Developments in Repeat Pass Interferometric Radar for Earth and Planetary Sciences

Paul A Rosen
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, CA 91109 USA
T: (818) 354-0023
F: (818) 393-3077
E: Paul.Rosen@jpl.nasa.gov

Abstract- **Repeat pass radar interferometry has developed into a wide ranging geodetic and change mapping tool from space. For large areas of the Earth, and for numerous applications that demand more persistent monitoring, the true potential of the repeat pass technique remains largely untapped. While the research community, has made enormous strides in extracting as much information as possible from existing data sets, fundamentally new observing systems are needed for breakthroughs in a number of areas. Repeat pass interferometry techniques applied on missions to the terrestrial planets, Earth's moon and the icy moons of Jupiter can reveal new insights in to the history of the surface and near subsurface.**

I. Introduction

NASA's vision for Earth science in the coming decades incorporates numerous active microwave missions. For land processes and Solid Earth science, the primary *radar* tool for remote sensing will be synthetic aperture radar (SAR). NASA's technology roadmap for 2010 and beyond includes radar constellations in low-earth, medium-earth, and geosynchronous orbits [1]. The aperture sizes grow with the distance from the Earth, and with increased desires for targetability, area coverage, and rapid repeat capability. These large apertures will necessarily require polarization diversity and flexible pointing agility. With prodigious amounts of data, and the desire by NASA scientists to receive real-time science products from the spacecraft, a powerful, flexible, fault-tolerant onboard processing architecture must accompany these radar platforms.

The SIR-C/X-SAR [2] and SRTM [3] SAR missions highlighted the unique capabilities and benefits of radar for terrain classification and mensuration. SIR-C/X-SAR (1994) was a three-frequency active-array radar, fully-polarimetric at two of the frequencies and demonstrated many new spaceborne modes. Many of the examples below in this paper are derived from SIR-C data. The principal limitation of SIR-C was that it operated for a total of 20 days on orbit over two shuttle flights separated by six months and covered only a portion of the Earth's surface. As a result, the data were not suited to characterizing the global state of the land surface and its change over time. SRTM was a milestone in mapping of the world, producing the first all digital, high-resolution topographic map of land between –60 and +60 degrees of latitude. SRTM also demonstrated a clear cost benefit for topographic mapping relative to more conventional topographic mapping approaches. The next generation of SAR missions for NASA will build on the successes of SIR-C and SRTM.

In the short term, after the successful mapping of the Earth's topography, and before large aperture systems or multi-satellite constellations are developed, the science community is calling for repeat pass interferometric SAR measurements to properly measure surface deformations due to physical processes such as earthquakes, volcanoes, ice sheet movement, and other important surface changes [4].

The development of the methods of repeat pass synthetic aperture radar (SAR) interferometry (InSAR) over the past

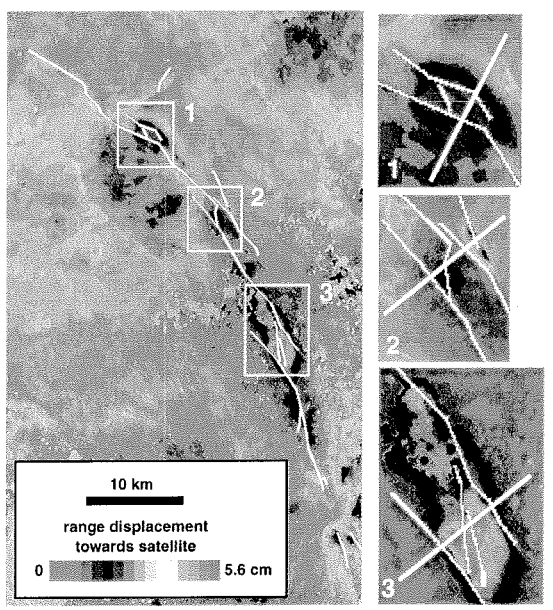

Figure 1. Post-seismic rebound in the shallow crust as an illustration of the subtle deformations of the surface visible from space. Three-pass radar ERS-1 interferogram along the Camp Rock, Emerson, Homestead Valley, and Johnson Valley faults following the 1992 Landers earthquake in California. [5]. Clearly visible are the signatures of crustal rebound in the fault step-overs. Fault traces are shown in white. The two lower fault discontinuities, which constitute pull-apart structures, have the opposite sense of displacement from the compressive structure in the upper portion of the image. Such features could not be recognized in GPS data without a dedicated deployment of a dense network. Repeat Pass Interferometric data can measure surface change a very fine spatial resolution, suitable for a variety of scientific and governmental applications.

