Synthetic Aperture Radar for Geodesy

Charles Meade and David T. Sandwell

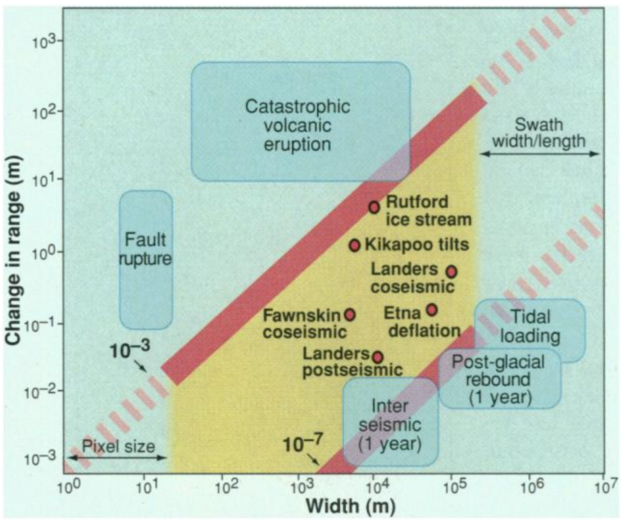
Synthetic aperture radar interferometry (InSAR) is receiving increased attention as a geodetic tool. Like the Global Positioning System (GPS), InSAR measures the relative positions of points on Earth's surface (for topographic mapping) and the displacements of these points over time (for surface change detection) (*1*). The high spatial resolution of a single SAR image is achieved by coherently adding individual radar echoes collected along the track of a satellite orbit, effectively increasing the aperture of the antenna from ~10 to ~4000 m (synthetic aperture). An interferogram is the phase difference between two SAR images collected from repeating orbits with a slight displacement in the cross-track direction (0 to 600 m). Larger cross-track antenna separation is best for topographic measurements, whereas shorter base lines are best for surface change detection (*1*). Although the accuracy of InSAR is less than that of GPS, it provides better spatial resolution, measuring the positions of millions of points over areas that may lack GPS coverage. Future InSAR missions may produce global topographic maps at a resolution of 3 m. With present data, InSAR has produced spectacular images of earthquake slip (*2*), deflating volcanoes (*3*), and flowing glaciers (*4*). Given this potential, some have speculated that use of InSAR will grow dramatically in the future (*5*) and may rival GPS in its value and applications in geodesy. Strategies to fulfill these predictions were the focus of a recent meeting at the National Academy of Sciences (*6*).

Presentations on surface-change detection showed that advances in processing methods and a better understanding of error sources have improved the accuracy and reliability of the technique. Under ideal conditions, InSAR can measure displacements of 3 to 10 cm along a swath 50 to 100 km wide, providing details of interseismic strain accumulation on complex fault systems [presented by G. Peltzer; see also (*1*)] and flow patterns in glaciers (C. Lingle; R. Gurnitz; L. Gray). For tectonic studies, presentations showed that these data are providing a wealth of new understanding compared to the spatially sparse recordings of GPS networks (G. Peltzer; M. Rossi; K. Feigl).

An example of a "practical" measurement focused on subsidence from ground-water withdrawal near Los Angeles (K. Hudnut). In Pomona, California, subsidence had not been detected because state and county survey data had not been coordinated. Results from the city of Lancaster, California, could be compared with previous leveling studies, demonstrating that InSAR accurately measures subsidence in urban areas. Other practical applications for InSAR included detection of subsidence around cavities at a Nevada test site (M. Rossi), assessment of infrastructure damage by the Kobe earthquake (P. Rosen), and delineation of land use patterns (agricultural, forested, and settled) (S. Coulson; C. Werner).

With these results, constraints on the applications for InSAR are becoming clear (see figure). Because of well-defined limits to the resolution of surface-change measurements, it is straightforward to assess the feasibility of new InSAR applications.

Several presentations emphasized the importance of InSAR measurements for constructing digital elevation models (DEMs) (S. Coulson; M. Baltuck; E. Paylor; H. Malliot). Such data are critical for topographic mapping and improved accuracy in surface-change measurements. Many believe that large-scale (global) DEMs will be the greatest achievement of InSAR technology because of the growing importance of digital spatial data for a vast range of scientific and practical applications. To this end, a presentation by the European Space Agency (ESA) described important new results (S. Coulson): Between August 1995 and May 1996, ESA had a unique opportunity to fly the ERS-1 and ERS-2 satellites in parallel orbits (200 m apart), separated by 1 day. This "tandem" mission simulated a single interferometric measurement for topographic mapping, and it imaged Earth up to six times over. Preliminary results suggest that these data could be used to construct a global DEM at a resolution of 10 m.



