Mapping Small Elevation Changes Over Large Areas: Differential Radar Interferometry

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A technique that uses synthetic aperture radar (SAR) images to measure very small (1 cm or less) surface motions with good resolution (10 m) over large swaths (50 km) is presented along with experimental results. The method could be used for accurate measurements of many geophysical phenomena, including swelling and buckling in fault zones, residual displacements from seismic events, and pre-volcanic swelling. The method is based on SAR interferometry, where two images are made of a scene by simultaneously flying two physically separated antennas. Then the phases of corresponding pixels are differenced, and altitude formation is deduced from some simple computation and image rectification. It is also possible to use one antenna flown twice over the same scene; then, if the second flight exactly duplicates the track of the first, an interesting possibility occurs. There would be no phase changes between the images at all unless there was a physical change in the scene, such as ground swelling, that would alter the distance from some resolution element to the antenna. Since the phase changes all occur at the short carrier wavelength, the basic limitation on sensitivity is only the phase noise in the system. When the two imaging passes are made from flight tracks that are separated (which is the case with the Seasat images used here), it is no longer possible to distinguish surface changes from the parallax caused by topography. However, with some additional computation, a third image made at some other baseline may be used to remove the topography and leave only the surface changes. This method was applied using Seasat data to an imaging site in Imperial Valley, California, where motion effects were observed that were ascribed to the expansion of water-absorbing clays. Phase change images of this area are shown, along with associated ground truth about the presence of water. Problems with the technique are explored, along with a discussion of future experimental possibilities on upcoming SAR missions like Earth Observing System (EOS), Earth Resources Satellite (ERS 1), SIR-C, and the Venus imaging radar, Magellan.

1. INTRODUCTION

It is possible to use multiple synthetic aperture radar (SAR) images to detect very small (1 cm or less) elevation changes over very large areas (50 km). The extreme sensitivity of this technique to altitude changes, high spatial resolution (typically 10 m), and broad swath coverage means it could be used to make extensive, accurate measurements of geophysical phenomena, including heaving and buckling in fault zones, plate motions, residual displacements from seismic events, and motion from pre-volcanic swelling.

In an airborne or spaceborne synthetic aperture radar, microwaves illuminate the terrain below the platform, and the echoes scattered from the surface are collected. Subsequent signal processing performed on the echoes produces an image of the scene, where each picture element (pixel) contains amplitude and phase information. A display of the amplitude information produces the familiar SAR images, which look very similar to photographs. It is also possible to use the phase information to make a SAR interferometer. In a SAR interferometer, two images are made of the same scene by two separated antennas. The antennas may be on the same platform, or the same antenna may be flown twice over a scene. If the antennas are separated in the "azimuth" direction, parallel to the line of flight, motions on the surface such as ocean currents may be measured. If the antennas are separated in the "range" direction, perpendicular to the line of flight, altitude information about the surface may be deduced. Both methods require registering the two images, typically accomplished by "stretching" (resampling) one image to make it overlay the other accurately. Then the phases corresponding to each pixel are calculated and differenced, resulting in an interferogram. Phase unwrapping and geometric rectification then yield the desired motions or altitudes. In the extension of SAR interferometry presented here, two interferograms are made from three (or more) SAR images of a scene taken at different times. After some processing, the interferogram phases are again differenced, resulting in a third interferogram, dubbed a "double-difference interferogram." This final step removes phase changes due to topography, leaving a new phase image with nonzero phases only in areas where the surface had been disturbed between the times of the observations. These phases can be used to deduce the amount of surface motion that occurred.

In the present work, three Seasat observations of an area in the Imperial Valley, California were used to make two interferograms and then a double-difference interferogram, which showed clear areas of phase change. These changes are attributed to swelling of water-absorbing clays in the scene.

2. SAR INTERFEROMETRY: REVIEW OF THEORY

Referring to Figure 1, the range from the antenna to point on the ground is denoted ρ for the first observation and ρ' for the second. The phases associated with these ranges are

\[ \phi = 4 \pi \rho \lambda \]  

where \( \lambda \) is the radar system wavelength.

For the present discussion, these are taken to be the phases associated with the pixels in the final images. This is not necessarily true since phase errors can occur in process-

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ing; however, as long as identical processing is performed to make all the images, the same errors are introduced everywhere, and constitute only a global phase constant that will disappear in the later phase differencing.

In order for the two sets of phases associated with a number of pixels to be mutually coherent, there are restrictions on the distance between antennas. Specifically, the observations must be made close enough together that the speckle in the images does not change substantially, requiring both observations to be within the effective beam width of a reradiating resolution element. This is discussed in detail elsewhere [Gabriel and Goldstein, 1988]. For the Seasat experiment discussed in this paper, the maximum allowable baseline is about 4 km, and the largest baseline used was about 1600 m.

