

System Concepts and Technologies for High Orbit SAR

(INVITED)

Alina Moussessian, Curtis Chen, Wendy Edelstein, Soren Madsen, Paul Rosen

Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, 91109-8099, USA

Abstract — This paper discusses large aperture, high orbit radar concepts for measuring sub-centimeter-level surface displacements from space. These measurements will enable applications such as earthquake simulation, modeling and forecasting. We will explain the need for large aperture, high orbit arrays and will discuss the technologies required to achieve these missions.

Index Terms — active arrays, phased array radar, radar, synthetic aperture radar.

I. INTRODUCTION

An Interferometric Synthetic Aperture Radar (InSAR) enabling continuous sub-centimeter-scale vector measurements over wide areas is one of the highest priorities identified by National Aeronautics and Space Administration (NASA) [1]. Such orbital InSAR will enable measurements of dynamics of Earth's crust, ice sheet motion, and other surface change measurements [2]. Observations of such phenomena with existing Synthetic Aperture Radar (SAR) sensors have shown the power of the interferometric technique, leading to exciting possibilities with future, more capable, systems. This is illustrated in Fig. 1, showing wide area observations of the large 1997 Manyi earthquake, made with an existing 35 day repeat SAR system, the European ERS-2 radar satellite. The interferometric observations were laboriously stitched together from observations made at six different times, leading to an impressive but limited snapshot of the surface deformation that occurred from before to after the event. In this case, there is an incomplete picture of the events leading up to the earthquake and how the crust responded to it over time. While current and planned sensors will have repeat periods on the order of one or more months, current science goals call for repeat periods of as little as one day. Improvements in temporal sampling of evolving surface phenomena are integral to the long-term vision for Earth system research. This vision would extend the results in Fig. 1 from a static depiction of two moments in the evolution of the crust to a complete time history of the straining crust leading up to the event and through its post-seismic relaxation. These would be essential observations for modeling and eventually prediction of Earthquakes. Access to higher orbital vantage points is an attractive way to obtain continuous observations in both space and time because as spatial coverage increases,

the spacecraft orbits can be tailored to repeat more frequently, thereby improving the temporal sampling as well. For example, a single Medium Earth Orbit (MEO) sensor at around 3000 km altitude could provide a two-day repeat period; a constellation of four such spacecraft could therefore provide an effective interferometric repeat period of six hours. As science models improve to the point that specific target areas on the Earth are to be monitored continuously, a pair of Geosynchronous Earth Orbit (GEO) SAR sensors could provide truly continuous coverage of such sites. High-altitude SAR instruments would thereby provide a vastly improved monitoring capability.

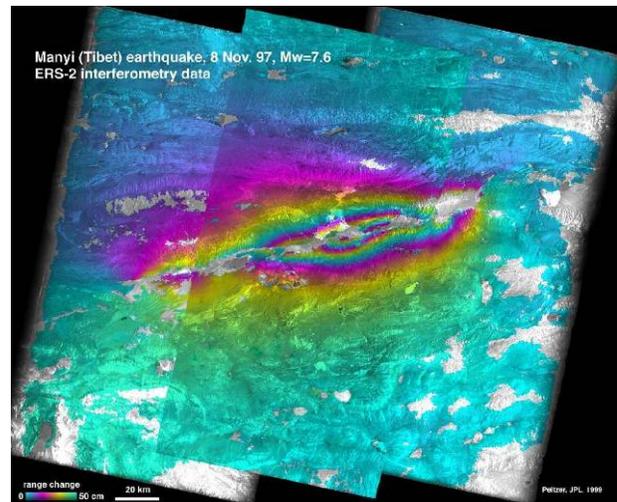


Fig. 1. Signature of Manyi Mw=7.1 earthquake. The color indicates relative displacement of the surface well over 1 meter from before to after the earthquake. This earthquake covered such a great extent that it was necessary to mosaic three adjacent tracks of repeat pass interferometric data [3].

In addition to Earth science applications discussed above radar measurements are also gaining increased relevance in planetary science. Radar measurements can be used to probe below the surface. Planetary SAR missions with the potential for breakthrough understanding of Mars' ice cap dynamics (flow, precipitation, and sub-ice melting), temporal variations of Europa's crust (i.e., as a definitive signature of the characteristics of a sub-crustal liquid water ocean), and the

surface deformation and/or volcanic activity of other planets (i.e., active hydrothermal or geothermal systems on Venus, Mars, etc.) are possible. All of these objectives are, at least in part, tied to the search for past or present life within the Universe, and as such are a major component of the NASA Vision. Especially for planetary missions mass and volume reducing technologies are key to reducing cost and enabling these missions.

