Observational Architectures for Enabling Earthquake Forecasting

Curtis W. Chen, Carol A. Raymond, and Søren N. Madsen

Jet Propulsion Laboratory, California Institute of Technology
4800 Oak Grove Dr.
Pasadena, CA 91109-8099

Abstract **Observational architectures for allowing the eventual forecasting of earthquakes are discussed. The science requirements imply that L-band InSAR systems with short repeat periods would be best suited to such measurements. Constellations of such sensors in orbits around 2000–5000 km altitude might provide optimal Earth coverage for interferometry, while higher orbits around 10,000–40,000 km might approach the goal of around-the-clock coverage for disaster-response applications.**

I. INTRODUCTION

Studies have been carried out to define the requirements and observational architectures needed to enable earthquake forecasting in the 20-year time frame [1]. These requirements are derived from current scientific understanding of earthquake physics, crustal rheology, and fault interactions; they are driven by expectations of the societal benefits brought about both by the dynamic definition and mitigation of seismic hazards as well as by the improved effectiveness of disaster-response efforts when and where large earthquakes occur.

An earthquake-forecasting capability is predicated on the understanding of stress accumulation during the earthquake cycle. Because geodesy is the principal means of monitoring the fault and lithosphere during the interseismic and postseismic parts of the earthquake process, and because the great value of space-based geodetic techniques has already been demonstrated, a spaced-based system for monitoring crustal deformation is the logical next step towards the goal of a predictive capability. Observations based on Global Positioning System (GPS) and Interferometric Synthetic Aperture Radar (InSAR) data over the last decade have provided important model constraints on complex ruptures, triggered earthquake sequences, and aftershocks. These insights have stimulated the development of models of stress shadowing and stress migration in the crust and upper mantle to explain correlated space-time deformation patterns. Theoretical models that examine earthquake clustering and stress evolution predict spatial and temporal deformation signals that could be measurable with future satellite systems, leading to significant advances in our ability to constrain the locations of future earthquakes.

A set of requirements has emerged for measuring crustal deformation using InSAR. The most important requirement is 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 atmospheric and other noise sources. The need for long-term correlation favors L-band radar. Although low-Earth-orbit (LEO) architectures were considered as well, this paper presents a discussion of higher vantage points which allow the achievement of the science requirements with a minimal number of satellites.

II. MISSION ARCHITECTURE AND COVERAGE

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.

Because SAR sensors obtain image resolution through range-Doppler mapping, data can only be acquired along swaths to the left and to the right of the platform ground track, with relative motion required between the platform and the Earth surface. A first-order estimate of the sensor coverage rate can therefore be made by multiplying the 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, 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

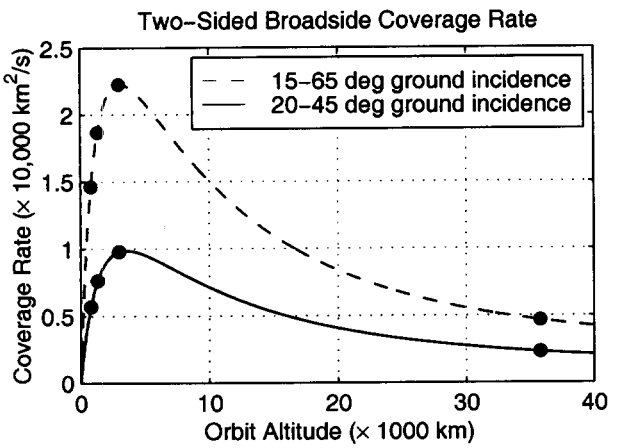

Figure 1: Coverage rates as a function of orbit altitude for swaths limited by ground incidence angle. Solid dots on these curves correspond to altitudes of 800 km (LEO), 1300 km (LEO+), 3000 km (low MEO), and 35,800 km (geosynchronous).

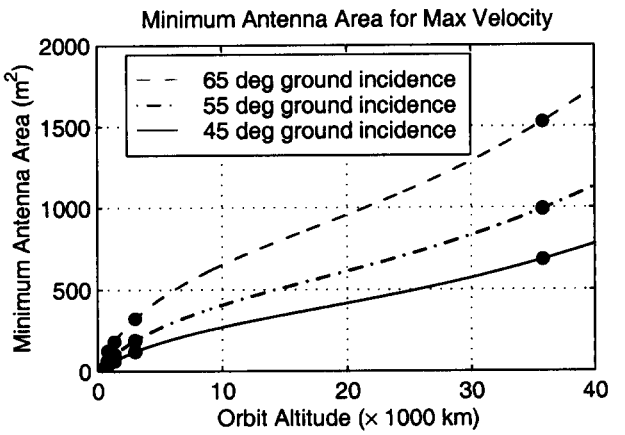

Figure 2: Required L-band antenna area vs. orbit altitude for assumed far-range ground incidence angles (symbols are as in Fig. 1).

data are acquired only at broadside and that the SAR swaths are 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, however.