decade has led to exciting new discoveries in the geophysics, civilian, and national communities [6]. Figure 1 shows an example of subtle deformation of Earth's surface following an earthquake using the European ERS-1 satellite as a data source.

If two images are acquired from the same vantage point in space but at different times, the interference pattern of these two SAR images (the "interferogram") records the changes of the reflecting surface that occurred between the capture of the two images. If the reflective surface change is broad enough without significantly disrupting the arrangement of the reflective layer, this "time-lapse" interferometer can measure motions much smaller than the radar wavelength, achieving millimeter to centimeter resolution. Repeat pass interferometry has now been demonstrated in a variety of geophysical applications, including earthquake displacements, volcanic inflation, and ground subsidence from the pumping of oil and water.

Starting with SeaSAT briefly, and continuing with ERS-1, ERS-2, JERS-1, RadarSAT-1, and ENVISAT, there has been over twenty five years of research and development in the exploitation of repeat pass interferometric data.

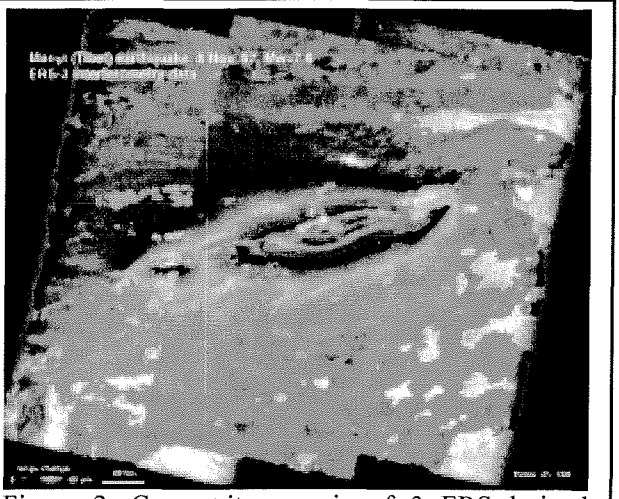

Figure 2. Composite mosaic of 3 ERS-derived interferograms, representing surface deformation from before to after the 1997 Manyi earthquake in Tibet [7]. Color represents change of the position of the surface projected into the radar line-of-sight direction. The color wheel from blue through yellow and magenta back to blue represents a relative change in range of 60 cm. (Figure courtesy G. Peltzer, JPL)

II. Techniques

An interferogram from two SAR images will be sensitive to only the component of surface change along the common radar line of sight. In order to obtain 3-dimensional displacement measurements, SAR measurements must be taken from different vantage points, e.g. combining right- and left-looking data acquisitions. Ascending and descending spaceborne acquisitions have been combined with an assumption of surface parallel flow to generate 3-dimensional velocities for ice caps and glaciers. Multiple SAR satellites become important when trying to completely describe surface change on a nearly continuous basis by providing flexibility in viewing geometry.

If the reflective surface is disturbed at wavelength or larger scales, then the spatially random elements in each image will have been altered, and the quality of the motion measurement is degraded, and can potentially be lost entirely. However, this "loss of coherence" is an important property in itself, indicating natural and man-made activity on the ground that may be of interest. This is known as "Coherent Change Detection" (CCD) in some communities.

While InSAR possibilities have been demonstrated using data from existing satellites, we are studying in detail spaceborne missions that would be revolutionary, providing breakthrough science. Such missions will require technology innovations such as active, accurate orbit control, ionospheric mitigation, and left-right pointing control, and novel aperture technologies that are large and electronically agile, but still affordable [6].