II. ORBIT SELECTION

To achieve the goals discussed earlier we need to fulfill two objectives: 1- high-resolution surface deformation measurements with an accuracy of 1mm/year over a decade. 2- Timely access and global coverage. L-band repeat-pass InSAR techniques can provide the required high-resolution requirement. For timely access and global coverage 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. As shown in Fig. 2, 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 [4, 5]. However, 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.

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 [4, 5]. The coverage rate is shown as a function of platform altitude in Fig. 3. 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.

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. 2). 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. 3.

To effectively use the accessibility provided by a high vantage point, very large antennas with electronically steered beams are required. Fig. 4 illustrates the ideal minimum antenna area as a function of platform altitude for various

maximum ground incidence angles [4, 5]. The antenna size for a geosynchronous SAR is on the order of 700m² for the lower incidence angles as compared to antenna areas of roughly 50m² required for Low Earth Orbit (LEO) systems. MEO SAR altitudes require antenna areas of roughly 400m².

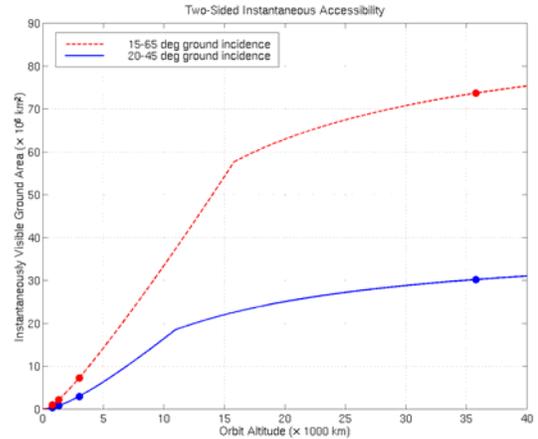


Fig. 2. Two-side sensor visible footprint. Markers for LEO (800 km), LEO+ (1300 km), low MEO (3000 km), and GEO (35,800 km)

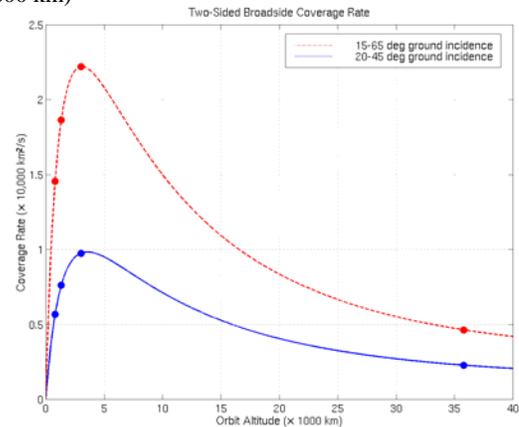


Fig. 3. Coverage rates as a function of orbit altitude for swaths limited by ground incidence angle. Markers on the curves correspond to LEO, LEO+, low MEO, and geosynchronous orbit.

Another important consideration in selecting the orbit is the radiation environment. 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 and it would undoubtedly drive the design and technology selection. In addition, higher altitudes require greater transmit power, while lower altitudes have more demanding antenna steering requirements.

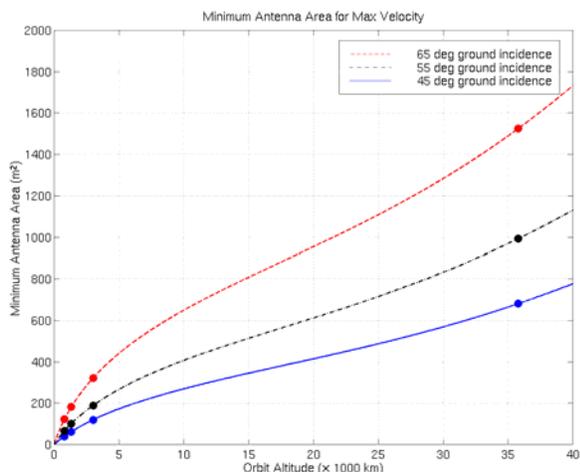


Fig. 4. Required L-band antenna area vs. orbit altitude for assumed far-range ground incidence angles (markers for LEO, MEO and GEO orbits).

