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Surface deformation and coherence measurements of Kilauea Volcano, Hawaii, from SIR-C radar interferometry

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Abstract. The shuttle imaging radar C/X synthetic aperture radar (SIR-C/X-SAR) radar on board the space shuttle *Endeavor* imaged Kilauea Volcano, Hawaii, in April and October 1994 for the purpose of measuring active surface deformation by the methods of repeat-pass differential radar interferometry. Observations at 24 cm (L band) and 5.6 cm (C band) wavelengths were reduced to interferograms showing apparent surface deformation over the 6-month interval and over a succession of 1-day intervals in October. A statistically significant local phase signature in the 6-month interferogram is coincident with the Pu'u O'o lava vent. Interpreted as deformation, the signal implies centimeter-scale deflation in an area several kilometers wide surrounding the vent. Peak deflation is roughly 14 cm if the deformation is purely vertical, centered southward of the Pu'u O'o caldera. Delays in the radar signal phase induced by atmospheric refractivity anomalies introduce spurious apparent deformation signatures, at the level of 12 cm peak-to-peak in the radar line-of-sight direction. Though the phase observations are suggestive of the wide-area deformation measured by Global Positioning System (GPS) methods, the atmospheric effects are large enough to limit the interpretation of the result. It is difficult to characterize centimeter-scale deformations spatially distributed over tens of kilometers using differential interferometry without supporting simultaneous, spatially distributed measurements of refractivity along the radar line of sight. Studies of the interferometric correlation of images acquired at different times show that L band is far superior to C band in the vegetated areas, even when the observations are separated by only 1 day. These results imply longer wavelength instruments are more appropriate for studying surfaces by repeat-pass observations.

Introduction

SIR-C Background

In April and again in October 1994 the space shuttle *Endeavor* mapped the Earth with the Space Radar Laboratory (SRL), composed of shuttle imaging radar C (SIR-C), a dual-frequency, four-polarization radar instrument plus the single-frequency and polarization X band synthetic aperture radar (X-SAR). The imaging radar suite measured the surface radar backscatter intensity and coherent backscatter phase at fine spatial resolution over the radar swath. Most of the radar investigations interpreted the multispectral, multipolarization measurements provided by SRL to map biomass, soil moisture, terrain types, and natural hazards. Many of these results are reported elsewhere in this issue.

The SIR-C spaceborne radar interferometry demonstration has literally added a new dimension to the more conventional imaging radar applications. In radar interferometry, multiple images of an area acquired on different orbits are combined coherently to obtain estimates of the surface topography and any change to the topography that occurred between the observations. Previous studies with airborne and spaceborne platforms have demonstrated the high level of precision and automation possible for topographic mapping applications afforded by interferometry [*Zebker and Goldstein*, 1986; *Zebker et al.*, 1992]. Spaceborne radars on the ERS 1 and JERS 1 satellites have been used for surface deformation studies, including coseismic deformation [*Massonnet et al.*, 1993; *Zebker et al.*, 1994b], volcanic deflation [*Massonnet et al.*, 1995], and glacier motion [*Goldstein et al.*, 1993] with millimeter-scale precision.

Interferometry requires that the spatial orbital separation, or "baseline," between the two observations be small. This small baseline was achieved using two very different geometries. Six-month temporal separation radar interferometry, which we emphasize in this report, was implemented by repeating some April orbit tracks during the October mission. Interferometric data were also acquired with a 1-day repeat period during the second mission under similar orbital constraints. Six-month interferometry has the potential for surface deformation measurements, while 1-day interferometry can be used for certain topographic mapping, coherence, and glacier motion studies.

Preflight uncertainty in orbit knowledge limited the scope of planned interferometry experiments. Mission planners adopted a conservative approach for orbit maintenance, aiming for zero baseline. In fact, during SRL 2 in October, shuttle engineers were very nearly able to reach their target, repeating orbits within a tube less than 200 m in radius. As a result, most of the interferometry orbit pairs form baselines too small for

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Table 1. SIR-C Radar System Parameters for Kilauea Observations

Radar Parameter	L band	C band
Frequency, GHz	1.240	5.285
Wavelength, m	0.2422	0.05656
Range bandwidth,[a] MHz	20	20
Peak transmit power, W	6000	3000
System noise temperature, K	1100	1300
Pulse repetition rate	1250–1850	1250–1850
Antenna dimensions, m	12 by 2.9	12 by 0.7
Antenna elevation beam width	5°	5°
Critical baseline length, m	4000	935
Satellite altitude, km	215	215
Look angle	55°	55°
Ground range swath,[b] km	42	42

[a]Value is 40 MHz for 1-day repeat orbit observations.
[b]Value is 21 km for 1-day repeat orbit observations.

accurate topographic mapping but well suited to surface deformation studies. Table 1 summarizes the characteristics of the missions relevant to interferometry.

Two of the most rapidly deforming sites in the world were targeted for 6-month interferometry experiments: Kilauea, Hawaii, and Long Valley, California. Rates from 2 to 10 cm/yr have been measured at these sites, affording an opportunity to observe an interferometric signature through the noise. This paper describes the analysis of the Kilauea experiment. Figure 1 illustrates the imaging swaths at Kilauea in map projection.

Motivation I: GPS Measurements of Deformation

The Kilauea volcano sits on the southeast flank of the island of Hawaii between Mauna Loa volcano and the sea. Kilauea has been active more or less continuously since 1983 with sporadic eruptions from the Pu'u O'o and Kupaianaha vents. Shallow magma reservoirs below the surface fill and empty over time, causing surface deformation. Dikes connecting subsurface chambers and the surface can form, causing eruptions. Kilauea's motion is well monitored by a (mobile) Global Positioning System (GPS) network. Displacement rates as high as 10 cm/yr have been measured (see Figure 2), along the coast seaward of the palis (the Hawaiian term for cliff).