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. Rather than minutes, however, current requirements for solid-Earth science call for revisit times on the order of hours to days, which might be achieved most efficiently from orbits around 3000 km.

Another important factor in SAR orbit selection is the required antenna size. In order to avoid range-Doppler ambiguities, the SAR instrument's real antenna aperture must have a minimum area given approximately by

$$A \geq \frac{4\rho\lambda v \tan\theta_{\text{inc}}}{c} \tag{1}$$

where ρ is the slant range, λ is the wavelength, v is the relative platform velocity, θ_{inc} is the incidence angle, and c is the speed of light. Higher altitudes therefore require larger antennas (see Fig. 2) in addition to greater transmit power. Altitudes around 3000 km might therefore be more attractive than higher altitudes from a technological perspective as well.

III. MEO POINT STUDY

Coverage analyses for the LEO+ and geosynchronous SAR cases have been presented previously [1, 2]. In this section we briefly describe the results of a coverage analysis for 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 assumed a 10×40 m L-band antenna aperture which could be steered to look either left or right of the ground track. This large aperture would allow data to be collected globally at ground incidence angles from 15–65°, corresponding to look angles 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.

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 ground 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

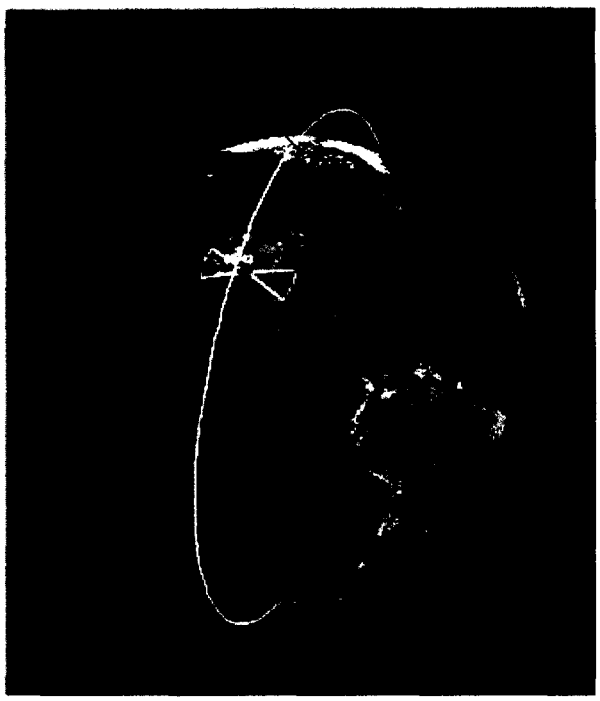

Figure 3: Orbits and accessible footprints of SAR systems at altitudes of 3000 km and 760 km. SAR swaths correspond to 15–65° ground incidence for both.

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 a 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.

Along with its advantages, however, the 3000 km orbit also involves serious technological challenges. First, and perhaps foremost, the radiation environment associated with this orbit is quite severe. Radiation could place serious limitations on the lifetimes of the radar instrument as well as the spacecraft bus. The large instrument antenna required would also be a challenge to build, deploy, and maintain, especially given the constraints on hardware technologies imposed by the radiation environment. Radiation effects are the subject of current study.

IV. HIGHER ORBITS

Anticipating observational requirements beyond the near term, it is apparent that 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 and have assumed aggressive designs for the radar instrument (e.g., very large antennas), such architectures might be worthy of further study if warranted by observational requirements.

V. CONCLUSIONS

Low MEO orbits at altitudes of 2000–5000 km are attractive from the perspective of Earth coverage for an InSAR system. Given the current solid-Earth science requirement of a short repeat period, an observational architecture based on such orbits might be most effective in providing data that would eventually enable the forecasting of earthquakes. Higher orbits might be attractive for the far-term goal of monitoring of events with shorter time scales.

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