III. Systems

The science community is eagerly looking to NASA to implement a free-flying InSAR satellite. In 2000, NASA formed the Solid Earth Sciences Working Group (SESWG) to formulate a scientific observational program for NASA in the next decade [4]. SESWG deliberated for nearly 2 years and has issued a final report that calls for "InSAR everywhere, all the time." NSF established an earth science program called EarthScope that seeks to answer fundamental scientific questions about the structure of the Earth's crust, its evolution, and the hazards such evolution poses. In recent years, NASA and other agencies have become members of an interagency EarthScope community. There are four principal "observatories" that comprise EarthScope: A very large seismic array (USArray), a fault observatory at depth (SAFOD), a GPS/Strainmeter array over the plate boundary in North America (Plate Boundary Observatory), and a geodetic imaging system (InSAR). InSAR is an integral component of this scientific endeavor.

The solid earth science community is interested foremost in L-band InSAR measurements and in unprecedentedly short-period repeat imaging. While the resolution of the InSAR system does not meet traditional commercial and intelligence standards, the flood of high quality, easy-to-use time-series and interferometry are very likely to spawn new ideas in both arenas. For a modest sized aperture, say 30 m^2 in area and on the order of 15 m in length along the flight track, the swath size is limited to on the order of 120 km. This would imply a repeat period of roughly 24 days to completely cover the earth at a fixed incidence angle. Scientists would prefer more rapid repeat capability. This can be accomplished with this size aperture by placing the satellite in a faster repeat orbit, for example 8 days, and imaging multiple, in this case, 3 swaths on each successive pass. The effective repeat period for global mapping is still 24 days, but a rapidly deforming surface feature can be imaged every 8 days if necessary. This is a compromise. Clearly true rapid repeat would be most desirable, but that requires a large swath than is possible nominally with a small aperture.

Ultra-wide-swath SAR

Ultra-wide-swath mode is motivated by the solid-earth science objective of characterizing the physics and phenomenology of earthquakes and volcanoes. To meet this objective, rapid-repeat pass interferometric SAR data for measuring surface deformation time series are needed. For repeating orbits, a spacecraft must return to the same orbital location in Earth-fixed coordinates in an integer number of orbits. Clearly, shorter repeat periods are executed with fewer orbits, resulting in wider separation of ground tracks. As a further example to that described above, the ERS spacecraft has a repeat period of 35 days and a ground track separation of about 90 km. Shortening the repeat period would widen the ground track separation, preventing the ERS radar, with a swath size of about 100 km, from having global coverage. Figure 2 illustrates the effect this has on the ability to study large earthquakes. It over one month and observations on three separate ground tracks to cover the Manyi, Tibet earthquake, which broke along a fault segment over 200 km long [7]. Note that the deformation pattern is not continuous across the figure. This is because the deformation of the surface is measured only along the radar line of sight, which changes across the swath, and each of the ground track swaths contains the same set of line-of-sight angles. In other words, the right side of the left most image has a different line-of-sight vector from the left side of the central image. By waiting over one month to capture the deformation of the earthquake, all transient information, either before the earthquake or after, is lost. Clearly, a radar with a much wider swath could capture the entire earthquake in one image, and would be able to study weekly transients because the repeat period would be much faster. Such a wide swath system would be an important step in fulfilling NASA science needs for rapid repeat observations.