Kilauea serves as a good demonstration site because Kilauea's motions have been well mapped by GPS and the deformation rates are relatively high. Eruption prediction is not the primary motivation for studying the site, as geologists have anticipated eruptive events by monitoring ground movements and seismicity.

Motivation II: Differential Interferometry Successes in the Past

Differential interferometry, a technique by which surface deformation is measured, is a powerful method for obtaining the displacement in the direction of the radar line of sight with millimeter-scale precision, at meter-scale resolution, and over kilometer-scale areas. A variety of deformation signatures have been mapped by this method, including millimeter-scale ground motion in agricultural fields [*Gabriel et al.*, 1989], meter-scale ice stream motion in Antarctica [*Goldstein et al.*, 1993], centimeter- to meter-scale coseismic displacements [*Massonnet et al.*, 1993; *Zebker et al.*, 1994b; *Peltzer et al.*, 1994; *Peltzer and Rosen*, 1995; *Massonnet and Feige*, 1995], and possible centimeter-scale volcanic deflation [*Massonnet et al.*, 1995]. Detailed analysis of the deformation signatures of both the 1992 Landers earthquake [*Peltzer et al.*, 1994] and the 1993 $M = 6.1$ Eureka Valley earthquake [*Peltzer and Rosen*, 1995] shows that, in addition to the overall consistency with standard geodetic measurements, the fine resolution and spatial coverage can provide insight into the slip mechanism that is unattainable from the seismic record, with or without a dense GPS network in place.

The SIR-C data are superior for interferometric studies in many respects to other SAR data, especially over Kilauea. SIR-C acquired imagery at two frequencies simultaneously, allowing direct observation of frequency-diverse scattering effects. Also the low orbital altitude and high transmit signal power give a very clean signal. ERS 1 data cannot presently be collected over Hawaii because Hawaii does not lie within range of an ERS ground receiving station. JERS 1 data are difficult to acquire for interferometry applications because coverage is limited and few repeat-pass images have sufficiently small baselines. JERS also suffers from a low signal level because the radar transmitter on board the spacecraft must be operated at a power level reduced from its design specification for technical reasons. Thus the SIR-C experiments contain fundamentally new observations that expand understanding of the strengths and limitations of repeat-pass interferometry.

Observations and Data Reduction

Interferometer Equations

The theory of differential interferometry has been presented a number of times [e.g., *Gabriel et al.*, 1989; *Zebker et al.*,

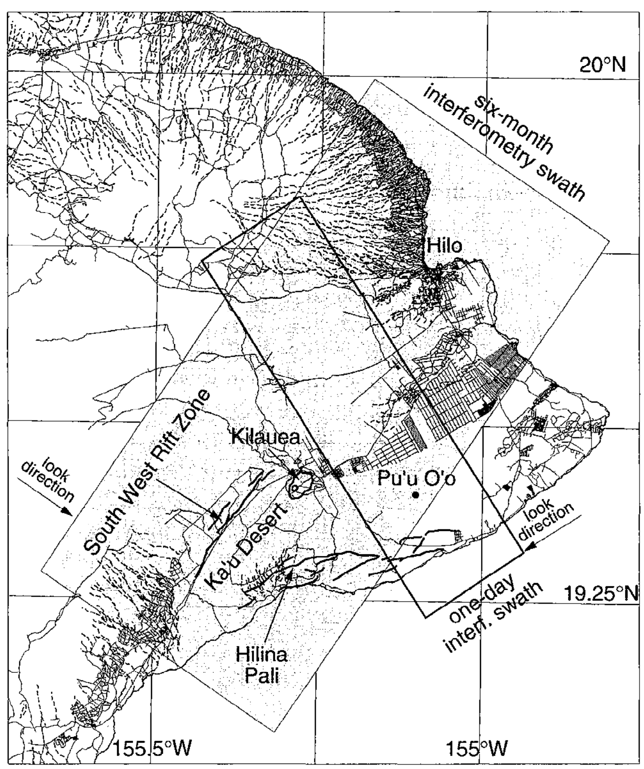

Figure 1. SIR-C imaging geometry of Kilauea, Hawaii. At 1420 UT on April 13 and October 4, 1994, SIR-C mapped the 50-km swath shaded in gray for 6-month surface deformation studies using radar interferometry. At 2140 UT on October 7–10, 1994, SIR-C mapped the 25-km crossing swath for studies of active lava flows. The abbreviation Ku marks the Kupaianaha vent.

