two-dimensional beam steering capability. This class of antennas requires apertures on the order of several hundreds of square meters transmitting up to sixty kilowatts of RF power. For this class of mission to be feasible and affordable, mass and launch volume must be low enough to fit into existing launch vehicles.

A notional concept for a geosynchronous SAR mission consisting of a large deployable hexagonal antenna is illustrated in Figure 4 [1, 5]. The 30m by 30m antenna aperture is deployed with horizontal booms and then tensioned to maintain flatness with two symmetric axially deployed telescoping booms and tensioning cables. The antenna aperture is constructed from flexible membrane material which is integrated with the active electronics for proper beam formation and transmit/receive signal amplification. The integrated solar arrays provide power to the antenna and spacecraft. These thin-film solar arrays are an integral part of the system and share the same structural elements. One solar array is an annular-ring formed around the perimeter of the antenna aperture. The second solar array is cone-shaped and is formed above the antenna surface supported by the tensioning cables. A half-cone solar array is implemented to give a cold-sky view to the antenna backside, allowing better thermal management, and also to mitigate the problems associated with high solar pressure. The solar arrays provide a large surface area for solar power collection from any sun orientation. There will also be sufficient batteries to operate for short periods in eclipse. On the tips of each mast are propulsion modules for orbit maintenance. Other spacecraft bus elements are centrally located near the center of the radar aperture.

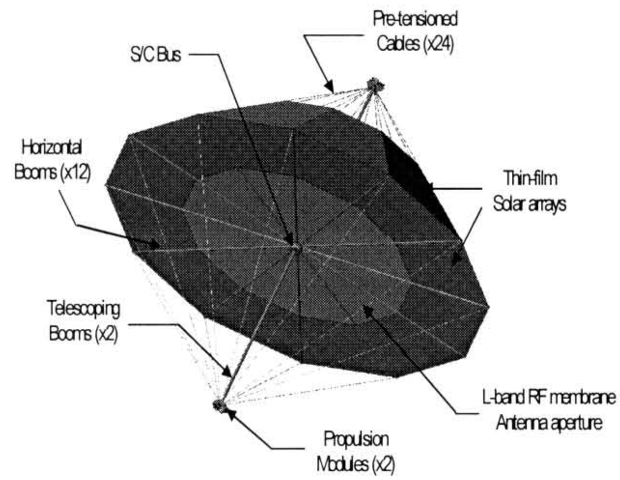

Figure 4. Geosynchronous SAR large antenna concept

The large array antenna must be stowable with high packaging-efficiency in order to fit the physical constraints of launch vehicle. Since low-mass and low stow-volume are critical requirements for these deployable antennas, a flexible membrane antenna architecture is a promising technology. Inflatable or deployable booms deploy the multi-layer thin membranes with printed microstrip patch radiating elements and power dividing transmission lines. Rigid honeycomb panels, such as those used in current LEO systems, will not meet the mass goals needed for a practical geosynchronous SAR system.

A key component in phased-array antenna architectures is the transmit/receive (T/R) module. While the architecture of the T/R module is conventional in the sense that it contains a power amplifier, low noise amplifier, a phase shifter and programmable attenuator, its packaging is not. In order to successfully mount T/R modules on a thin membrane and maintain the ability to fold and roll it, the modules must have a low mass and a small footprint. This requires highly integrated mixed-signal electronics. At the higher orbits (particularly high MEO), the radiation environment is quite severe. This requires the use of highly radiation tolerant semiconductor technologies requiring little or no shielding.

The MEO SAR system architecture requires a smaller antenna and lower power compared to the geosynchronous SAR system concept. For the MEO SAR system, the antenna area must be roughly 400 m^2, and could be implemented as either 10m x 40m or possibly a longer and narrow shape such as 5m x 80m. There is some flexibility in the antenna geometry due to the relatively straight platform flight tracks with respect to the rotating Earth, compared to the flight track of a geosynchronous SAR, which is highly curved in the horizontal direction. There are a number of emerging technologies (i.e., inflatable trusses) that can more easily package long, narrow antennas as opposed to the roughly circular antennas required for geosynchronous orbits. Regardless of the exact architecture implemented for the MEO SAR system, similar ultra-lightweight antenna technologies are essential. The specific technology requirements and the roadmap to enable InSAR measurements from both MEO or GEO vantage points are described in the next section.

