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MEO SAR System Concepts and Technologies for Earth Remote Sensing

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Next-generation interferometric synthetic aperture radar (InSAR) systems may provide the basis for establishing an earthquake-forecasting capability within a twenty-year time frame. Such systems would need to provide data with fine temporal resolution, so the system architecture would need to allow for wide-area coverage in order to minimize the effective interferometric repeat time. This paper discusses the coverage advantages associated with medium-Earth orbit (MEO) InSAR systems for observing geophysical phenomena. As MEO architectures dictate the need for large radar antennas, this paper also presents a discussion of advanced antenna technologies—and associated challenges—that might provide revolutionary decreases in the mass densities of large radar aperture antennas.

I. Introduction

FUTURE spaceborne systems may be able to provide the measurements necessary to enable earthquake forecasting within a twenty-year time frame.[1] Such observational systems could therefore bring about great societal benefits, yet in order to realize these benefits, the system would need to meet a demanding set of requirements. Architectures for advanced system concepts capable of such a role are the subject of this paper.

The value of space-based geodetic techniques has already been proven, and their extension to next-generation systems for improved monitoring of crustal deformation is the logical next step towards the goal of an earthquake-forecasting capability. Over the last decade, observations based on data from the global positioning system (GPS) and interferometric synthetic aperture radar (InSAR) techniques have provided important insights into our understanding of earthquake physics, crustal rheology, and fault interactions. Current models based on these insights predict that knowledge of the spatial and temporal deformation signals detectable by future satellite systems may significantly advance our ability to constrain the locations of future earthquakes.[2] A set of requirements for measuring crustal deformation using L-band InSAR has thus emerged.[1]

While the accuracy of the InSAR displacement measurements is naturally a key requirement on the system, another requirement of great importance is the need for short revisit times—on the order of days for science and hours for disaster response. Fine temporal sampling is needed so that precursory phenomena can be separated from the coseismic, postseismic, and aftershock signals that accompany a large earthquake. More frequent measurements will also result in better models of earthquake and fault interactions. Moreover, frequent sampling allows for improved displacement resolution through stacking and time-series processing in order to mitigate the effects of noise sources. The requirement for fine temporal sampling, and therefore for short orbit repeat periods, is therefore a major driver in the architecture of the system. This paper presents a discussion of MEO vantage points and their advantages over LEO architectures in achieving the science requirements with a minimal number of satellites. A MEO architecture places greater demands on the InSAR instrument, however; perhaps the greatest technological challenge with operating a MEO SAR instrument is the large antenna required. Consequently, this paper also discusses technologies for large, lightweight antenna systems that could enable MEO SAR observations for earthquake forecasting.

II. MEO Architecture

Orbit selection is perhaps the most defining step in the architectural design of an InSAR observing system, and because the image resolution of a SAR sensor can be made nearly independent of range, Earth coverage is probably the most relevant performance metric in the selection of an appropriate orbit. Greater coverage implies shorter revisit times and thus higher temporal resolution and more extensive data sets of target areas.

SAR sensors are generally side-looking instruments which acquire data only along swaths to the left and right of the platform ground track. A first-order estimate of the sensor coverage rate can therefore be obtained by multiplying the ground velocity of the platform nadir point by the two-sided visible swath width. This quantity is related to the ground area accessible by the SAR (i.e., the effective field of regard), although it should be noted that the SAR cannot necessarily acquire data over the entire accessible area simultaneously.

The Earth-coverage rate of a single SAR as a function of platform altitude is shown in Fig. 1, assuming that data are acquired only at broadside, with the SAR swaths limited by the range of allowable signal incidence angles on the ground. The curves peak at altitudes around 3000 km because the visible swath increases with altitude while the platform nadir velocity decreases with altitude.

Note that the curves of Fig. 1 are somewhat oversimplified in that they assume specific orbit inclinations and antenna sizes and capabilities, etc., but the general conclusion can be made that altitudes around 2000-5000 km might be most favorable from the perspective of Earth coverage. The precise locations of the curves' peaks depend on system-level assumptions.