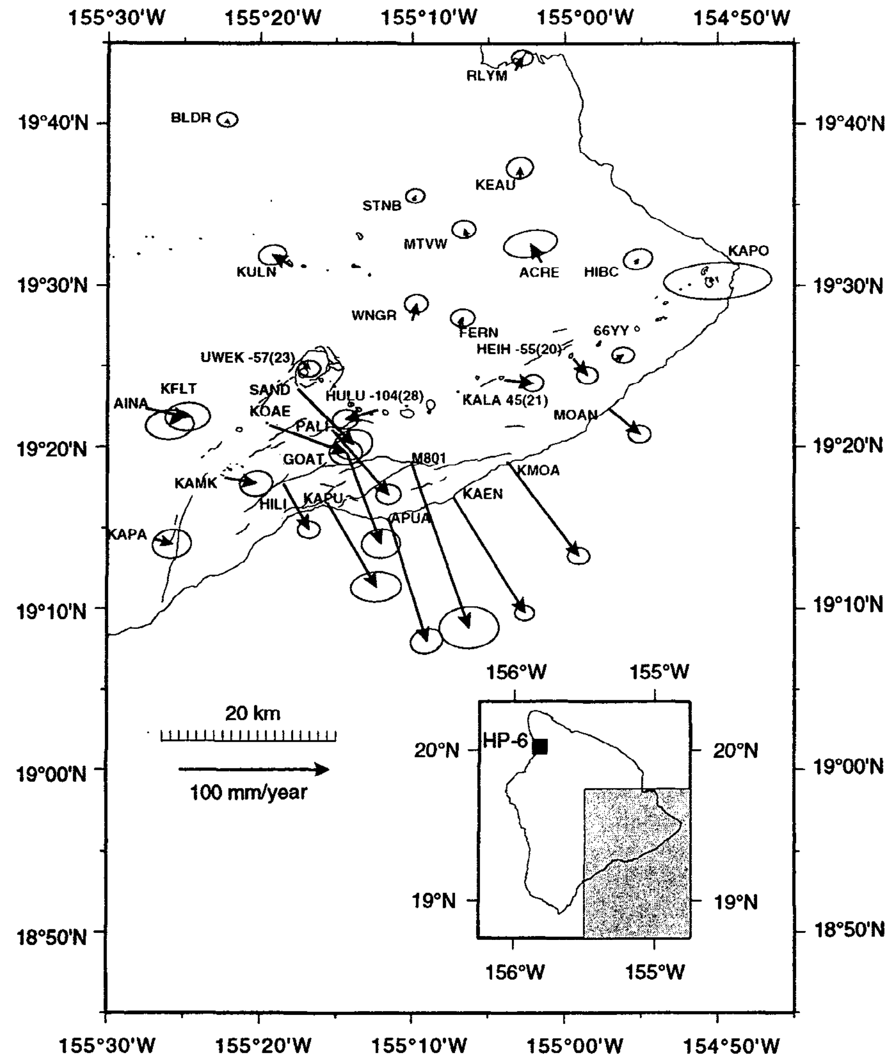

Figure 2. GPS measurements of surface deformation (reprinted from *Owen et al.* [1995]. Copyright 1995, American Association for the Advancement of Science.) The secular rate of deformation is as high as 10 cm/yr near Hilina Pali.

1994b], but certain relations are important to state here to support interpretation of the measurements.

The two imaging radars depicted in Figure 3a separated by the "baseline vector" **B** are in motion perpendicular to the page, and represent the SRL platform nearly repeating its track. The phase at each point in a radar image is the sum of the backscatter phase ϕ_{bi} and the propagation phase $\phi_{pi} = -(4\pi/\lambda)r_i$, where r_i is the range from antenna i to the imaged point. For two radars imaging a scene at the same frequency and with similar viewing geometry, the backscatter phase will be nearly equal: $\phi_{b1} \approx \phi_{b2}$. Under these assumptions, the phase difference between the two images at a given point is

$$\Delta\phi = \phi_1 - \phi_2 = -\frac{4\pi}{\lambda}(r_1 - r_2) \tag{1}$$

For spaceborne geometries, where $|\mathbf{B}| \ll r$, we may write

$$\Delta\phi = -\frac{4\pi}{\lambda}\mathbf{B}\cdot\mathbf{l} = -\frac{4\pi}{\lambda}B\sin(\theta - \alpha) \tag{2}$$

where **l** is a unit vector in the look direction. In words, the phase difference is proportional to the component of **B** in the look direction, $B_\parallel = B\sin(\theta - \alpha)$. This is the parallel ray approximation used by *Zebker and Goldstein* [1986].

To see how this phase relates to topography, consider a surface devoid of local topography. Then,

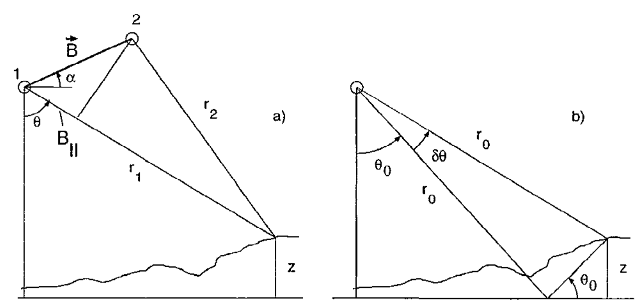

Figure 3. Interferometric geometry. (a) Two apertures separated by a baseline **B** are flying into the paper imaging a swath on the ground. For SIR-C, apertures represent a single antenna, nearly repeating its orbit track. (b) Conventions in linearizing the interferometer equations.

$$\Delta\phi_0 = -\frac{4\pi}{\lambda} B \sin(\theta_0 - \alpha) \quad (3)$$

where θ_0 is the look angle to a given pixel. If topography is present, the look angle for a given range will be altered by $\delta\theta$ as illustrated in Figure 3b:

$$\Delta\phi = -\frac{4\pi}{\lambda} B \sin(\theta_0 + \delta\theta + \alpha) \quad (4)$$

The "flattened" phase difference, formed by removing flat-Earth phase

$$\Delta\phi_{\text{flat}} = \Delta\phi - \Delta\phi_0 \approx -\frac{4\pi}{\lambda} B \cos(\theta_0 - \alpha)\delta\theta \quad (5)$$

is to first order proportional to the perpendicular component of the baseline referenced to the flat Earth, $B_{\perp 0} = B\cos(\theta_0 - \alpha)$, and to the small angle $\delta\theta$, which in turn, is proportional to the topographic height z: $\delta\theta \approx z/r_0 \sin\theta_0$. The so-called ambiguity height is the elevation change required to alter the phase difference by one cycle (2π rad) and is given by

$$h_a = \frac{\lambda r_0 \sin\theta_0}{2B_{\perp 0}} \quad (6)$$

For the 6-month repeat L band Kilauea observations, h_a = 570 m.