5. EMERGING TECHNOLOGIES AND ROADMAP

The basic InSAR instrument design and measurement techniques have already been validated in space (i.e., SIR-C, ERS-1/2). For the near-term missions (in LEO orbits), there is little technology development required. Evolutionary advances in technology to reduce instrument mass and power will lead to incremental improvements in performance. Incorporating advanced technologies to reduce mass, power and complexity will help make the LEO mission more affordable. However, to enable the most ambitious mission concepts, such as a constellation of SAR systems in either MEO or geosynchronous orbits, revolutionary new technologies are essential. If current state-of-the art technology is used to implement either the MEO or GEO systems, the mass of the antenna alone would be prohibitively large to fit into existing launch vehicles. Studies suggest that antenna mass densities must be reduced by an order of magnitude (from 10-20 kg/m^2 to less than 2 kg/m^2) to make this class of systems practical and affordable. Table 2 illustrates this by comparing the antenna mass of the geosychronous SAR point design [1] using current state-of-the-art technology and lightweight membrane antenna technology. The three largest contributors to the overall antenna mass are the antenna aperture (rigid honeycomb vs. membrane), T/R modules (where over 15,000 modules are required) and the deployment structure (mechanical deployment structures vs. inflatable/rigidizable structures). These three areas are thus high-priority areas to develop innovative new technologies for order-of-magnitude reduction in system mass.

Table 2. Antenna mass comparison of implementing the geosynchronous SAR system using current technology and membrane array technology.

		Using 2004 Technology		Using 2020 Technology	
System/Subsystem	**# of units**	**Unit Mass (kg)**	**Total Mass (kg)**	**Unit Mass (kg)**	**Total Mass (kg)**
Antenna Structure			**3814 kg**		**388 kg**
Antenna Aperture	36	80	2880	4	144
Mast (zenith and nadir)	1	170	170	74	74
Horizontal booms	12	57	684	10	120
Cannister	2	40	80	25	50
Antenna Electronics			**1421 kg**		**278 kg**
T/R modules	15616	0.06	937	0.006	94
Interconnects	15616	0.005	78	0.001	16
Signal distribution	1	120	120	30	30
Power distribution	1	180	180	90	90
Array processor	1	50	50	25	25
Digital receivers	61	0.5	31	.05	3
Power converters	244	0.1	25	0.08	20
Instrument Mass Total			**5235 kg**		**666 kg**
Total with 30% margin			**6806 kg**		**866 kg**

While the implementation of a large-aperture, high-power SAR antenna using ultra-lightweight phased array antenna technology (i.e., flexible membrane) presents many challenges, none of the obstacles appear insurmountable. To achieve the antenna scan requirements, thousands of distributed T/R modules are required (one per element). Therefore, efforts to increase integration and thus reduce mass, power and cost of these modules will be very beneficial. Because of the high average transmit power of the antenna array, it is essential that the power amplifiers be as efficient as possible. Class-E/F amplifiers with over 70% efficiency at L-band (1.2 GHz) have been demonstrated [7-9] and show promise for use in the T/R module in future large aperture radar antennas. Continued research into other membrane-compatible electronics is also required. The ultimate goal is a low-cost, high reliability process for producing highly integrated, radiation-hardened, mixed signal circuits and attaching them reliably to a membrane substrate. Another area for continued research is interconnect technologies where lightweight, low-loss, membrane-compatible interconnects for RF, data and power distribution must be developed. Furthermore, these interconnects must be highly reliable and manufacturable. The antenna structures can be implemented using either mature mechanically deployable structures or the emerging technology of inflatable/rigidizable structures. The primary structural challenge is the development of lightweight precision structures to maintain acceptable antenna flatness while maintaining a high packing ratio. Adaptive metrology and calibration methods to compensate for deformation in the array flatness are needed, particularly since these lightweight antennas will likely not have the stiffness that conventional rigid antennas have.