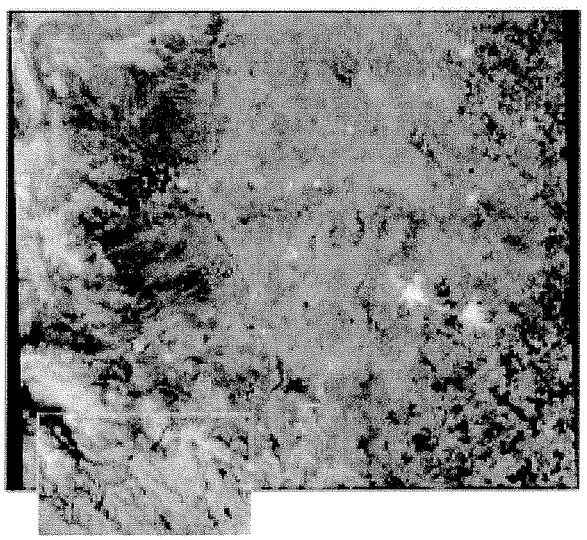

Figure 3: L-band ScanSAR image of Midland/Odessa region of West Texas (245 km x 225 km) as an illustration of very-wide-swath mapping. To attain such wide swaths, the ScanSAR technique was used. A mode of operation better suited to interferometric applications would be to lengthen the aperture and narrow it in elevation to allow a wider listening window without range ambiguities. The smaller inset image is a standard SIR-C image showing a portion of the same area, 100 km x 57 km, taken at a different time. The bright spots on the right side of the image are the cities of Odessa (left) and Midland, Texas The Pecos River runs from the top center to the bottom center of the image. Along the left side of the image are, from top to bottom, parts of the Guadalupe, Davis and Santiago Mountains. North is toward the upper right. Illumination for this L-band scene is from the top of the image. The beams were scanned from the top of the scene to the bottom, as the shuttle flew from left to right. Image and parts of caption from NASA/JPL http://photojournal.jpl.nasa.gov.

SIR-C demonstrated very wide swath mapping using the ScanSAR technique (Figure 3). In ScanSAR mapping, shortcomings in the size of the range swath imposed by a small antenna size and ambiguity limits are overcome by time-sharing the beam at several range swaths over the time of a synthetic aperture. A burst of pulses is transmitted at fixed elevation steering angle, followed by a burst at another elevation steering angle, and so forth until the desired range swath is covered [8]. This sequence of bursting is repeated continuously along track. Each burst is a fraction of the synthetic aperture time, and the total swath must be covered within a synthetic aperture time, so that a continuous map can be constructed.

Figure 3 gives a flavor for what can be done with the 2 m x 50 m dual-use system, though it is only half the expected swath coverage and it is a ScanSAR observation. ScanSAR mapping is not desirable for interferometry because the bursts in general must align in time from pass to pass. This constrains the observational system unnecessarily and complicates the processing severely [8]. Nonetheless, careful attention to the timing of the ScanSAR bursts will allow interferometric observations to be viable.

A preferred approach to wide swath mapping would be to increase the length of the aperture and reduce the elevation extent of the aperture. This allows a lower pulsing rate for the radar, a wider illumination swath, and therefore more swath width that can be recorded. The images can be continuous wide swath strips, allowing straightforward interferometric combinations of multiple data sets from a collection of orbit passes.

There are added benefits to increasing the length of the aperture. If the antenna and radar can be segmented into multiple phase centers, it is possible to observe ocean waves using along track interferometric techniques, and a long aperture gives greater sensitivity to slower moving currents. With more than two phase centers, a variety of along-track baselines can be reconstructed for tailored sensitivity to different velocity ranges.

More rapid repeat pass interferometry – Airborne platforms

Even with a very wide swath rapid repeat pass orbital

system, the most dynamic measurements cannot be sampled adequately with days to weeks separating the observations. For example, volcanoes in the eruption process are continuously deforming at a rapid rate, and repeat observations over an hour or less would be needed to fully characterize the dynamics of the eruption.

Airborne repeat pass InSAR is an exciting area of research and development that would enable these rapid repeat intervals, albeit difficult because of the technical challenges of flying a platform reliably for interferometry. The advent of SAR instruments on UAV platforms will bring about a new generation of multi-temporal and multi-spatial observations. The key to reliable interferometry is to minimize the decorrelating effects of differing imaging geometries. This amounts to maintaining small cross track baselines and baseline variability, and significant Doppler commonality among repeat pass data takes (or equivalently similar pointing directions from pass to pass). For moderate resolution L-band systems, the challenges are flying a repeatable controlled track to within 10 meters, and maintaining a fixed beam pointing direction while the aircraft dynamically changes its attitude in the wind to minimi interferometric correlation. Kinematic GPS solutions of position and velocity controlling the flight management system must be incorporated into the UAV avionics to maintain track. At L-band with a fairly sizable antenna on a UAV, it is difficult to gimbal an antenna. Thus, a phased array with beam-steering controlled by the attitude of the UAV is needed to actively steer the beam to fixed Doppler pointing.