The phase difference in repeat-pass observations measures any ground displacement in addition to topography. The range change in the second image Δr due to displacement enters into the phase difference directly:

$$\Delta\phi_{\text{flat}} = -\frac{4\pi}{\lambda} B \cos(\theta_0 - \alpha) \frac{z}{r_0 \sin\theta_0} + \frac{4\pi}{\lambda}\Delta r. \quad (7)$$

Note that the phase difference is far more sensitive to changes in topography (surface displacement) than to the topography itself. From (7), $\Delta r = \lambda/2$ gives one cycle of phase difference, while z must change by h_a to affect the same change.

Characteristics of the Interferometric Phase

There are several fundamental problems in isolating the motion signature in an interferogram. The first is the occurrence of backscatter phase changes between observations. These changes can lead to systematic biases to the phase difference measurements, and to randomization of the phase through signal decorrelation. Decorrelation can be a significant impediment to repeat-pass interferometric analysis. The measure of correlation is

$$\gamma = \frac{|\langle c_1 c_2^* \rangle|}{(\langle c_1 c_1^* \rangle \langle c_2 c_2^* \rangle)^{1/2}} \quad (8)$$

where c_1 and c_2 are the complex valued resolution elements of the two images that form the interferogram, the asterisk denotes complex conjugation, and angle brackets denote statistical expectation, realized in practice by spatial averaging with a rectangular filter when the interferometric phase varies slowly. There are three major factors that contribute to decorrelation in repeat-pass interferometry: thermal noise, geometric decorrelation resulting from slightly different imaging geometrics and volumetric scattering, and temporal decorrelation resulting from random wavelength-scale motion of scatterers within a resolution element [*Zebker and Villasenor*, 1992].

The second major problem in isolating motions from other phase modulations in an interferogram is the topography itself. Removing the topographic phase signature from an interferogram requires either a reference digital elevation model (DEM) of sufficient resolution and accuracy, or an independent interferogram with no motion present. Using a DEM, we may synthesize an interferogram if the imaging geometry is known. Subtracting the phase differences pixel by pixel removes the topographic phase and leaves only the phase due to motion. For the 6-month separation Kilauea observations, only two passes were available. Since no topography-only interferogram could be generated, the DEM method is used.

A third problem in isolating motions is the effect of the atmosphere on the radar signal. In observing the Earth, radar signals must propagate through the atmosphere, which induces additional phase shifts that are not accounted for in the geometrical model described above. There is extensive literature on this problem, mostly related to radar altimetry studies. We refer the reader to the review of *Goldhirsh and Rowland* [1982 and references therein] for more details.

Propagation through both the "dry" atmosphere and through atmospheric water vapor adds additional phase delays to the interferogram. In each case the amount of phase delay is inversely proportional to wavelength, that is, the medium is nondispersive. Since the effect is evidenced as a nearly constant time delay of the radar signal, independent of frequency at microwave wavelengths, the contamination of the signal cannot be corrected using dual-frequency measurements, such as those commonly used in ionospheric corrections. Variability in the atmospheric medium on a timescale similar to the repeat orbit interval then represents an unpredictable error signal which adds to the desired phase signal.

Thus any interferometric technique will be compromised if propagation effects such as these variable time delays alter the observed phase significantly. In the case of surface deformation, the true motion of the ground between observations will be falsely indicated in the interferogram by an amount equal to the difference of the equivalent excess propagation length through the atmosphere on the two passes. In the case of topographic measurements, the distortion depends also on viewing geometry and baseline parameters, as reflected in equation (7) above for topographic error.

The amount of delay that might be expected from atmospheric variability can be estimated from an equation used by the Seasat radar altimeter science team to remove both the dry and wet tropospheric influences from that instrument's data. Their model, as quoted by *Goldhirsh and Rowland* [1982], is

$$\Delta x = 2.277 \times 10^{-3}\left(0.05 + \frac{1255}{T_s}\right)e_s + (2.277 \times 10^{-3} - 1.11 \times 10^{-5}\cos\Lambda)P_s \quad (9)$$

where Δx is the nadir-looking excess path length through the atmosphere, P_s is the surface atmospheric pressure in millibars, T_s is the surface temperature in kelvins, e_s is the surface partial pressure of water vapor in millibars, and Λ is latitude. These constants are assumed valid to within about 0.5% for frequencies up to 30 GHz and normal variations in pressure, temperature, and humidity.

If the nadir-looking path length is scaled by the obliquity factor due to our look direction, and multiplied by $4\pi/\lambda$ to get phase, we can estimate the phase signature of atmospheric variation. We find that a change in pressure from 1000 to 1025