III. TECHNOLOGY NEEDS

Along with their advantages, the high orbit SAR 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/m² to enable the large-aperture SARs of the previous section to be lifted into space using available launch vehicles [5] (for comparison, the phased array used in the Shuttle Radar Topography Mission had a mass density of about 20 kg/m²). 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 [6, 7]. 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. 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:

High Efficiency Integrated MMIC T/R module: T/R modules are one of the most critical components of a phased array, allowing 2-D steering of the beam. Since the ultimate goal is to keep the weight and stowed size of the antenna small conventionally packaged T/R electronics are not appropriate. It is desirable to integrate all the electronics on a single chip and deal with the pick and placement of only one chip per unit cell. High Efficiency, rad-hard, MMIC T/R modules with thermal compensation capability are essential. High-efficiency T/R modules would reduce power requirements and improve the thermal management of the array. Current candidates for L-band are GaAs and Si. The radiation tolerance of GaAs needs to be weighed against the better thermal characteristics, lower cost and robustness of thinned flex-Si. Current SOI CMOS technology might be a good alternative to GaAs and more work in this area needs to be done to access the feasibility of a fully integrated Si T/R module.

Low loss phase shifters: One example is a phase shifter using MEMS technology that has the potential to lower the loss of the phase shifter. The space qualification of MEMS components is the current obstacle for this technology.

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.

Power tiles: Membrane-compatible power tiles, which are the combination of solar cell and battery, can be used for integrated and distributed power generation and storage on large aperture membrane antennas.

Flexible and large area electronics (macroelectronics) using amorphous, low temperature polysilicon, and various organic and inorganic nanocrystalline semiconductor materials is beginning to show great promise. While much of activity in macroelectronics has been display centric, a number of

technologies are showing promise for use in radar applications [ref].

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 the electronics need to be integrated with a thin film membrane. The attachment and/or embedding of a die onto the membrane and its reliability is a challenge. Technologies such as flip-chip on flex need to be improved and new technologies such as embedding of electronics inside the thin membrane for added reliability have to be developed [ref]. Embedded or integrated passives can be used to integrate the passives onto the membrane structure.

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:

Metrology and calibration: 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. 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) is essential [ref].

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.

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.

Manufacturability: Techniques such as roll to roll processing might assist in the manufacturing of future very large arrays. Issues such as testing and reworkability of components on a large array must be considered to obtain a reliable, low-cost final product.

IV. 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. A constellation of InSAR systems in MEO orbit 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

ACKNOWLEDGEMENT

The research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

REFERENCES

- [1] <http://solidearth.jpl.nasa.gov>
- [2] S.N. Madsen, C. Chen, and W. Edelstein, "Radar options for global earthquake monitoring," *IEEE Symposium on Geoscience and Remote Sensing*, IGARSS '02, July, 2002.
- [3] Gilles Peltzer, Frédéric Crampé, Geoffrey King, "Evidence of Nonlinear Elasticity of the Crust from the Mw7.6 Manyi (Tibet) Earthquake", *Science*, Vol 286, Issue 5438, 272-276, 8 October 1999.
- [4] C. W. Chen and A. Moussessian, "MEO SAR system concepts and technologies for Earth remote sensing," *AIAA Space Conference*, September 2004.
- [5] W. Edelstein, S. Madsen, A. Moussessian, C. Chen, "Concepts and technologies for Synthetic Aperture Radar from MEO and Geosynchronous orbits", *SPIE International Asia-Pacific Symposium, Remote Sensing of the Atmosphere, Environment, and Space*, November 2004, Honolulu, Hawaii USA.
- [6] Huang, Lou, Fera, and Kim, "An inflatable L-band microstrip SAR array," *IEEE AP-S/URSI Symposium*, Atlanta, GA, June 1998, pp. 2100-2103.
- [7] J. Huang, M. Lou, E. Caro, "Super low mass spaceborne SAR array concepts," *IEEE Antennas and Propagation Symposium*, Montreal, CA, July 1997.
- [8] Moussessian et al "Active membrane phased array" *IMS 2005*, Long Beach, CA, June 2005.