IV. Applications

Some of the most compelling science and national benefits of repeat pass InSAR are:

Earthquakes, Volcanoes, and Ice:

One of the most compelling and widely acknowledged capabilities of InSAR is tracking the changes of the Earth's surface associated with earthquakes, volcanic activity, and the motions of glaciers and ice streams. These changes range from meters of motion during an earthquake or volcanic eruption to millimeters of change associated with the slow evolution of the tectonic plates or magma at depth. InSAR can measure millimeters of change over long periods of time, allowing scientists to capture the state of the Earth's crust at depth for assessing seismic or volcanic risk, or in the case of ice, to track the changes in flow and melt rates of ice as indicators of climate change.

Fluid (oil, gas, water) withdrawal:

Interferometry has been used to measure the cycle of withdrawal of oil and injection of water to free new oil from rock pores. The related subsidence and uplift has been measured with centimeter precision. Water withdrawal and recharge in aquifers is an important aspect of civil, military and humanitarian assessments of an area. Particularly in arid areas that rely on aquifer sources, knowledge of water usage is critical. Interferometry has been used to measure subsidence and uplift in several cities in the western US. These studies have led to increased awareness of the state of the soils in aquifers and aquitards. In some cases, pumping practices have been altered to preserve the ability of the aquifer to be replenished.

Tunneling:

Mining and tunneling for subterranean construction of, for example, a subway system, are known to cause observable deformation on the surface. Several papers have shown the capability of SAR interferometry to measure this deformation to the sub-centimeter level of accuracy[3,9]. Only the surface near the tunnel mouth is disrupted. Elsewhere the surface is untouched, so depending on the depth of the tunnel, the composition of the rock above it, and the tunnel's extent, deformation can be observed. By acquiring a series of images on a regular basis, the evolution of the tunnel system can be mapped from the changing deformation pattern and pattern of coherence loss near its mouth. The technique of using

Construction and Damage Assessment:

Disturbance of the reflective surface on the order of a radar wavelength (between 5-20 cm depending on the radar band) may still be detected through the loss of correlation and can provide a valuable indication of surface change of either natural or manmade origin. Examples include the detection of troop or equipment movement over unpaved roads or terrain. By detecting changes to the surface caused by vehicle or foot traffic, the time and location of the movement can be ascertained. Construction activities and stockpiling of material also change the surface resulting in a loss of correlation.

Flooding:

The extent of a river can be seen in radar imagery alone, and time-series analysis of rapid repeat L-band SAR data can track river changes from day to day. InSAR mapping in the Amazon has also shown flood stages. Floods typically evolve more rapidly than orbital repeat times, and a observation strategy employing satellites for week-scale change and airborne sensors for synoptic hourly views can be very useful for damage assessment and prediction.

Unstable dunes:

Dunes that are not anchored by vegetation are inherently unstable and can change shape rapidly after a wind-storm. Studies have shown that unstable dunes maintain their coherence over short intervals with no heavy weather, but totally lose coherence after a storm. Time-lapse analysis of interferometric observations can easily identify unstable dunes, allowing civil planners to track desertification trends over large areas, and military planners to accommodate these regions in their operations. Partially vegetated dunes have a more stable reflective surface. The characteristic patterns of sand dunes, such as barchans, yardangs, star patterns, and replication can be seen in the radar brightness image as well, further helping to characterize the sand surface.

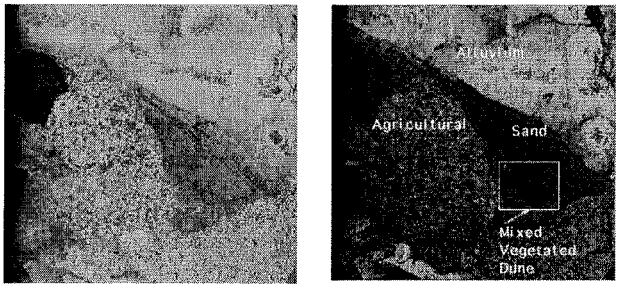

Figure 2. (left image) Correlation image in radar coordinates of Algodones Dunefield, CA, measuring the sameness of the two images acquired one day apart used to form a radar interferogram. Blue color denotes low correlation, purple moderate correlation, and yellow-green high correlation. Salton Sea decorrelates because water changes from one second to the next. Some agricultural fields and dune areas decorrelate from over the one day period. Mountains decorrelate from geometric effects rather than temporal effects. Dunes remain well correlated in general over one day. (right) Five month correlation map showing large decorrelation in the unvegetated Algodones dunes but significantly less in much of the vegetated area to the west (in box)