It should also be noted that if continuous coverage is desired, for disaster-response applications for example, the simple model assumed by Fig. 1 would be inadequate. In that case, higher orbits (10,000-40,000 km) would likely be more effective in offering nearly instantaneous global accessibility. Current requirements for solid-Earth science call for revisit times only on the order of hours to days, however, and these might be achieved most efficiently from orbits around 3000 km.

Naturally, issues related to the required size and complexity of the SAR antenna constrain the design of the observational architecture. In order to avoid range-Doppler ambiguities, the SAR instrument's real antenna aperture must have a minimum projected area given approximately by

$$A \geq k\frac{4\rho\lambda v\tan\theta_{\text{inc}}}{c}$$

where ρ is the slant range, λ is the wavelength, v is the relative platform velocity, θ_{inc} is the incidence angle, c is the speed of light, and k is a design constant (typically 1.2-1.5 for a single-polarization system). Higher altitudes therefore require larger antennas (see Fig. 2) in addition to greater transmit power. Higher altitudes therefore motivate the pursuit of advanced technologies for large, lightweight antennas.

Coverage analyses for the LEO and geosynchronous SAR cases have been presented elsewhere.[1-2] Here, we briefly describe the results of a coverage analysis for

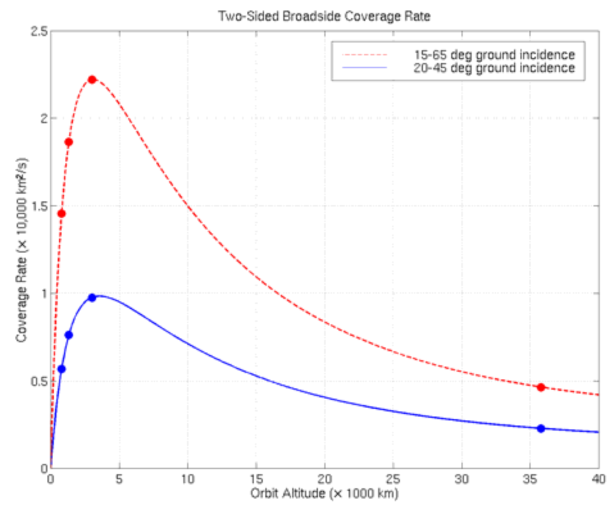


Figure 1. Coverage rates as a function of orbit altitude for swaths limited by ground incidence angle. Solid dots on these curves correspond to altitudes of 800 km (LEO), 1300 km (LEO+), 3000 km (low MEO), and 35,800 km (geosynchronous).

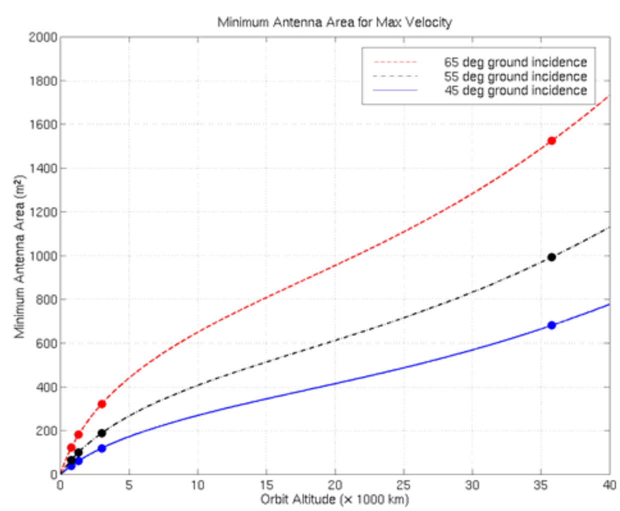


Figure 2. Required L-band antenna area vs. orbit altitude for assumed far-range ground incidence angles (symbols are as in Fig. 1).

a SAR operating at an altitude of approximately 3000 km. The orbit inclination is 112˚ (sun synchronous), and the orbit repeats every two days (19 orbits).

Our point study assumes a 10×40 m L-band antenna aperture which can be steered to look either left or right of the ground track. Although such a large aperture would likely require the use of technologies such as those discussed in the following section, the sensor would be able to collect data globally at ground incidence angles from 15-65˚, corresponding to look angles (off nadir) from 10-38˚ (see Fig. 3). As all points on the ground would be visible multiple times throughout the two-day orbit repeat cycle, maximum wait times before a given area could be imaged after an event would be on the order of 12 hours for a single satellite. The wait time and the effective interferometric repeat time could be further reduced by employing a constellation of satellites.

