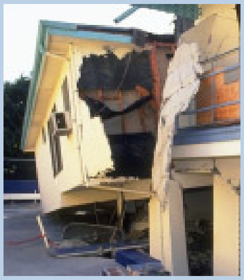
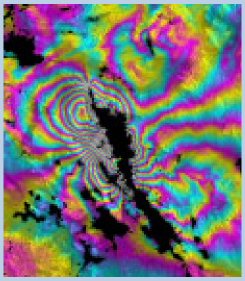
GESS

GLOBAL EARTHQUAKE SATELLITE SYSTEM

A 20-YEAR
PLAN TO
ENABLE
EARTHQUAKE
PREDICTION

MARCH 2003





Earthquake Hazard Assessment in the Future

CHAPTER ONE

Understanding the earthquake cycle and assessing earthquake hazards is a topic of both increasing potential for scientific advancement and societal urgency. A large portion of the world's population inhabits seismically active regions, including the megacities of Los Angeles, Tokyo, and Mexico City, and heavily populated regions in Asia. Furthermore, the recent devastating Gujurat earthquake in India and the New Madrid series of earthquakes in the U.S. underscore the vulnerability of areas not thought to be tectonically active. Population growth will exacerbate the potential for huge earthquake-related casualties, and economic losses of tens of billions of dollars will likely occur as a result of future large events. Since earthquake losses, human and material, are primarily the result of structural failures, enforcing appropriate building codes and retrofitting structures can reduce the overall hazard.

Knowledge of the overall earthquake hazard, and more specific regional and local earthquake risk (at the scale of fault systems) is needed to effectively mitigate these earthquake hazards. A global earthquake observing system will monitor the behavior of interacting fault systems, identify unknown (subsurface) faults, guide new models of the deforming crust, and verify those dynamic models. This knowledge will translate into tangible societal benefits by providing the basis for more effective hazard assessments and mitigation efforts.

Inset and background: Effects of the Northridge, California, earthquake. (Robert Eplett, CA OES)

During the last decades, powerful new tools to observe tectonic deformation have been developed and deployed with encouraging results for improving knowledge of fault system behavior and earthquake hazards. In the future, the coupling of complex numerical models and orders of magnitude increase in observing power promises to lead to accurate, targeted, short-term earthquake forecasting. Dynamic earthquake hazard assessments resolved for a range of spatial scales (large and small fault systems) and time scales (months to decades) will allow a more systematic approach to prioritizing the retrofitting of vulnerable structures, relocating populations at risk, protecting lifelines, preparing for disasters, and educating the public. The suite of spaceborne observations needed to achieve this vision has been studied, and the derived requirements have defined a set of mission architectures and enabling technologies that will accelerate progress in achieving the goal of improved earthquake hazard assessments.

Three decades ago, earthquake prediction was thought to be an achievable goal. Such optimism has all but vanished in the face of current understanding of the complexity of the physics of earthquake fault systems. The advent of dense geodetic networks in seismically active regions (e.g., SCIGN, the Southern California Integrated Global Positioning System Network), and satellite interferometric synthetic aperture radar (InSAR) from the European Remote Sensing (ERS) satellites, have resulted in great progress in understanding fault ruptures, transient stress fields, and the collective behavior of fault systems, including transfer of stresses to neighboring faults following earthquakes (Freed and Lin, 2001; Pollitz and Sacks, 2002). These improved observations of surface deformation, coupled with advances in computational models and resources, have stimulated numerical simulations of fault systems that attempt to reveal system behavior. As InSAR and Global Positioning System (GPS) data become more spatially and temporally continuous in the future, the modeling environment will rapidly evolve to achieve revolutionary advances in understanding the emergent behavior of fault systems. This in turn will enable finer temporal resolution (dynamic) earthquake hazard assessments on the scale of individual faults and fault systems. Dynamic earthquake hazard assessment, coupled with rapid postearthquake damage assessments will enable more effective management of seismic disasters.