Usually, two images of the same scene cannot be overlaid directly, especially when they are produced from serial observations. Typically, the flight paths will be slightly divergent, making it necessary to resample one image to remove a linear shear. Then one image may be multiplied by the complex conjugate of the other, resulting in a phase difference image, or interferogram.

Each of the phases from the original images is measured to the nearest multiple of $2\pi$. Thus two targets will appear at the same phase if their ranges differ by an integral number of wavelengths. Similarly, in an interferogram, targets at different altitudes will appear at the same phase. It is necessary to find the multiples of $2\pi$ that disappeared or were “wrapped.” The general approach is to start at some location in the interferogram where the phases have little noise, producing fringes that are bright and clear. Then the adjacent pixel’s phase differences are integrated in contours, and $2\pi$ is added to them each time they become one multiple of $2\pi$ greater than the seed. Problems arise where the image is noisy, or on steep slopes where the phase becomes noiselike because there are many resolution elements at the same range. This can lead to phase ambiguities for adjacent nonnoisy areas; this problem is treated in detail elsewhere [Goldstein et al., 1988].

The above procedures are necessary to generate all SAR interferograms. Subsequent processing, however, depends on the antenna configuration. For two antennas flying together, but separated in range [Zebker and Goldstein, 1986], the derivation of topography depends on estimating the small components of the baseline (line connecting the antennas) that are not perpendicular to the line of flight, and then applying various geometric rectifications. Images from two coflying antennas separated in azimuth can be processed to compensate for pitch, yaw, and roll of the platform, and will then yield estimates of real-time surface motions such as ocean currents [Goldstein and Zebker, 1987]. If the images are made from repeated serial observations, height sensitivity is limited by phase errors originating from speckle effects, which places limits on the acceptable geometries [Li and Goldstein, 1988]. If the orbits are at an angle that is sufficiently large to cause a linear phase shift along the image, a type of interferometric mapping is possible but extensive computation is necessary to derive altitudes [Gabriel and Goldstein, 1988].

In this work, two interferograms were made from three passes of the Seasat synthetic aperture radar separated by baselines of approximately 159 m and 1636 m. (If the flight path had repeated itself exactly, only two observations would have been necessary to detect changes; however, with a nonzero baseline, surface changes become scrambled with the topographic information, necessitating a third observation.) The observations spanned 12 days in 1978. Phase unwrapping was performed, yielding two unrectified topographic maps spanning different periods of time. The phases in these maps were differenced, removing the effects of topography; any residual phase changes then represented actual gross (larger than a pixel) physical motions or other changes of the surface. Local (size less than a pixel) surface disruptions caused the speckle patterns of the surface to change, resulting in noisy phases.

3. Theory of Multiple-Pass Differential Interferometry

In this section, a general theory of surface change detection from multiple orbits is derived; it may be bypassed by readers not interested in the mathematics without substantial loss of continuity.

Figure 2 indicates the geometry associated with three serial observations of a scene. The phase associated with a given resolution element (rezel) is given by (1), and the phase difference obtained from the first two observations of that rezel is

$$\Delta \phi_{12} = (4\pi/\lambda)p \cos \theta$$

Similarly, the first and third observations yield

$$\Delta \phi_{13} = (4\pi/\lambda)q \cos (\theta + \alpha)$$

Fig. 2. Geometry of multiple-observation interferometry. Three observations of a scene are made from three locations separated by baselines $p$, $q$, and $r$. 
parallel, the ellipse in Figure 3 will be slightly different at range $21^\circ < \theta < 23^\circ$ and $\alpha = 180^\circ$, so the ellipse almost tilted at $45^\circ$.

Note that $\Delta \phi_{12}/p$ and $\Delta \phi_{13}/q$ are the coordinates corresponding to the parametric equations of an ellipse (Figure 3). In the case of the Seasat data used here, $\theta$ is confined to the narrow range $21^\circ < \theta < 23^\circ$ and $\alpha = 180^\circ$, so the ellipse almost degenerates into a straight line. If the orbits are not exactly parallel, the ellipse in Figure 3 will be slightly different at different locations in azimuth.

The two phases $\Delta \phi_{12}$ and $\Delta \phi_{13}$ cannot be differenced directly. Unless $p/q$ (or $q/p$) is an integer, the phase discontinuities in the two interferograms will not occur in the same places, so each interferogram must be unwrapped, as described in section 2. Then $\Delta \phi_{12}$ and $\Delta \phi_{13}$ are plotted against each other, as in Figure 3. Disturbances of the surface then show up as deviations of the points from the best-fit ellipse. Where the surface has been heavily disturbed (changes smaller than a pixel), as from plowing or a landslide, the phase sets have no relationship to each other. The resulting plot shows only randomly scattered points.