Table 3 summarizes some of the key technologies that need to be further developed to enable the types of advanced SAR missions described in this paper. The LEO InSAR mission can be implemented without any technology development required. However, a number of technological breakthroughs are needed to make the larger antenna systems viable.

Table 3. SAR technology assessment for LEO, MEO, GEO systems.
CR (cost reducing technology), E (enabling technology), NR (not required for mission)

Component	Technology	LEO	MEO	GEO
Large lightweight structures	High-stiffness deployment systems with high packing efficiency; inflatable and mechanically deployable structures; membrane tensioning.	CR	E	E
Large membrane antennas	Durable, low-loss, thin-film membrane antenna materials; array feed techniques compatible with the membrane electronics and array architecture.	CR	E	E
Integrated, rad-hard, low power electronics	Single-chip MMIC T/R module; low-power signal generator; true-time-delay devices; L-band digital receivers.	CR	E	E
High power, high-efficiency transmitters	High-efficiency Class-E/F L-band T/R modules; Si, SiC, SiGe, GaAs, GaN power amplifiers.	CR	E	E
Advanced materials	New technologies for devices, structures, thermal, shielding.	CR	CR	CR
Advanced packaging	Eliminate conventional T/R module packaging; technologies for reliable, direct attachment of die onto membrane; die thinning for increased flexibility and radiation hardness.	CR	E	E
Signal distribution and interconnects	Technologies to simplify the electrical interconnections of thousands of elements on the array; reliable, lightweight, low-loss, membrane-compatible interconnects for RF, data and power distribution.	CR	E	E
Shielding for radiation tolerance	Radiation protection of the devices through other methods of lightweight shielding or coatings.	CR	E	E
Passive and active thermal management	Radar-transparent thermal control coatings; variable emissivity materials; micro heat pipes.	CR	E	E
Power generation	Thin-film solar cells; power tiles for integrated and distributed power generation and storage on the membrane.	NR	E	CR
Thin-Film Transistors (TFTs)	TFTs fabricated directly on the membrane aperture for health monitoring, calibration and potentially for RF circuits.	NR	CR	CR
Large-scale manufacturing	Low-cost methods of attaching thousands of components on the membrane antenna which is reliable, manufacturable and testable.	CR	CR	CR
System	Digital beamforming and digital TTD steering; calibration, metrology and phase-correction.	CR	E	E

Figure 5 shows a possible roadmap for the technology development required for a future membrane-based SAR antenna. Inflatable membrane phased-array antennas have been an area of research for the past several years with several engineering prototypes developed to demonstrate that inflatable structures can be used to deploy and stretch flat membrane antenna apertures with good RF performance [10-12]. Work is currently ongoing to demonstrate that membrane antennas can indeed be populated with electronic components to achieve high transmit powers with electronic beam steering capability [13]. Since membrane antenna technology is revolutionary, smaller scale demonstrations are needed, including potentially an in-space demonstration, using a "spiral" development approach to incrementally demonstrate and validate new technologies added to the architecture. Thus, over time, the mass and cost of the antenna will continue to be reduced as emerging technologies are inserted into the architecture. The current mass aggressive antenna mass density using rigid panel construction is 8-12 kg/m2. The development of very lightweight active antenna aperture technologies can reduce this to 4 kg/2 within the decade. Higher levels of integration can ultimately lead to antenna mass densities less than 2 kg/m2 in the next 10 to 15 years.