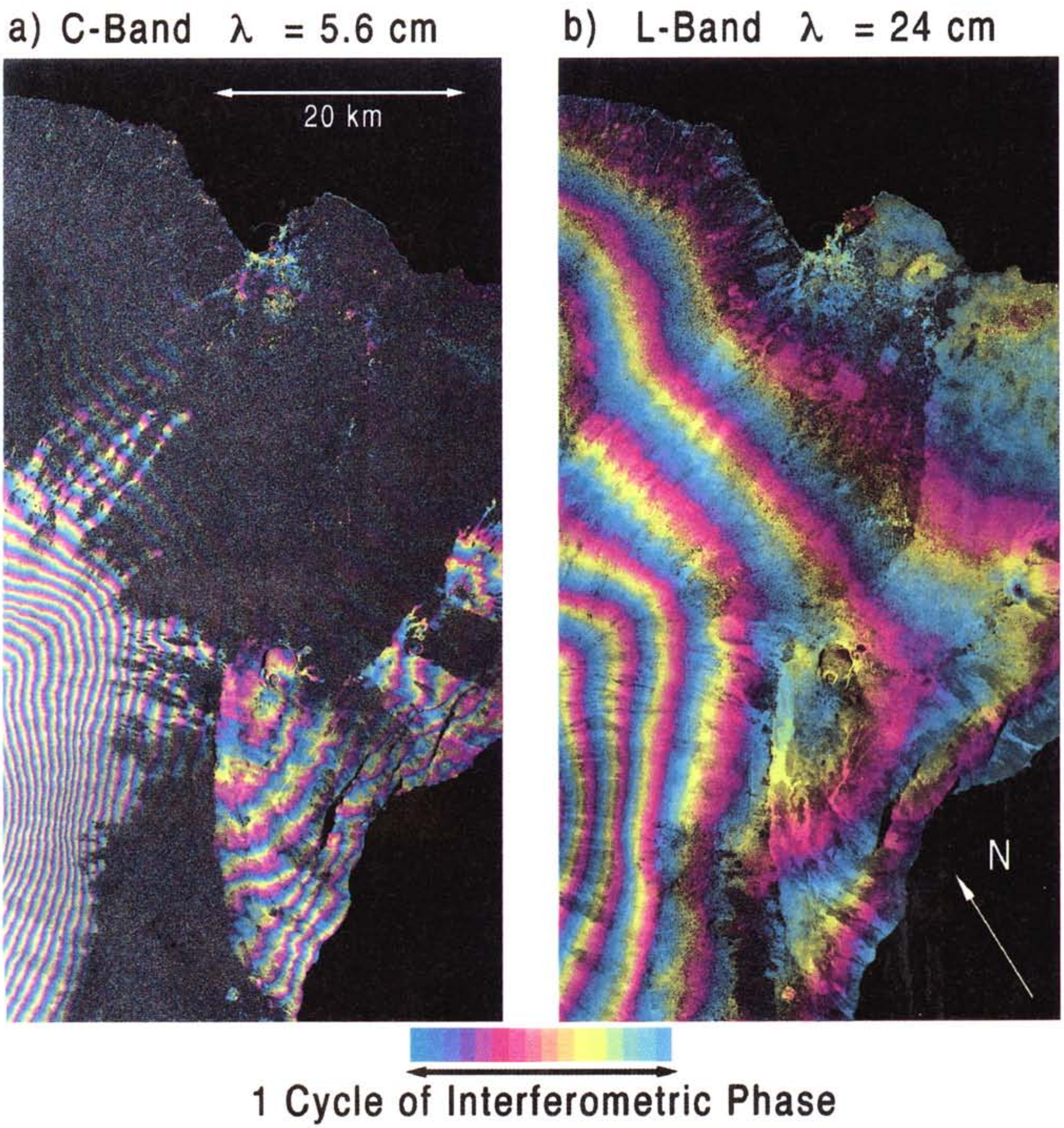

Plate 1. SIR-C interferograms of Kilauea, Hawaii, at (a) C band and (b) L band formed from April and October images. One cycle of interferometric phase change, or "fringe," is coded as one excursion around the color wheel. Color is modulated in brightness by the magnitude of the mean cross correlation of the images $|\langle c_1 c_2^* \rangle|$. Bright areas have high correlation and good fringe quality. Dim areas have poor correlation and fringe quality. One L band (C band) fringe corresponds to 570 m (135 m) of topographic variation.