The Global Earthquake Satellite System (GESS) study began with the requirements generated for the LightSAR mission, as well as those generated in an EarthScope workshop focused on InSAR (J. B. Minster, personal communication, 2001). EarthScope is a National Science Foundation (NSF) initiative, carried out in partnership with the United States Geological Survey (USGS) and NASA, to study crustal deformation in North America. NASA's proposed contribution to the initiative is an InSAR satellite. Under EarthScope, NSF will field an array of approximately 1000 GPS monitoring sites across western North America, one or more strainmeters, and several deep drill holes near the San Andreas fault. The USGS will upgrade and expand its digital seismic network as its contribution. The synergistic combination of these measurements and InSAR-observed surface deformation is expected to yield major advances in understanding of the crustal structure and rheology of the continent.

Whereas the requirements for a near-term InSAR satellite are well understood, the future needs, which are not well defined, are the driver for our study. Therefore, we have examined the outstanding questions concerning the physics and forecasting of earthquakes, and used these as the basis of a Request for Proposals, issued by JPL, to fund studies that defined measurement requirements for an observing system that could answer them. These questions are:

1. How does the crust deform during the interseismic period between earthquakes and what are its temporal characteristics (if any) before major earthquakes?
2. How do earthquake ruptures evolve both kinematically and dynamically and what controls the earthquake size?
3. What controls the space–time characteristics of complex earthquakes and triggered earthquakes and aftershocks?
4. What are the sources and temporal characteristics of postseismic processes and how does this process relate to triggered seismicity?
5. How can we identify and map earthquake effects postseismically or identify regions with a high susceptibility to amplified ground shaking or liquefaction/ground failure?
6. Are there precursory phenomena (potential field, electromagnetic effects, or thermal field changes) preceding earthquakes that could be resolved from space?

Incorporating this community input, we have formulated a more stringent set of requirements for measurement of surface deformation that will answer questions 1–4, and we consider approaches to addressing questions 5 and 6. The drivers for these requirements are discussed below and in Chapter 2.

Elements of a Global Earthquake Satellite Observing System

Efforts to advance understanding of earthquake physics require detailed observations of all phases of the earthquake cycle (pre-, co-, and postseismic), across multiple fault systems and tectonic environments, with global distribution. Satellites offer the best way to achieve global coverage and consistent observations of the land surface. While ground seismometer and GPS networks are and will remain critical, the synoptic view of the deforming crust that is possible using satellite data drives the need for a global earthquake satellite observing system. In addition, knowledge of the character of the shallow subsurface is critical to assessing expected ground accelerations.

Surface Deformation Measurements

Measurement of surface change (displacement) constitutes a powerful tool for resolving the deformation fields resulting from tectonic strain (Figure 1.1). Surface deformation includes other components besides tectonic strain, such as surface motion due to groundwater storage and retrieval (Bawden et al., 2001). The InSAR technique relies on correlated image-pairs to derive displacements to the resolution of a fraction of the radar wavelength. If topography is known, two images can be used to derive a map of the displacement in the range direction. Additional image pairs obtained from different look directions (i.e., ascending versus descending) improve the resolution of vertical and horizontal displacements. If topography is not known, three images can be differenced to derive the topography and its change. The accuracy of the measurement depends on several factors, including the radar signal-to-noise ratio (SNR), orbit determination precision, and removal of signal path delays caused by the variations in spurious ionospheric electron density and tropospheric water vapor. All of these errors must be minimized to achieve long-term absolute accuracy of interseismic strain accumulation.