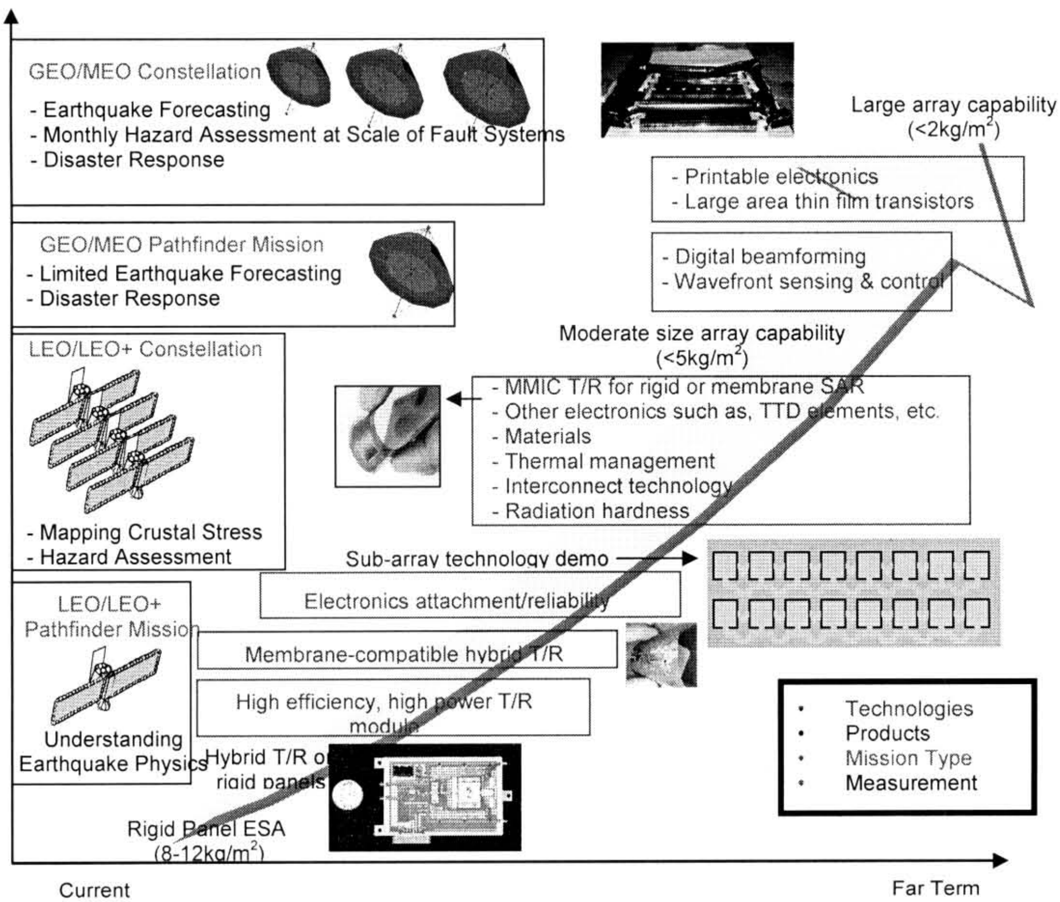

Figure 5. Technology roadmap for future membrane-based SAR antenna.

6. CONCLUSIONS

InSAR is an important technique to improve our understanding of earthquakes and other natural hazards and may one day provide the capability to forecast or predict earthquakes. The orbit geometry is a key parameter to improving global and temporal coverage and we have defined an optimal orbit that might strike a good balance between Earth coverage and instrument complexity. A constellation of InSAR systems in MEO orbits will further increase the accessibility so that near real-time accessibility is achievable. Mission system studies have determined that existing lightweight antenna technologies will not meet the mass and cost goals needed to make these systems practical. Ultra lightweight, large aperture, electronically steered phased arrays are needed. To fit in even the largest available launch vehicles, an antenna mass density of less than 2 kg/m^2 for the aperture, electronics, structure and deployment mechanisms will be necessary. One promising new technology that can achieve this challenging mass goal is active membrane antenna technology. We have defined the technology roadmap that could lead to these breakthroughs in lightweight antenna technology and ultimately to important and exciting new measurement capabilities to enable an InSAR mission at distant orbits. Moreover, this roadmap can also benefit near-term missions by significantly reducing mass and ultimately cost of the antenna.

ACKNOWLEDGMENTS

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