Figure 3. Orbits and accessible footprints of SAR systems at altitudes of 3000 km and 760 km. SAR swaths correspond to 15-65˚ ground incidence for both.

Because the system could offer global coverage with a diversity of viewing geometries, the 3-D displacement accuracy of the system would be excellent for most parts of the world. Moreover, the system could provide complete Earth coverage between ±84˚ latitude at incidence angles between 20-45˚. At these steeper incidence angles, the antenna area would be sufficient for polarimetric operation, which might enhance deformation measurements by allowing vegetation to be more easily excluded from the underlying surface signature. Polarimetry would also enable many other types of measurements, although it was not assumed to be a design driver for our analysis.

The InSAR system in our point study would be in view of land 78% of the time, significantly more than an equivalent LEO system. Given enough power, data storage, and downlink capacity, the system could therefore provide a greater volume of useful data than would be available from a lower orbit. The higher altitude would also allow downlink stations to be in view for longer durations on each pass, although a more optimal communications scheme can be envisioned if a constellation is assumed.

Anticipating observational requirements beyond the near term, it is apparent that even higher orbits would be more attractive if nearly instantaneous accessibility is required. That is, the ability to keep an area of interest on the ground in view continuously would be best provided by a constellation of higher-altitude sensors.

Previous study[1-2] has examined the coverage provided by a ten-satellite geosynchronous SAR constellation, finding that most areas on the ground could be kept in view continuously for many hours at a time. Because SAR sensors require relative motion between the platform and the Earth surface, however, geo*stationary* orbits are not useful. While inclined geosynchronous orbits remain over fixed sets of Earth longitudes and might be useful for optimizing coverage of specific regions, this property might also prove disadvantageous if global coverage is desired. For such cases, the advantages of geosynchronous orbits therefore arise mainly from their high altitudes, not their geosynchronicity per se. High MEO orbits (10,000-25,000 km) might consequently offer similar advantages in around-the-clock Earth coverage at reduced cost.

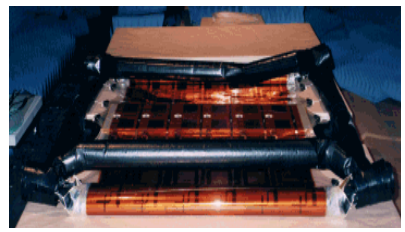
Our studies suggest that a nine-satellite MEO SAR constellation at approximately 14,000 km altitude (8 hour period) could maintain most areas on the surface in view more than 50% of the time, with typical coverage gaps of no more than two hours. A six-satellite constellation at approximately 20,000 km altitude (12 hour period) could keep the continental U.S. in view continuously, though it would not provide global coverage. While these two studies have been rather brief, such architectures might be worthy of further study if warranted by observational requirements. Both have assumed aggressive designs for the radar instrument (e.g., very large antennas), and thereby underscore the need for advancements in technology.

III. Enabling Technologies

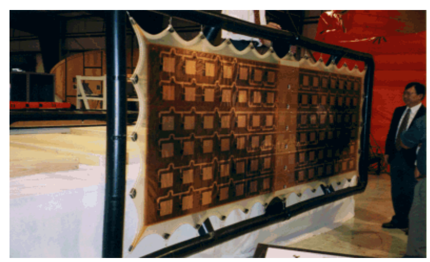
Along with their advantages, the MEO architectures described above also involve serious technological challenges. First, and perhaps foremost, we require revolutionary antenna technologies to enable these increasingly complex systems. These large active antennas would be a challenge to build, deploy, and maintain.