However, where many resels have been affected the same way (changes larger than a pixel), such as from an earthquake displacement, a regular deviation from the ellipse will occur. The expression

$$\Phi = \Delta \phi_{12}/q - \Delta \phi_{13}/p + c$$

is used to estimate the amount of phase deviation, where $p$, $q$, and $c$ are taken from the best-fit ellipse for all of the data. Equation (4) highlights an ambiguity which cannot be eliminated using radar data alone. Motion of an area giving rise to changes in the phases of the associated pixels may have occurred between observations 1 and 2 (thereby changing $\Delta \phi_{12}$) or may have occurred in the opposite direction between observations 1 and 3 (thereby changing $\Delta \phi_{13}$). In general, either a fourth observation or some independent measurement (such as ground truth or a digital topographic map) must be had to resolve this problem completely. There are, as discussed below, special cases where this requirement can be relaxed.

The sensitivity of SAR interferometry depends on the geometry of observation. In the best type of experiment the baseline would be zero, only two observations would be necessary, and the sensitivity is limited only by the systemic noise in the radar. For a 10-dB snr the phase of a four-look image, averaged over four pixels, can be measured to about $5^\circ$. For single-difference interferograms with nonzero baseline, the phase sensitivity can be calculated as a complicated function of baseline length and image snr [Li and Goldstein, 1988]. Double-difference interferograms are even more complex, since they are formed by scaling and then combining two single-difference interferograms. There are two possibilities that have different sensitivities. A phase change (and associated noise) occurring in the first interval would be scaled by $p/q$ or 1; occurring in the other, it would be scaled by 1 or $q/p$. The resulting combined phase noise is in general some intermediate value. In the present case ($\lambda = 24$ cm) the two noise levels ($1 \sigma$) are 3 cm and 0.3 cm, consistent with the observed phase noise in the double-difference interferogram, which is about 1 cm. Sensitivity can be increased at the expense of spatial resolution by averaging over pixels.

This interferometric SAR technique measures only one-dimensional changes along the line of sight. If other sets of interferograms can be made along other (nonparallel) directions, surface motions may be recovered in their entirety by resolving the observations into their vector components.

4. IMAGE PROCESSING

The Seasat L band SAR, which flew in 1978, had some orbits that met the criteria of section 2 for interferometry. A full description of the Seasat radar and correlator may be found elsewhere [Ulaby et al., 1981] and is not repeated here. The area in the Imperial Valley of southern California, used as the site of the experiment is shown in Figure 4.

In correlating images from the raw data, it was necessary to be sure that the azimuth focusing was identical for each of the three images, or errors would have been introduced into the phases, with a resulting loss of phase coherence. This was accomplished by performing a standard focusing algorithm on the first image; the resulting azimuth chirp rates were then used in the other two images as well.

The Seasat orbits in question were not exactly parallel, resulting in a very slight shearing of the images, which meant they could not be overlaid exactly. The second and third images were resampled using a procedure described elsewhere [Gabriel and Goldstein, 1988] to correct this, and two interferograms were formed from the triplet; one of them is shown in Plates 1a and 1b, which exhibits local regions (individual fields) of both noisy phases and shifted phases. The phase contours in Plate 1 are fairly straight because the Imperial Valley is extremely flat. In this particular image the phase shifts associated with surface changes are easily distinguished, because of both the regularity of the adjoining fringes, and the association of visible shifts with the field boundaries in one (but not both) of the interferograms. This removes the ambiguity of (4) in this image but does not apply in general; effectively, the extra observation needed was synthesized by equating the Imperial Valley to a plane.

The phase of each interferogram was then unwrapped and scaled by the baseline ratio, as described above, and the interferogram phases were differenced, producing a new image, dubbed a “double-difference interferogram.” The slight divergence between orbits also produced a small phase gradient across this image and was corrected by fitting a plane to the resulting phase difference map, which is equivalent to finding the small changes in the constants $p$, $q$, and $c$ mentioned above. Thus any linear phase errors in the along-track or the cross-track directions are removed. The consequence of this procedure is that changes within a given
Plate 1a. Single-difference interferogram of Imperial Valley. Phases are presented as color and are shown. The fields with noisy phases had apparently been plowed between observations, resulting in a loss of phase coherence.
Plate 1b. As for Plate 1a, but showing only the phase colors.
Plate 2. Double-difference interferogram of the Imperial Valley. Two interferograms like Plate 1 were differenced to generate this image, which shows changes that occurred between the observations. The dominant yellow color represents zero phase change, as evidenced by the very bright yellow spot on the left center, which is a radio tower. Black areas represent the loss of phase coherence, where the noisy phases of Plate 1 have been left out. The various colors, from blue to red to green, indicate small motions (2–3 cm) of the fields from swelling or shrinkage associated with watering.
image may only be interpreted in terms of surface motion; in other words, comparing difference interferograms from different sets of orbits must allow for different phase gradients in each image.

