Measuring earthquakes from space

towards a better understanding of Earth crustal deformation

Bam, Iran, 2003: 31 thousand people killed. Sumatra, Indonesia, 2004: close to 228 thousand people killed, the third largest number in history. Kashmir, Pakistan, 2005: over 80 thousand fatalities. Three recent examples serve to illustrate that despite all technological advancements, earthquakes still pose a major threat to the world and its inhabitants. The recent widespread availability of spaceborne radar (SAR) measurements has been a great boost in the understanding of tectonic systems, and should lead to much more accurate seismic hazard assessments than hitherto possible.

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The Earth is divided in tectonic plates; relatively thin shells that fracture, fold and drift around on the convective flows of the asthenosphere, a partly fluid part of the Earth's mantle.

A view, of course, that most of us are used to since early schooldays. And one that makes sense: how else can it be that the South-American and African coasts fit so neatly together. Still it took well into the 20th century for this idea to become accepted. The assumption of a solid earth was hard to abandon, and early explanations involving continents 'grinding' over the sea floor never really got hold. It was only 1960 that Harry Hess published his now well accepted theory of seafloor spreading. This is less than 50 years ago.

Earthquake prediction

Our view of earthquakes, as being the release of strain energy resulting from relative plate motion, is thus a recent one. By now the main driving mechanisms are reasonably well understood. And yet, understanding the mechanisms has not yet resulted in the power of prediction. The main difficulties-high complexity of the system and little information about the current state-has led most scientists in this field to the view that accurate short term prediction will not soon and most probably never be possible.
Rather than predicting the time of an event, attention is shifting towards the probability of occurrence within in a certain time frame. Seismic hazard assessments are invaluable for local governments, emergency services, construction and insurance companies. The information input comes mostly from seismic stations, such as the Global Seismic Network that covers the globe with over 128 stations. Centroid-Moment-Tensor (CMT) solutions, identifying location, orientation, and magnitudes of the event, are now produced on a routine basis for events with magnitude greater than 5.5 by the CMT project.
Seismicity is transient, short-term deformation that travels in waves. Another potential source of information is the permanent deformation that remains after the earthquake has ceased. Clearly, a field rupture gives accurate information about the fault plane close to the surface. But also on a more wide-scale level the Earth will deform to the new state of equilibrium. However measuring co-seismic deformation involves two field surveys; one before and one after the earthquake. Even now that classic triangulation has been superseded by GPS, the time

and costs involved remain so high that this is not usually considered feasible, and frequently there are no measurements before the earthquake.

Satellite imaging radar: InSAR

Though not GPS, it was a spaceborne technology that caused the major breakthrough in research of co-seismic deformation. Synthetic Aperture Radar Interferometry (InSAR) technology emerged in the mid 90's, after the launch of ESA satellites ERS-1 and ERS-2. Proof of concept studies had been performed on data collected by SEASAT, the first Earth-orbiting satellite that carried a Synthetic Aperture Radar (SAR). This active instrument uses electromagnetic waves for remote sensing just like conventional radar, except that software post-processing is used to focus the received data - thus 'synthetically' enlarging the antenna size or aperture.

The raw product is a complex SAR image. Each pixel holds the sum of information returned by all objects in a resolution cell: the section of the earth's surface that is associated with the pixel, typically several meters large. This information is recorded as complex-valued data; signal magnitude and phase. Roughly speaking, the magnitude depends on the objects' roughness and orientation with respect to the satellite; the phase mostly on their distance to satellite. However, due to the large ratio between resolution cell dimension (meters) and wavelength (5.6cm for ERS), the phase change over neighboring pixels is random and cannot be used to infer distance.

However, when a second SAR image is taken from a slightly different angle, it turns out that distance information is hidden in the correlation between the two phase images. This compares to the human visual system: even though the separate eyes do not provide any distance information, correlating the two images does give a sense of depth. For SAR the correlating process is interferometry (InSAR), producing what is called an interferogram. The technique gives roughly meter level height accuracy, depending on many factors such as satellite angular distance. Because of the cyclic nature of the electromagnetic phase this information is presented in wrapped form. Like with a contour map, to get a height difference between any two points requires counting cycles.

Taking two images from the same angle, the interferogram represents deformation, rather than topography, spanning the time between the two images. This is differential InSAR (DInSAR), with typically sub-centimeter level accuracy. Figure 1 shows the 1999 Hector Mine earthquake. Compared to expensive and time consuming field measurement campaigns, DInSAR provides far denser spatial coverage and much higher revisit rates, with an archive of images to chose an image before the earthquake. This makes it the ideal tool for deformation monitoring and earthquake hazard assessment. An important limitation is that the measured deformation is only the component in the satellite line of sight; the two perpendicular components of motion are not detected. This is partially fixed by combining ascending and descending orbits, thus adding a second line of sight.

Fault plane inversion

The unprecedented spatial density made it possible for the first time to verify theories about the mechanical behavior of the Earth's crust. Geoffrey King and colleagues had shown in 1994 that stress distributions computed using a very simple model, assuming homogeneous, isotropic elasticity, agree well with aftershock distributions for a number of large earthquakes. DInSAR confirmed these assumptions, to first approximation, for relatively short time scales. For a given fault geometry and relative slip, co-seismic displacements can be predicted by solving the equations of elasticity. Yoshimitsu Okada had done so already in 1985, and his analytical solutions are now widely used as a forward model for co-seismic displacements. Forward modeling is one thing; far more interesting is it to reverse directions and find a fault geometry and slip distribution that match InSAR measured deformation. The forward model is a link between observables and the state of the subsurface. Reversing direction is not at all straightforward, as inverse problems are often ill-posed and it is not easy to single out a solution that best fits the data. That said, InSAR does prove very useful to augment the seismic solutions where it comes to complex fault geometries and testing hypotheses.

Now that InSAR is maturing, the time has come to push its application further. Okada models agree well with CMT solutions, but to get more detailed information about subsurface change close to the earthquake local geological information should be included. Soil type, layering, often the information is available but it cannot be used because of simplicity of the model. Finite element methods are much more flexible in that respect, and stochastic finite elements can even model error sources in the InSAR acquisition process. Also in the inversion a lot can be gained: rather than to aim for a single solution, we should try to identify exactly what information is hidden in an interferogram, and avoid drawing unjustifiable conclusions.

Predicting earthquakes is still several steps further on up the road, perhaps beyond the horizon. But it starts with the correct interpretation of data, with drawing the right conclusions. That is where we hope to make our contribution.

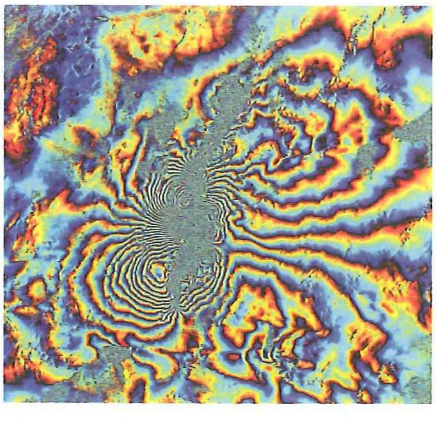

figure 1 (left): Interferogram showing deformation caused by the 1999 Hector Mine earthquake in an area surrounding the epicenter. Each cycle corresponds to 28mm relative motion in line with the satelite.

figure 2 (right): Arg-e Bam citadel (Unesco world heritage list) stood for over 300 years and the human history of Bam extends back for about 2000 years. In all of that time, there had been no reports of earthquakes in the Bam area (Ambraseys & Melville, 2002). That was until the earthquake of December 26th 2003, M_w 6.6.