Planetary Applications:

Repeat pass interferometric techniques are relevant in planetary science as well. While the lunar and Martian surfaces are for the most part quite static, interferometry using long wavelengths, in the decimeter range, can provide topography of the surface and near subsurface. At moons that are thought to be actively deforming, such as the Galilean satellites of Jupiter theorized to tidally distort up to 30 m every three days, repeat-pass interferometry is a natural observational tool, and potentially the only way to measure small scale changes remotely.

V. Conclusions

While a number of exciting international SAR data sets exist that are suitable for repeat-pass interferometric observations, no civilian science mission or program has been optimized exclusively for repeat-pass interferometric science applications. Given the wide dynamic range of spatial and temporal scales of processes on Earth, a dedicated interferometric observing program would open a new window on the dynamic Earth. Low-frequency (such as L-band) sensors will reduce sensitivity to very small scale changes in the surface. Orbit SAR with very wide swaths and area revisit rates on the order of days, and suborbital SAR targeted for very rapid repeat on the order of hours, can cover a range of temporal evolution spanning from hours to decades, often globally. To achieve wide swaths, radar systems will evolve to either ScanSAR interferometric systems, similar to SRTM but that operate in repeat pass, or to longer antennas narrower in elevation that will allow a wider imaging swath (or perhaps both). Multiple phase centers within this long aperture can be useful for along-track interferometric observations of oceans and other meter-second velocity scale objects. Similarly, for airborne SAR systems with persistence, UAV platforms with accurately controllable flight management systems and radars with beam steering antennas will enable observation of a new class of geophysical events and a unique capability for disaster monitoring.

Acknowledgment

This work was performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

References

[1] NASA Earth Science Enterprise Strategic Plan. www.earth.hq.nasa.gov (2000)

[2] Evans, D.L., J.J. Plaut, E. R. Stofan. "Overview of the Spaceborne Imaging Radar-C/X-Band Synthetic Aperture Radar (SIR-C/X-SAR) missions," *Remote Sensing Env.*, 59(2) 135-140, (1997)

[3] Rosen, P. A., S. Hensley, F. Li, I. Joughin, S. Madsen, D. Goldstein (2000). Synthetic Aperture Radar Interferometry, Proc. IEEE, 88(3), 333-382.

[4] NASA Solid Earth Science Working Group Report (2002)

[5] Peltzer, G., P. Rosen, F. Rogez K. Hudnut (1998). Poroelastic rebound along the Landers 1992 earthquake surface rupture, J. Geophys. Res. 103(B12), 30,131-30,145.

[6] Rosen, P. A., M.E. Davis. "A Joint Space-Borne Radar Technology Demonstration Mission for NASA and the Air Force," Proc. 2003 IEEE Aerospace Conference, Big Sky MT (March 2003)

[7] Peltzer, G., F. Crampe, G. King. "Evidence of non-linear elasticity of the crust from the Mw7.6 Manyi (Tibet) earthquake," *Science,* 286, 272-276 (1999).

[8] Lanari, R., S. Hensley, and P. Rosen. Chirp-Z transform based SPECAN approach for phase-preserving ScanSAR image generation, IEE Proc., Radar, Sonar, Navig., 145(5), 254-261 (1998).

[9] M. Tesauro, P. Berardino, R. Lanari, E. Sansosti, G. Fornaro, G. Franceschetti (2000). Urban subsidence inside the city of Napoli (Italy) observed by satellite radar interferometry, Geophys. Res. Lett., 27(13) 1961-1964.

[10] Rosen, P. A., S. Hensley, H. A. Zebker, F. H. Webb, E. J. Fielding (1996). Surface deformation and coherence measurements of Kilauea Volcano, Hawaii from SIR-C radar interferometry. J. Geophys. Res., 101, 23,109-23,125.