

# Understanding and Responding to Earthquake Hazards

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**Abstract** – Understanding the earthquake cycle and assessing earthquake hazards is a topic of both increasing potential for scientific advancement and social urgency. A large portion of the world's population inhabits seismically-active regions, including the megacities of Los Angeles and Mexico City, and heavily populated regions in Asia. Population growth will exacerbate the potential for huge earthquake-related casualties. However, powerful new tools to observe tectonic deformation have been developed and are being 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.

## I. EARTHQUAKE HAZARD ASSESSMENT IN THE VISION ERA

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 [GPS] Network), and satellite interferometric synthetic aperture radar (InSAR) has 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 [1]. These improved observations of surface deformation, coupled with advances in computing and information technology, have stimulated numerical simulations of fault systems that attempt to reveal system behavior. As InSAR and GPS data become more spatially and temporally continuous in the Vi-

sion era, 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 post-earthquake damage assessments will enable more effective disaster preparedness for, and response to, large damaging earthquakes.

## II. 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 post-seismic), 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. Other types of geophysical data may also shed light on the subsurface processes. The different types of measurements that might comprise a global earthquake satellite system are discussed below.

### A. *Surface Deformation Measurements*

Measurement of surface change (displacement) constitutes a powerful tool for resolving the deformation fields resulting from tectonic strain. Surface deformation includes other components besides tectonic strain, such as surface motion due to groundwater storage and retrieval [2]. The InSAR technique relies on correlated image-pairs to derive displacements to the resolution of the radar wavelength. If topography is known, two images can be used to derive a map of the displacement in the range direction. A second image pair obtained from a different look direction (i.e., ascending

versus descending) improves 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 radar signal to noise, orbit determination precision, and removal of signal path delays caused by the interference of ionospheric electron density and tropospheric water vapor. All of these errors must be minimized to achieve long-term absolute accuracy of interseismic strain accumulation.

### B. 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. Liquifaction, 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 liquifaction hazard to be folded into the overall dynamic earthquake hazard assessment, scaled by the degree of saturation of the vulnerable layers. Radar sounders, along with InSAR displacements, can provide data to characterize the subsurface.

### C. 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 has led to a substantial decrease in the correlated signals [3]. Magnetic anomalies associated with mainshocks 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 altitude is challenging. These correlations are likely best tested using carefully configured ground networks in seismogenic zones.

A strong ephemeral infrared (IR) thermal anomaly was observed near the epicenter of the October, 1999 Hector Mine earthquake. This and other suggested correlations of thermal IR anomalies and earthquakes has 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 ASTER (Advanced Spaceborne Thermal Emission Radiometer) mis-

sion will provide data to test existing hypotheses.

## III. SPATIAL AND TEMPORAL MEASUREMENT REQUIREMENTS

The remainder of the paper will focus on measurement of surface deformation, as this has emerged as the top priority for space-based observation of the earthquake cycle. LIDAR (Light Detection and Ranging) systems can provide precise measurements of surface change through clear air and even beneath vegetation canopy. Wide-swath LIDAR is a promising technique for future observing systems.

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 slow, transient deformation such as post-seismic relaxation and stress transfer following earthquakes, aseismic creep, and slow earthquakes. To maximize correlation between scenes, especially at inter-annual time scales, an L-band system is preferred. The mid-term and far-term requirements are presented in Table 1.

TABLE 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 y)	1 mm/yr (over 10 y)
Temporal Accessibility	8-days	1-day
Daily Coverage	$6 \times 10^6$ km <sup>2</sup>	Global (land)
Map region	$\pm 60^\circ$ latitude	Global
Spatial resolution	100 m	10 m
Geo-location accuracy	25 m	3 m
Swath	100 km	500 km
Data latency in case of event	1 day	2 hours after acq.

Observing interseismic strain accumulation drives the need for very precise long-term accuracy. To distinguish between blind thrust and shallow faults, and their hazards, requires deformation rates to be resolved at the 1mm/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 process is steady, so stacking and filtering techniques can be used to remove these sources of noise [4]. Consequently, the length of the data series is more important than the revisit frequency and 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 post-seismic 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 post-seismic strain, as well as aseismic creep and slow earthquakes drive the need for frequent revisit times to capture these events.

These requirements can be met by a constellation of 6-24 SAR satellites in LEO or LEO+ (1325 km) orbits, or by 3-6 geosynchronous SARs [5]. A few LEO+ satellites can optimize most of the requirements, but to achieve the very short revisit requires a larger investment.

#### IV. DYNAMIC EARTHQUAKE HAZARD ASSESSMENTS

The underlying stress-strain dynamics of fault systems is generally unobservable, but this obstacle can be surmounted by comparing observations to numerical simulations to test and improve models of fault system behavior. Scaled measures of strain, such as the Local Ginzburg Criterion" (LGC), a normalized measure of surface shear strain across faults, appears to be a proxy for the unobservable coulomb failure function that governs fault rupture. Developing and evolving models of complex fault systems and creating a community modeling environment will be key to exploiting the revolutionary advances in observing capability that are expected within the next 20 years. Capable models will ingest the observations in real-time and may adjust the earthquake hazard assessments based on the emerging system behavior. While predicting the time, location and size of a particular earthquake will remain elusive, much higher fidelity earthquake forecasts appear within reach.

#### V. DISASTER RESPONSE

Temporal revisit times on the order of hours following an event are required to effectively support disaster response efforts. While displacement maps are useful for understanding the dynamics of the rupture and to predict the transient post-seismic behavior, decorrelation maps will be most useful to the emergency workers on the ground. Decorrelation maps will 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 that is immune to illumination conditions.

To satisfy the requirements for disaster response support, a dense LEO or LEO+ constellation, or 3-6 geosynchronous satellites will be needed. Such a constellation could provide global accessibility with 24 hour revisit time, while the geosynchronous constellation would allow a staring capability that would reveal the details of transient post-seismic 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.

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