Figure 1.1 Earthquakes can cause significant surface deformation, such as this meter offset from an earthquake in the California desert. (Robert Eplett, CA OES)

Subsurface Characteristics

The type of material in the shallow subsurface, and its saturation, affect the ground acceleration experienced as a result of a particular earthquake. Directivity of seismic energy during fault rupture can result in quite different patterns of deformation. Liquefaction, the sudden release of water from saturated, permeable layers, is of particular concern in coastal landfill areas, and on steep slopes. Mapping the degree of saturation in the shallow subsurface will help determine landslide hazards, and may allow the liquefaction hazard to be folded into the overall dynamic earthquake hazard assessment. Radar sounders, along with InSAR displacements, can provide data to augment surface measurements that seek to characterize the subsurface.

Electromagnetic and Thermal Anomaly Precursors

Many claims have been made concerning the correlation of magnetic fields, electric fields, and seismicity, including precursory electromagnetic signals. Mechanisms to produce such correlative variations include movement of fluids in fault zones as a result of stress changes preceding ruptures, and piezomagnetic effects of stress field changes. Improvements in data quality and quantity over the past 40 years have led to a substantial decrease in the correlated signals (Johnston, 1997). Magnetic anomalies associated with main shocks are well documented and can be accounted for by piezomagnetic effects. The subject of precursory electromagnetic signals, and a satisfactory mechanism to explain them, requires more laboratory and field research, as well as high-quality continuous ground and satellite magnetic field data series with proper reference control. Recognizing subtle signals generated at the surface against the background of the highly dynamic external magnetic field at satellite altitudes is challenging. These correlations are likely best tested using carefully configured ground networks in seismogenic zones.

A weak infrared (IR) thermal anomaly was observed near the epicenter of the October 1999 Hector Mine, California, earthquake (Figure 1.2). This and other suggested correlations between thermal IR anomalies and

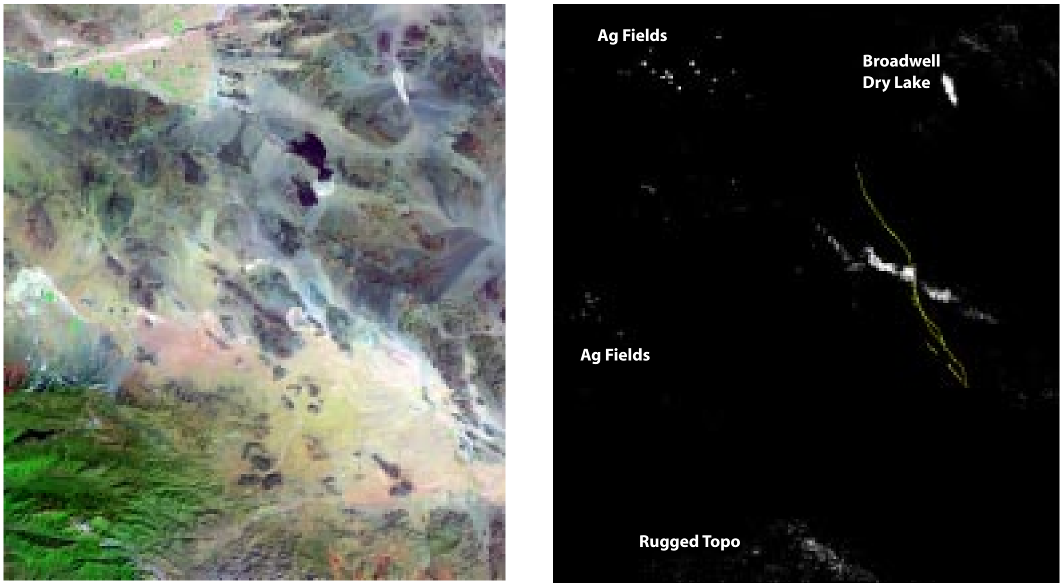


Figure 1.2 Landsat data for Mojave Desert, California, on October 15, 1999, hours before the Hector Mine earthquake. The visible scene is on the left, and the thermal difference between October 15 and an image from September 29, 1999 is shown at right. A weak thermal anomaly intersects the fault segment that broke in the Hector Mine earthquake (yellow line). (R. Crippen, JPL)

earthquakes have been studied with inconclusive results. As with electromagnetic anomalies, more robust correlations and plausible mechanisms are needed to assess this potential stress indicator. The current Advanced Spaceborne Thermal Emission Radiometer (ASTER) and Landsat ETM+ instruments have good spatial resolution, and may provide data to test existing hypotheses, but coverage is sparse.