Resolution limits of surface-change measurements made with satellite-based InSAR. The figure compares the line-of-sight displacements (vertical axis) to the surface dimensions (horizontal axis) for a range of geophysical phenomena. The size of the pixels and the radar swath provide lower and upper bounds, respectively, for the resolution of features in an InSAR scene. On the basis of the radar wavelength, the upper and lower bounds for strain measurements are 10^{-3} and 10^{-7}, respectively (indicated by the diagonal lines). The region of the figure within these limits defines a range of length scales over which InSAR is capable of detecting changes in the surface. The comparison shows that coseismic deformation, volcanic deflation, and ice flows are well within the capabilities of InSAR. Interseismic deformation, postglacial rebound, tidal loading, and volcanic eruptions are marginally feasible. Detection of fault rupture will not be possible. [Figure courtesy of K. Feigl]

Participants noted, however, two problems that may introduce large uncertainties into the analysis of the tandem data. First, the SAR images may be decorrelated over vegetated regions because of the 1-day time lag, making it difficult to construct interferograms from the data. The debate over this problem has not been resolved because much of the tandem data has not been analyzed. Second, delays in the radar echoes due to variability in atmospheric water vapor between successive images can introduce large uncertainties in interferograms, particularly over humid and tropical regions. Indeed, discussions of model calculations (H. Zebker) and comparisons between InSAR images collected at different times (M. Rossi) demonstrated large radar phase shifts from small changes in humidity. In the analysis, both of these effects are difficult to deconvolve from the topographic signal. For these reasons, arid and arctic environments have been the most desirable locations for InSAR measurements, although there is great interest in developing InSAR applications in humid and tropical regions. Model calculations suggest that repeat measurements at multiple wavelengths could isolate the phase shift from water vapor (H. Zebker), but this strategy has not been tested.

Policy issues that will shape the development of InSAR were also discussed. Most important was increased access to SAR data and to specialized processing software for interferometric analysis. At present, data and software are unevenly distributed among institutions and countries because of copyright restrictions,

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proprietary interests, and the policies of particular space agencies and governments. There was a strong sentiment that these restrictions hinder the development of InSAR because they limit the scope of research. For example, ESA has formed agreements with individual institutions and research groups governing free distribution of limited data sets from the ERS-1 and ERS-2 satellites. In the United States, this policy provides large amounts of data to scientists at research institutions such as the Jet Propulsion Laboratory (JPL) and the Alaska SAR Facility. In this setting, new U.S. investigators often have difficulty obtaining SAR images, and in some cases they must purchase the data on the open market (at $300 to $900 per 100 km by 100 km scene). Because InSAR investigations require hundreds of scenes, the costs are prohibitive for many scientists.

For U.S. radar missions, restricted access to data will limit the scope of research. In this area, NASA discussed its plans for the Shuttle Radar Topography Mission (SRTM), which will produce a global topographic map between latitudes of 60°N and 60°S (M. Baltuck; E. Paylor). (Because it will simultaneously image Earth with two radar sources, decorrelation and changes in atmospheric water vapor will not impact the measurements.) This mission, to be funded jointly by NASA and the Department of Defense (DOD), has been scheduled for May 2000. The DOD has indicated, however, that it will restrict access to data for regions outside of the United States.

The future community of InSAR users could be quite large. A recent report by an interagency SAR working group has identified InSAR applications for many agencies ranging from the Central Intelligence Agency to the U.S. Forest Service (D. Montgomery). A group from JPL and NASA is also investigating collaborations with private industry. This broad base of support will be both difficult and helpful. On the one hand, developing and funding the infrastructure for acquiring, processing, and archiving data for many applications with specialized and potentially conflicting needs (such as proprietary interests, classified issues, and open research requirements) has been a problem for previous remote sensing missions. On the other hand, it is widely recognized that the needs of diverse interests will be the greatest driver for InSAR imaging. Consider the case of GPS. Despite difficult technical and public policy issues that have hindered its implementation (7), GPS has flourished because of widespread demand. InSAR will also grow strongly if it can be developed in an open environment for a wide range of scientific, engineering, and commercial uses.