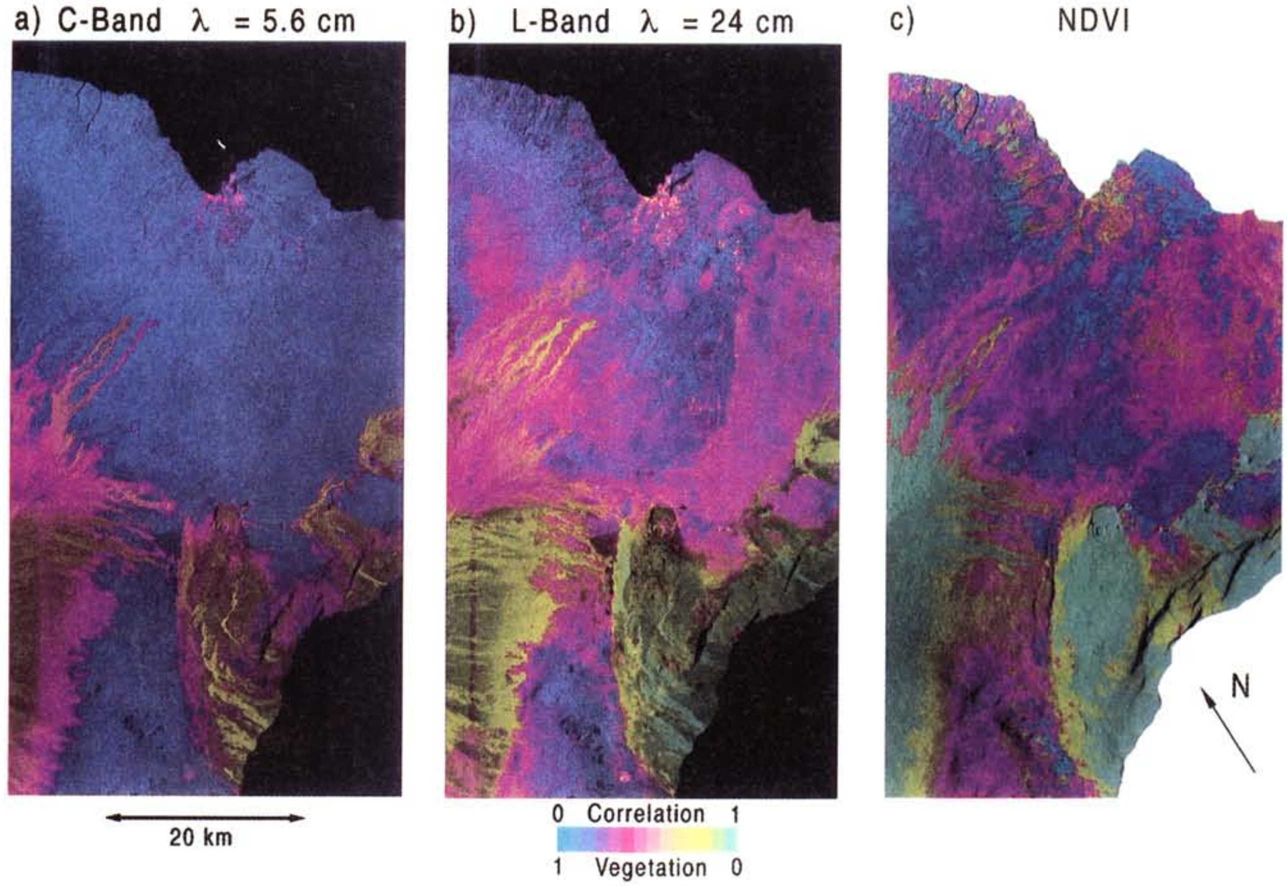

Plate 2. SIR-C correlation maps of Kilauea, Hawaii, at (a) C band and (b) L band. (c) NDVI vegetation measure mapped to radar coordinates. Areas of poor correlation generally correspond to areas of high vegetation. C band interferograms decorrelate much more severely owing to vegetation than L band data.

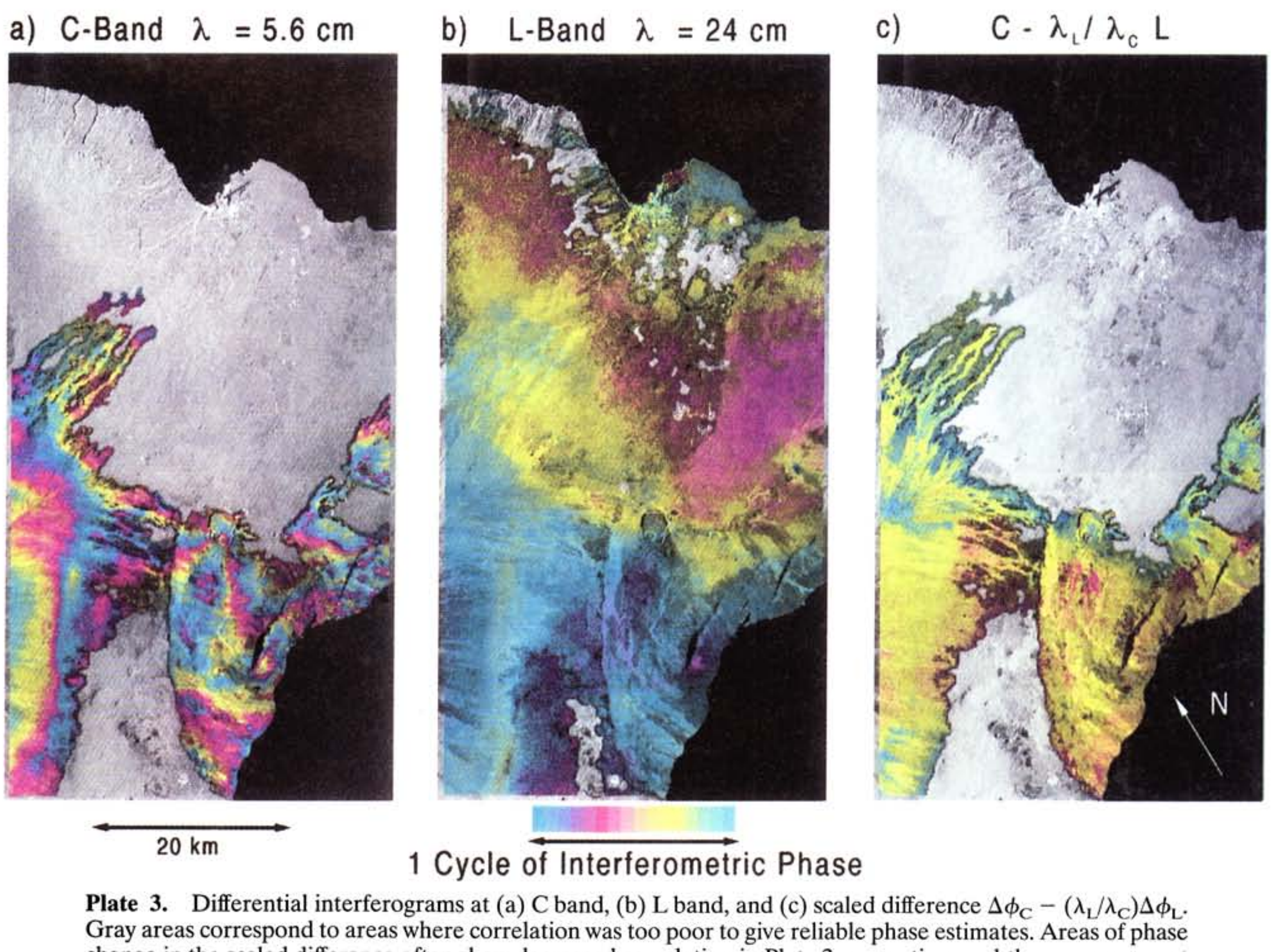

Plate 3. Differential interferograms at (a) C band, (b) L band, and (c) scaled difference $\Delta\phi_C - (\lambda_L/\lambda_C)\Delta\phi_L$. Gray areas correspond to areas where correlation was too poor to give reliable phase estimates. Areas of phase change in the scaled difference often show decreased correlation in Plate 2, suggesting a subtle rearrangement of surface scatterers from April to October.