Spatial and Temporal Measurement Requirements

The primary focus of the GESS study was the measurement of surface deformation, as this has emerged as the top priority for space-based observation of the earthquake cycle. Light detection and ranging (LIDAR) systems can provide precise measurements of vertical surface change through clear air and even beneath vegetation canopies. Wide-swath LIDAR is thus a promising technique for complementing InSAR (Hofton and Blair, 2002; Chao et al., 2002), especially in vegetated areas.

Detailed requirements for InSAR data gathering have been collected to support three main objectives: long-term measurement of interseismic strain accumulation (to <1 mm/yr resolution), detailed maps of coseismic deformation to define the fault rupture, and measurement of transient deformation such as postseismic relaxation and stress transfer following earthquakes, aseismic creep, and slow earthquakes. To maximize correlation between scenes, especially at interannual time scales, an L-band system is preferred. The mid-term and far-term requirements are summarized in Table 1.1.

Observing interseismic strain accumulation drives the need for very precise long-term accuracy. To distinguish between hazards from blind thrust and shallow faults requires deformation rates to be resolved at the 1 mm/yr level over 10 years. Achieving this accuracy requires mitigating the tropospheric and ionospheric noise in the images, as well as reducing orbit errors. Fortunately, the strain accumulation process is steady, so stacking and filtering techniques can be used to remove these sources of noise. Short repeat periods enable frequent data acquisitions to support these needs. A promising approach to mitigate the tropospheric water vapor delay is to combine the radar observations with other atmospheric data to derive the water vapor content along the radar line-of-sight. For interseismic strain measurements, the length of the data series may be more important than the revisit frequency and the requirement is on the order of 10 years for an L-band system.

Observation of coseismic deformation drives the need for precise instantaneous accuracy and short revisit times. Exponentially decaying postseismic processes will obscure the coseismic signals with time following the event. Also, good spatial resolution is needed to precisely map the decorrelation and displacement close to the rupture. Transient postseismic strain, as well as aseismic creep and slow earthquakes, drive the need for frequent revisit times to capture these events. Chapter 2 discusses the measurement needs in greater detail.

Concept Mission Architectures

The scientific requirements for studying earthquakes drive two main components of a proposed Global Earthquake Satellite System: accurate, high-resolution surface deformation measurements; and timely, global coverage.

Interferometric synthetic aperture radar techniques provide spatially continuous observations of surface movements in the form of high-resolution displacement maps. InSAR produces unique, spatially continuous, distributed observations. The line-of-sight components of surface displacements can be determined to fractional-wavelength accuracies over hundreds of kilometers at high resolutions (tens of meters). Three-dimensional vector displacement information can be derived by combining ascending, descending, right-looking, and left-looking data.

A key performance parameter for a disaster and hazard monitoring system is the timely access to and coverage of the target area. InSAR deformation maps can only be generated when the SAR sensor passes overhead and a prior reference data set exists; therefore, the instantaneous field of view (accessible area), and the likelihood that any given target will be covered within a given time are crucial design parameters.

As such, two point designs were selected early in the study to provide innovative radar mission architectures that add perspective to the traditional and tested low-Earth orbit (LEO) missions flown at altitudes from 560–870 km.