It is estimated that we need antennas with mass densities of 2 to 4 kg/m^2 to enable the large-aperture (10×40 m) SARs of the previous section to be lifted into space using available launch vehicles[3] (for comparison, the phased array used in the Shuttle Radar Topography Mission had a mass density of about 20 kg/m^2). These mass densities include the antenna support structure, the aperture, and all antenna-mounted electronics. One approach for achieving the necessary order-of-magnitude reduction in mass density is the use of thin film membrane material for the antenna aperture, along with lower-mass support structures.[4-6] Figure 4 shows an example of a membrane-based antenna. However, a system with less structural support is prone to surface deformation and errors. For phased-arrays, accurate knowledge and control of wavefront phase is the driving requirement. Physical displacement and component phase both contribute to the deformation of the 'phase surface' of an active array. Membrane antennas differ from standard, rigid phased-arrays in that physical displacement may be a significant contributor to phase-front error and can be rapidly changing temporally and spatially. Therefore, for a membrane-based antenna without a rigid support structure, sophisticated metrology and calibration (adaptive aperture control) are essential. Increasing the structural support of the antenna or adaptive aperture control are two basic methods for maintaining the required phase stability of a membrane array. The mass, complexity, and cost of rigid manifold and membrane-based systems need to be weighed against the resulting performance. In the short term, a membrane-based antenna with more structural support could be an acceptable solution, with more mechanically flexible systems following as the technology matures.

Roll-up Antenna (stowed)



Partially Deployed Antenna



Fully Deployed Antenna

Figure 4. JPL's passive membrane phased array. The antenna is rolled up during launch (top). It deploys and becomes flat once in space (bottom).

Below is a list of technologies that need to be investigated to enable a low-cost, large aperture antenna for future SAR applications. We assume a membrane-based antenna, although as discussed above, the level of the mechanical flexibility of the membrane antenna needs to be further studied.

Structure
We need new technologies for large, lightweight antennas including the deployment system, launch restraints and releases, and membrane tensioning and support frames. We would also benefit from more advanced technologies such as smart, self-reparable structures adaptable to changing environments and functional requirements.

Aperture
We need new single and dual polarization antenna designs and architectures compatible with membrane antennas. This includes designs for the RF radiating elements and antenna feeds. We can also benefit from new, durable, and reliable thin film materials with rip stopping capabilities.

Advanced Radar Electronics

Some examples of advanced electronic technologies are:

1- *High-efficiency integrated Transmit/Receive (T/R) modules*: T/R modules are one of the most critical components of a phased array, allowing 2-D steering of the beam. High-efficiency T/R modules would reduce power requirements and improve the thermal management of the array. Reliable integration of these T/R modules with the membrane would require miniaturization of integrated T/R modules.
2- *True Time Delay (TTD) components*: Because of the large size and operating bandwidth of the antenna, true time delays are required for proper beam formation. It is impractical to apply a true time delay to each array element; instead we can break the array into sub-arrays and apply a true time delay to each sub-array. This could be achieved in analog circuitry, using electrical or optical delays, or in digital circuitry.

Integration of Electronics

In addition to the need for new technologies for the aperture and the electronics, the reliable integration of these electronics with a large aperture would also require innovative technologies. This is especially true for flexible membrane antennas where T/R modules and other electronics such as true time delay circuitry need to be integrated with a thin film membrane.

Antenna System Integration

Just as new technologies would be required for integrating the antenna electronics with the aperture, the integration of the entire system requires new technologies as well. Examples of these technologies are:

1- *Metrology and calibration*: As discussed above, SAR measurements require the precise knowledge of the phase of the signals received. This requires the knowledge of the position of the antenna, phase of the electronics, etc. Metrology and calibration are more complicated for a large antenna, especially if it lacks mechanical rigidity. These issues need to be studied and new wavefront control systems developed.
2- *Interconnect technology*: We need new architectures and interconnect technologies to simplify the connection of thousands of unit cells on a large array. This includes RF, DC, and digital signal distribution.
3- *Passive and active thermal management*: Thermal management of a large array is critical for the radar performance and is more challenging for a membrane array. New technologies such as radar transparent thermal control coatings, variable emissivity surfaces/coatings, integrated phase change thermal storage, and mini/micro heat pipes can be used for adaptable thermal control. Eventually, active techniques such as capillary loops or mechanically pumped loops, micro-channel heat sinks, micro loop heat pipes, and micro heat pumps can be developed.
4- *Manufacturability*: Issues such as testing and replacement of components on a large array must be considered to obtain a reliable, low-cost final product.

Compounding the challenges associated with the large size of the radar antenna is the MEO radiation environment. Because radiation effects are quite severe at MEO altitudes, radiation could place serious limitations on the lifetime of the radar instrument as well as the spacecraft bus. Therefore, the development of rad-hard electronics and materials is critical to enable future MEO missions. Radiation effects in MEO need to be further studied.