mbar, a reasonably large (and unlikely) pressure difference, yields a line-of-sight two-way range difference of 8 cm, corresponding to a phase change of 4 rad at L band, at a temperature of 300 K and a latitude of 35°. Similarly, a columnar change in relative humidity of 10% induces a two-way range difference of 4.9 cm (2.5 rad at L band) under the same conditions. Either of these effects could easily mask or mimic centimeter-level deformation or small topographic features. These values will be compared below to the Kilauea interferogram measurements.

Table 2. Interferometric Processing Parameters

Parameter	Value
Radar altitude	217,820 m
Near slant range	387,880 m
Processed range resolution	6.66 m
Processed azimuth resolution	6 m
Doppler centroid	0 Hz
Interferogram range looks	6
Interferogram azimuth looks	12

Data Reduction

Interferograms and Correlation Maps

For the methods of SAR image and interferometric processing, the reader is referred to the literature [e.g., *Curlander and McDonough*, 1991; *Zebker et al.*, 1994a]. The SIR-C processing team at the Jet Propulsion Laboratory (JPL) provided raw L and C band SAR data. Data acquired on the April and October flights were processed directly to interferograms using the processing parameters listed in Table 2. The pixel spacing in the interferogram is roughly 50 m in ground range and in azimuth after 72 total looks. All interferometric images discussed in this work were manipulated at this pixel spacing. Plates 1a and 1b show the L and C band interferograms. The interferograms have been "flattened" as described above (equation (5)), so that the fringes are primarily due to topography.

The most striking feature of these interferograms is the poor visibility of the fringes at C band over most areas and good visibility at L band everywhere. One way to quantify the quality of the fringes is through the correlation maps in Plate 2. Regions with poor fringe quality in Plates 1a and 1b correspond to regions of poor correlation in Plates 2a and 2b. The loss of correlation, in turn, corresponds to the presence of vegetation on the surface. Plate 2c depicts the presence of vegetation on Hawaii as measured by the normalized difference vegetation index (NDVI), formed from a combination of red and near-infrared channels of SPOT multispectral data. The NDVI is more a measure of chlorophyll density than biomass; however, in the tropical canopy of Hawaii, they are closely related. The color scale in Plate 2c has been chosen to highlight the relationship between decreased correlation and increased vegetation index. Referring to Plate 2, recent lava flows in areas of the Pu'u O'o, Kupaianaha, and Mauna Ulu vents are relatively devoid of vegetation. Similarly, the Kilauea crater and desert region to its southwest are barren from lava flows and acid rain formed from sulfurous gases vented from Kilauea. The Mauna Loa slope to the west shows evidence of recent flows and is also unvegetated. All these regions have high correlation at both C and L band. All other regions have varying degrees of vegetation cover, and the interferometric correlation is accordingly lower.

The correspondence between decorrelation and vegetation is not one-to-one. The Mauna Loa flows directed northeast toward the city of Hilo appear to be barren in the NDVI figure but show decorrelation in the radar data. Similarly, the coastal agricultural regions west of Hilo have much greater variation in vegetation index than the correlation maps show. Some changes to the vegetation cover may have occurred between the times of the SPOT and SIR-C images, particularly in the cultivated areas. Changes to soil moisture and water present on lava between the April and October SIR-C acquisitions can also influence the correlation.

One conclusion is readily apparent from these data and has been corroborated with dozens of scenes examined by the authors at other sites: repeat-pass correlation at C band in vegetated areas is poor, even with only 1 day between images. It is often so poor that surface properties such as topography or surface deformation are impossible to discern. Despite the abundance of C band radar data available from ERS 1 and 2 and the upcoming RADARSAT instruments, large portions of the Earth will continue to elude interferometric scrutiny. Early attempts at measuring volcanic deformation were carried out using ERS 1 data in Alaska [*Zebker et al.*, 1994b], highlighting the limitations of the technique. Changes in the surface properties of the volcanos from weather and vegetation led to decorrelation of the images and no detectable deformation signature. Not until SIR-C have the advantages of longer wavelengths been so clearly demonstrated. The L band signal more easily penetrates the canopy and scatters off the trunks and branches, which move less between observations. As the fringes of Plate 1b show, L band is a far more robust wavelength for repeat-pass interferometry in vegetated areas.

Two-Pass Differential Interferometry

Because SRL 1 and 2 made only two repeated ascending passes over Kilauea, it was necessary to remove the topographic contribution to the interferometric fringes by simulating an interferogram with topographic fringes from a 30-m DEM grid consisting of four mosaicked U.S. Geological Survey (USGS) 7.5 arc min quadrangles. Substantial errors exist in this DEM because it was made well before the last decade, when the area around Pu'u O'o has rapidly built up from erupting lava. Pu'u O'o vent itself has grown by roughly 100 m. Fortunately, another high-precision DEM exists of the chain of craters, made by the TOPSAR topographic mapping system [*Zebker et al.*, 1992] in 1993. The TOPSAR DEM was mosaicked into the USGS mosaic.

Appendix A describes the procedure for simulating the interferogram. Approximate initial knowledge of the interferometer baseline plus the use of many ground control points from the DEM permitted a solution for the interferometric baseline. The baseline vector is not well constrained because of phase distortions in the ground control points; however the most relevant component, $B_{\perp}$, is well constrained. See Appendix B for a discussion.