Most LEO SAR designs to date, including those of the widely used ERS 1 and 2 satellites, have involved swath widths of around 100 km, and therefore have required orbit repeat periods of around 30–40 days in order to provide global coverage. With the use of ScanSAR techniques (Tomiyasu, 1981), as on RADARSAT and the Shuttle Radar Topography Mission (SRTM), the SAR swath can be extended significantly at the expense of image resolution. This can be a worthy trade, as characterizing coseismic fault rupture requires rapid accessibility — the ability to map a specified target area at a critical time — but only moderate resolution. However, to implement repeat-pass interferometry with a ScanSAR system, the along-track ScanSAR bursts would have to be precisely aligned between orbits. This has not been done before. Increasing the satellite elevation can also enhance the accessibility of a SAR sensor, as doing so generally increases the area the satellite can view at any given time. Generally,

Table 1.1 Requirements for surface deformation measurements.

	MINIMUM	GOAL
Displacement Accuracy	25 mm instantaneous	5 mm instantaneous
3–D Displacement Accuracy	50 mm (1 week)	10 mm (1 day)
Displacement Rate	2 mm/yr (over 10 yr)	<1 mm/yr (over 10 yr)
Temporal Accessibility (Science)	8 days	1 day or less
Temporal Accessibility (Disaster)	1 day	2 hrs
Daily Coverage	6×10^6 km^2	Global (land)
Map Region	±60° latitude	Global
Spatial Resolution	50–100 m	3–30 m
Geolocation Accuracy	25 m	3 m
Swath	100 km	500 km
Data Latency in Case of Event	1 day	Minutes to hours

it is found that a SAR will only operate satisfactorily if it has a certain minimum antenna area. That area, A, is

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

where ν 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 1.4–2.0. As the range R increases with platform altitude more quickly than the velocity ν decreases, the antenna size must increase with orbit elevation. However, the accessible area increases as well. Thus, to the extent that the mission cost is not 100% dominated by the radar aperture size, one will achieve greater efficiency in terms of accessible area per dollar by raising the elevation of the satellite. As past SAR system studies have focused on elevations in the range 560–820 km, and the performance of such systems is fairly well understood, we have studied the placement of a SAR satellite in a higher, “enhanced LEO” configuration (LEO+) at an altitude of 1325 km.

This design is largely evolutionary relative to present and past LEO SAR systems. The orbit is a proven TOPEX-class orbit, and the radar hardware could be built from existing technology. However, the higher altitude affords a much larger accessible area than traditional LEO systems.

By increasing the satellite elevation even higher for the purpose of improving its accessibility, one can imagine operating a SAR in a geosynchronous orbit (Figure 1.3). Such a system provides an enormous instantaneous field of view, and is also able to provide data at very high resolution, in contrast to optical sensors at those altitudes. However, the technological challenges are significant not only because of the very large active antenna aperture required, but also due to issues relating to processing the extremely long apertures, in particular in higher resolution modes (2–10 m horizontal). As a SAR uses the relative motion between itself and the target to achieve high resolution, synthetic aperture formation will be impossible from a geostationary geometry, where the radar location is fixed in Earth body fixed coordinates (EBFC). However, when the inclination of the orbit is not zero, the satellite will be moving in EBFC. We have primarily studied circular orbits with inclinations between 50° and 65°. In these cases, the ground track will resemble that shown in Figure 1.3 (a figure eight). In terms of the Earth surface area that is in view from a single satellite at a given time, a geosynchronous satellite will outperform a LEO-type satellite by two orders of magnitude, thus requiring far fewer satellites to cover the globe entirely at all times. The trade-study comparing LEO-type systems to geosynchronous SAR systems is, however, complicated for several reasons. A geosynchronous SAR would require an extremely large antenna aperture, which would involve the use of technologies that are not yet mature. A geosynchronous SAR would also differ from a LEO SAR in its coverage characteristics. Contrary to LEO satellites, a geosynchronous satellite can be placed to provide focused regional coverage for a limited set of Earth longitudes. A minimum of three geosynchronous satellites will be required for global coverage.