References

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Trypanosome RNA Editing: Resolved

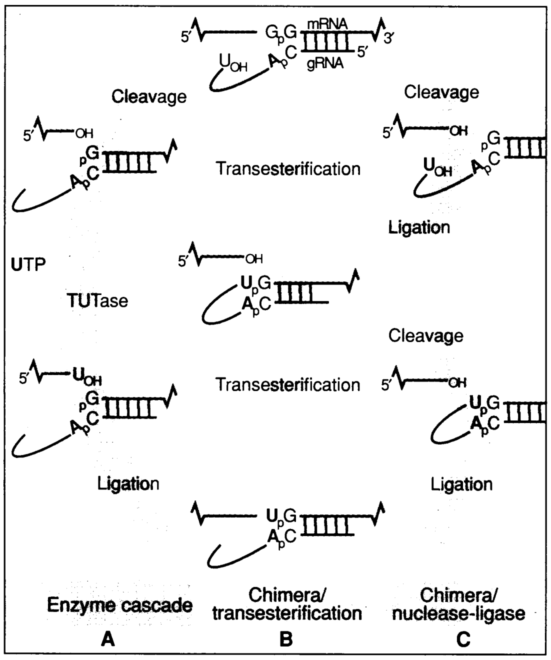
Barbara Sollner-Webb

In the last 15 years, unexpected kinds of RNA processing—orchestrated changes of the nucleotide sequence of an RNA transcript—have been discovered. Arguably the most bizarre and massive of such changes is the RNA editing that occurs in trypanosomes and related protozoa, and for the last decade the Holy Grail in the field has been how this editing takes place. Work culminating with the Kable *et al.* research article in this issue (*1*) now provides the basic answer, which turns out to be notably different from the model most popularly envisioned only 2 years ago.

In trypanosome RNA editing, uridylate (U) residues are precisely inserted into primary mitochondrial transcripts, and less frequently U residues are deleted, to generate mature functional mRNAs (*2*). In some transcripts, U residues are inserted at over 100 different places to constitute over half the protein-coding nucleotides. This RNA editing therefore must be impressively precise, for misediting at only one of these sites would yield an inactive, frame-shifted mRNA.

A major breakthrough was the discovery of guide RNAs (gRNAs), short mitochondrial transcripts with complementarity (Watson-Crick and G:U) to edited sequence, which by base-pairing could sequentially direct the U insertions and deletions (*3*). The major focus then became to understand the mechanism underlying this RNA editing. One possibility—supported by the presence of an endonuclease specific for editing domains (*4*), terminal-U-transferase (TUTase) (*5*), and RNA ligase (*5*) in trypanosome mitochondria—was that editing on precursor mRNA (pre-mRNA) was enzymatically catalyzed by these activities (*3*) (see figure, model A). However, the finding of gRNA-mRNA chimeric molecules in vivo (*6*) supported an attractive alternative model where each round of editing involves two transesterification reactions (*6, 7*). The first joins the oligo-U 3′ tail of the gRNA to the downstream half of the pre-mRNA at the targeted editing site, generating a gRNA-mRNA chimeric intermediate; the second transesterification at an adjoining bond re-forms the mRNA with U residues appropriately transferred in or out (see figure, model B). The elegance and similarity of this model to mRNA splicing gained widespread support (for example, *8*). Nonetheless, an analogous chimera-based mechanism could involve endonuclease and RNA ligase (*9*) (see figure, model C).

Attention then focused on the mechanism of gRNA-mRNA chimera formation, since it appeared to



Models for U-insertion RNA editing. This hypothetical pre-mRNA and gRNA base-pair to the first editing site, where the A (in red) of the gRNA directs U insertion in the mRNA. Models (**A**) (*3*) and (**C**) (*9*) propose endonuclease cleavage just 5′of the base-pairing, together with RNA ligase and TUTase. Model (**B**) (*6, 7*) shows transesterification attack by the gRNA's 3′ oligo-U and then by the new 3′ mRNA end. U-deletional models are analogous, but a distinct U-specific nuclease may catalyze U removal in (A).

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