Figure 5 depicts a conceptual design for a very large aperture antenna.[1] This antenna aperture is deployed with the horizontal booms and then tensioned to maintain flatness with two asymmetric axially deployed masts and tensioning cables. The antenna aperture is constructed from flexible membrane material that is integrated with the active electronics for proper beam formation and transmit/receive signal amplification. The antenna aperture and thin-film solar arrays are labeled in the figure.

IV. Conclusion

InSAR techniques offer the potential for making wide-area observations of geophysical phenomena with unprecedented accuracy. So great are the capabilities of these sensors that next-generation InSAR systems may form the foundations for an earthquake forecasting capability within a twenty-year time frame. In order to achieve these goals, such systems will need to meet many demanding requirements, one of which is the need for short interferometric repeat times. Because temporal sampling can be increased with wider coverage, system

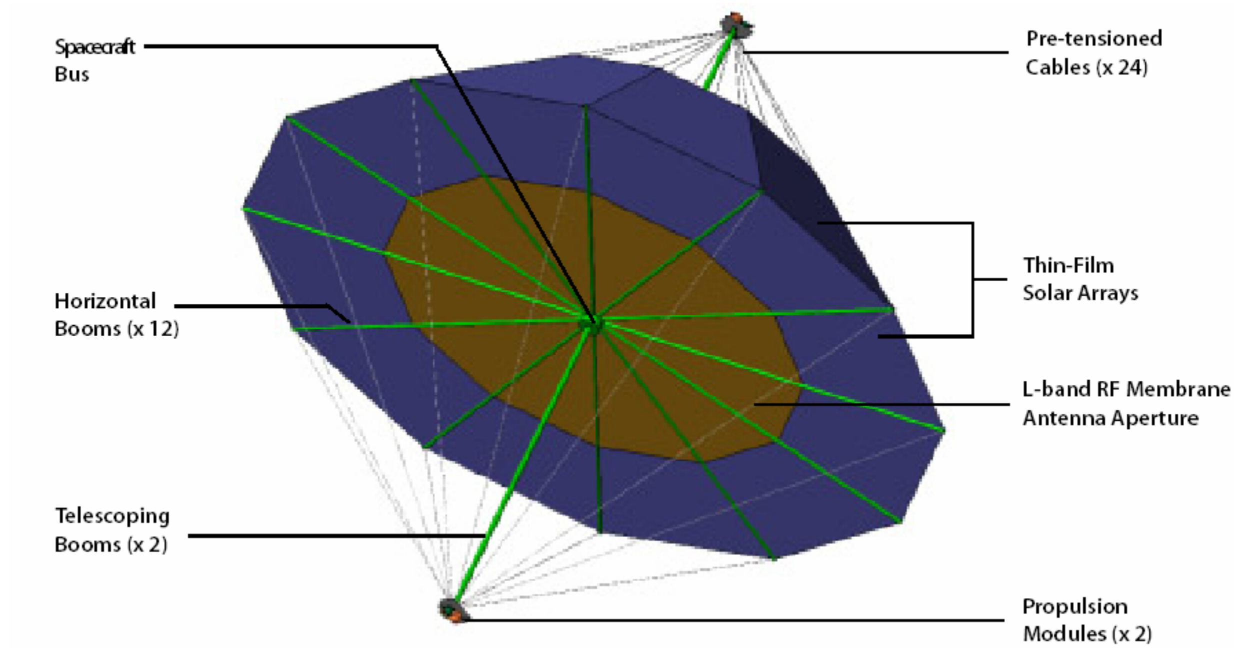


Figure 5: Conceptual drawing of a very large aperture SAR spacecraft.

architectures that offer advantages in accessibility are very attractive. Among candidate architectures, a MEO system around 3000 km might offer unique advantages in coverage. At MEO altitudes, however, the requirements on radar hardware are much more severe than those for LEO orbits. Specifically, higher orbits require larger radar antennas, which in turn dictate the need for antenna technologies with low mass densities. Advanced technologies such as membrane antennas offer significant promise in this context, yet several challenges remain in order to make these technologies realizable.

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