The radar processing required for a geosynchronous SAR would also differ quite dramatically from that of a LEO system because of the peculiar characteristics of geosynchronous orbits, as well as atmospheric changes over the long integration times that arise from the long apertures and low relative velocities. It will also be necessary to address dynamic atmospheric (troposphere and ionosphere) correction, which is presently not well understood and not tested at all.

In addition, we study constellations based on those two point designs. The constellations provide insight as to what future systems could provide in terms of an operational mapping capability. Constellations of satellites capable of providing observations on a very frequent basis (many observations each day) were studied for the LEO+, MEO (medium Earth orbit), and geosynchronous cases. In these evaluations, the relevant performance measure was the likelihood that a given position on the ground would be mapped within a given time. The constellations were also assessed for accuracy in providing 3-D displacement measurements.

A key concern in repeat-pass interferometry is so-called temporal decorrelation. While InSAR measurements reflect the collective displacement of all scatterers within a given image resolution cell — typically tens of meters wide to fractional-wavelength accuracy — the technique breaks down when the scattering centers within the resolution cell experience different displacements, or when the dominant scatterers change from one observation to the next. For example, the vegetation in the resolution cell might induce temporal decorrelation. At longer wavelengths, the radar returns would come mainly from plant branches and trunks, so the signal might decorrelate over periods of weeks to months. At short wavelengths, the radar echoes might come primarily from the leaves, which can decorrelate in seconds as the leaves move with the wind. Precipitation and the freezing or thawing of the ground will also introduce significant temporal decorrelation. Longer wavelengths tend to exhibit better correlation properties over extended time periods. In rela-

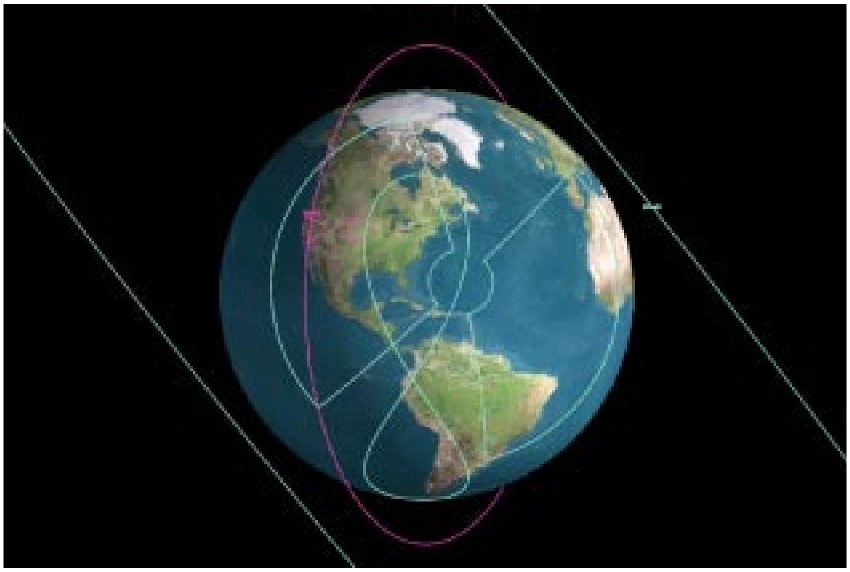


Figure 1.3
Orbit and ground trace of a geosynchronous satellite at a 50° orbit inclination (figure eight). Instantaneous field of view for a 5000-km SAR swath is shown (blue). Orbital path and instantaneous field of view for a LEO+ SAR is also shown (pink).

tion to vegetation, longer wavelengths tend to look through the lighter components, such as leaves, to primarily "see" the more stable elements such as branches, trunks, and the ground. The frequency trade-off is counterbalanced by issues such as the ionosphere, and the antenna size. These factors suggest that L-band (approximately 24 cm wavelength) is a good compromise for the frequency selection. The designs presented are based on a single polarization design, to keep cost at a minimum. It is conceivable that a polarimetric capability would allow forming interferograms from polarimetric combinations that would reduce the decorrelation from vegetation.