The final double-difference interferogram is shown in Plate 2.

5. DISCUSSION OF RESULTS

The Imperial Valley of California is an extremely busy agricultural area, having many active fields (Figure 4) that are constantly cultivated. If a field is plowed or harvested, its surface changes, and the speckle associated with the surface changes. Thus two images of a field plowed between observations would yield noiselike phase characteristics when they were interfered as the signals are no longer coherent. Such is the case with several of the fields in the interferogram of Plate 1: their relative phases do not correlate. The fact that the noiselike phases follow field boundaries is conclusive evidence that a physical change occurred; the effect is not from some systematic error in the experiment.
which case the large dielectric constant of water might cause a propagation delay through the wet soil. However, it seems unlikely that phase coherence would be maintained if subsurface scattering was occurring at different depths. A better explanation is that the soils in the area are composed of hydroscopic clays and salts that expand when wet [Muffler and Doe, 1968; R. G. Blom, private communication, 1988].

Thus the phase changes observed probably result from expansion of an entire field when it was watered or contraction when it dried out. While such motions would not be large, the sensitivity of the method is so high that it could be visible.

Each field served by the Imperial Valley Water District has one or more gates that allow in water from one of the surrounding canals. It was possible to collect some ground truth, consisting of 10-year-old watering records from the area. Records exist for approximately 85% of the fields in Plate 2 that exhibited a significant phase (color) change. In addition, at each such site, records were sought for at least two nearby fields that had no phase change (fields that are yellow in Plate 2).

The watering records were interpreted using the model presented in Figure 5, which shows the motion of the surface resulting from watering and indicates schematically the changes in propagation path associated with the motion. The water was assumed to be absorbed (causing swelling) over a period of a few hours, and to evaporate (causing shrinkage) over a few days. Based on the watering records, which gave the date (but not, unfortunately, the hour) and amount of water supplied to each field, estimates of the amount of moisture present were made for each of 52 sites in the image. For sites where the watering occurred on the same day as the observation, estimates were made to account for whether observation occurred before or after watering. Then (4) was used to estimate the expected phase change, which was classified into seven categories from strongly negative through zero to strongly positive. Each of the 52 sites was similarly assigned to one of seven categories of color, from green (negative) to yellow (zero) to red (positive). The two lists were then compared, with one color category allowed for errors.

In 48 cases, there was agreement between the theory and the experiment; in two cases the result was ambiguous because the color was too noisy for clear classification. In the final two cases the color disagreed with what was predicted, which was attributed to a clerical error in looking up the watering records.

6. Applications

It is not hard to think of numerous applications for the type of instrument demonstrated, which can measure accurately extremely small changes in terrain over the large swaths associated with SAR imaging, especially since the sensor can work at night and through clouds or precipitation. Loss of phase coherence over local portions of an image could be used to find areas of disruption, as from landslides or plowing.

The possibilities include accurate measurement of preseismic swelling and buckling, and residual displacements from seismic events; the Palmdale bulge controversy [Savage et al., 1981; Castle et al., 1976] could have been definitively settled. This technique could be used repeatedly from such an instrument as the Earth Resources Satellite (ERS 1) or the
Earth Observing System (EOS) in the 1990s over an active fault zone, such as the San Andreas Fault or Parkfield, to monitor long-term motion, possibly resulting in earthquake predictions. In the western United States, there are many areas remote from the San Andreas fault that are distorting at rates comparable to the estimated 5 cm/yr motion of the Pacific and North American plates [Jordan and Minster, 1988]. These motions should be detectable with a reasonable amount of time between observations. Preeruptive swelling in volcanic areas could be quantitatively measured. Monitoring glacier motion, even in dark arctic winters, is possible, and swelling of large-scale structures (like mountains) from diurnal heating or Earth tides are other possibilities. Finally, there is the possibility of making the above geodynamic measurements on Venus using the Magellan SAR.

7. CONCLUSIONS

A new technique has been demonstrated which uses interferometric SAR methods to measure very small (1 cm) motions of terrain with high (10 m) resolution over large (50 km) swaths. There is every reason to believe that the accuracy can be improved, since it is only fundamentally limited by the amount of phase noise present in the radar. Other fundamental limitations are imposed by the requirements of spatial coherence. A demonstration of the technique was given for a site in the Imperial Valley of California, where water-absorbing clays in the soils caused ground swelling and shrinking.

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References


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