Also, to bridge the two extreme design points of LEO+ and geosynchronous, we performed a parametric analysis indicating key performance parameters at altitudes in between. Interestingly, the analysis hints that for future around-the-clock monitoring, medium Earth orbit (MEO) configuration, with somewhat smaller antennas and reduced costs relative to geosynchronous, might offer a very capable and effective trade-off.

The scientific requirements outlined in Table 1.1 can be met by various SAR architectures. The report details those architectures in the following chapters. The most promising concepts are a constellation of six to twenty-four SAR satellites in LEO or LEO+ (1325 km) orbits, or three to six geosynchronous SARs. A few LEO+ satellites can optimize most of the requirements, but very short revisit times require larger constellations.

Expected Benefits

Improved Earthquake Hazard Assessments

Current seismic hazard assessments rely on historical earthquake catalogs to predict the statistical probability of future earthquakes. However, there is a spectrum of crustal deformation driven by plate motions that is transient and/or aseismic. Our incomplete knowledge of the deformation budget is a major obstacle to improving predictive capabilities. It is difficult to verify predictive models against infrequent and sparse seismic and geodetic data. There is a debate as to whether the crust is in a constant state of self-organized criticality in seismic zones, or whether the crust approaches and retreats from that state in a cyclic pattern; the answer has profound implications for the predictability of earthquakes. One promising model posits that normalized surface shear strain across faults, obtainable from dense InSAR data, appears to be a proxy for the unobservable stress-strain dynamics that govern fault rupture (Rundle et al., 2002). The ability to resolve surface deformation to the centimeter level over the entire globe will result in hundreds of earthquakes each year that can be analyzed to test and improve predictive models (Melbourne et al., 2002). Community models will produce dynamic earthquake hazard assessments by using observations in real time, mining the data, and adjusting the earthquake hazard assessments based on the emerging model system behavior. This will allow more effective use of portable ground networks or arrays of instruments (laser strainmeters, seismometers, magnetometers) to capture information on transient fault behavior leading up to an event. While predicting the time, location, and size of a particular earthquake will remain elusive, much higher fidelity earthquake forecasts appear within reach.

The total seismic risk includes the likelihood of a particular seismic event, and the response of any particular site to the seismic waves generated. The worst damage occurs in regions of directed seismic energy, and liquefaction (the sudden liquification of permeable sedimentary layers) often amplifies the damage. Very precise surface deformation measurements will help to identify aquifer discharge and recharge, and can provide information on the saturation of vulnerable subsurface sedimentary layers (Tobita et al., 2002). This knowledge can be folded into the earthquake hazard assessments to produce a localized, dynamic measure of seismic risk.

Disaster Management

The dynamic earthquake hazard assessments described will provide the disaster management community with information to focus mitigation efforts. Such efforts include prioritizing retrofitting projects to protect lifelines and infrastructure, educating the public, staging emergency supplies, and establishing mobile communication networks. Earthquake hazard assessment models should be interfaced with decision support systems to guide mitigation efforts.

Temporal revisit times on the order of hours following an event are required to effectively support disaster response efforts. Mapping zones of decorrelation will be most useful to the emergency workers on the ground. Areas that decorrelate between interferograms obtained prior to a seismic event and those that span the event indicate changes in the built environment, and zones of intense shaking that can focus response efforts. InSAR has the advantage of being an all-weather capability for either day or night, an important consideration for obtaining time-critical measurements. Radar-equipped uninhabited aerial vehicles may play an important role in disaster response efforts.

A SAR constellation would allow a staring capability that would reveal the details of transient postseismic behavior and could be particularly useful in the hours and days following a great earthquake to assess the stress transfer and loading of neighboring fault systems, potentially predicting large damaging aftershocks and triggered earthquakes.

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Space Administration

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JPL 400-1069 03/03