The simulated topographic phase was removed from the interferogram before phase unwrapping (Appendix B). Additional smoothing of this differential interferogram to a resolution of 100-m reduced phase noise for the phase unwrapping procedure, particularly in the decorrelated vegetated areas.

Plate 3 shows the differential interferograms at C band

Table 3. GPS Control Points for Least Squares Adjustment of Phase Field

UTM Location, deg		Displacement Vector, cm			Radar Line-of-Sight Displacement, cm	
Latitude	Longitude	North	East	Up	Full Vector[a]	No Vertical[b]
19.58892	−155.16576	0.57 (0.38)	0.27 (0.20)	−0.2 (1.9)	0.19 (0.79)	0.14 (0.18)
19.52525	−155.02570	−0.22 (0.74)	1.16 (0.35)	3.2 (2.9)	−1.15 (1.06)	−0.36 (0.37)
19.46511	−155.16674	0.29 (0.47)	1.10 (0.25)	−0.7 (2.2)	0.01 (0.88)	−0.16 (0.22)
19.45806	−155.11532	−0.19 (0.52)	1.10 (0.30)	0.2 (2.4)	−0.38 (0.96)	−0.33 (0.23)
19.42111	−155.28680	0.24 (0.41)	−0.56 (0.22)	−7.4 (2.3)	2.10 (0.98)	0.22 (0.19)
19.40259	−155.06557	2.36 (0.42)	−0.23 (0.22)	3.9 (2.1)	−0.03 (0.82)	0.91 (0.20)
19.39293	−155.29144	4.78 (0.67)	−3.79 (0.42)	−5.5 (4.8)	4.01 (2.15)	2.62 (0.28)
19.37333	−155.45803	2.55 (0.81)	−0.30 (0.37)	−3.1 (5.2)	1.78 (2.32)	0.98 (0.40)
19.37149	−155.20542	−0.53 (0.49)	−0.61 (0.26)	−9.3 (2.7)	2.26 (1.11)	−0.04 (0.23)
19.36821	−155.42064	−0.88 (0.82)	−0.43 (0.41)	4.8 (7.6)	−1.45 (3.54)	−0.21 (0.39)
19.35539	−155.32242	5.08 (0.61)	−2.08 (0.31)	−8.5 (4.0)	4.47 (1.74)	2.32 (0.29)
19.35053	−155.25422	4.68 (0.52)	−4.38 (0.26)	−1.8 (2.3)	3.19 (0.90)	2.74 (0.25)
19.32647	−155.22809	1.44 (0.85)	−5.83 (0.41)	−3.2 (3.8)	2.72 (1.47)	1.93 (0.42)
19.30098	−155.37127	2.52 (0.67)	−0.32 (0.34)	−0.6 (5.4)	1.13 (2.43)	0.98 (0.32)
19.29451	−155.30732	2.11 (0.44)	−2.98 (0.23)	0.9 (2.0)	1.25 (0.80)	1.47 (0.21)
19.27570	−155.25958	2.55 (1.24)	−5.50 (0.43)	−7.8 (5.6)	4.18 (2.09)	2.25 (0.69)
19.25985	−155.19265	4.26 (0.85)	−7.64 (0.40)	4.1 (4.1)	2.40 (1.58)	3.40 (0.42)
19.23781	−155.44720	1.50 (0.63)	−0.15 (0.39)	2.0 (7.6)	0.06 (3.63)	0.57 (0.26)

GPS vectors courtesy of Hawaiian Volcano Observatory. Yearly rates divided by 2 to obtain 6-month displacements. Values in parentheses are one-sigma uncertainties.

[a]Projection of the three-component GPS displacement vector into the radar line-of-sight direction.

[b]Projection into radar direction assuming the vertical component of GPS displacement vector is zero.

(Plate 3a) and L band (Plate 3b). Plate 3c shows the difference in the C and L band phase after scaling the L band phase by the ratio of the wavelengths. Colorless regions of radar backscatter correspond to areas where unwrapping was not possible due to excessive noise.

Interpretation

Plates 3a and 3b show strong differential phase variations. Since topography has been removed, the variations here are related to surface deformation, or atmospheric or ionospheric propagation delays, or errors in the DEM used to remove topography. The DEM-induced errors are likely to be very small, since the ambiguity height of the interferogram is so large. From (7), a positive phase change (blue to red to yellow in the plates) corresponds to an increase in the range Δr. If the phase changes are due to deformation, then the area south of Kilauea crater and on the seaward side of Hilina Pali show motion away from the radar. The area north of Kilauea in the rain forest, on the other hand, shows motion toward the radar. If the phase changes are due to propagation effects, the observations imply that there was more delay in October than in April south of Kilauea and at the pali, and vice versa in the rain forest.

The scaled phase difference in Plate 3c does not have topographic, deformation, or nondispersive propagation delay contributions; all are inversely proportional to wavelength and cancel in the difference. The remaining phase signature is related to dispersive propagation or surface scattering effects. The low altitude of the shuttle's orbit would rule out ionospheric effects. The strongest effects appear to correspond with surface features, implying that these are probably related to moisture content, vegetation density, or roughness characteristics of the lavas. The phase in Plate 3c is scaled to match the C band phase; it is small compared to the phase excursions in Plate 3a. Several features in Plate 3c correspond to local areas of partial decorrelation in Plate 2b, notably in Kilauea crater itself, and in the Mauna Ulu area.

GPS-Radar Comparison

The phase of the L band interferogram in Plate 3b has a roughly constant value along the coast. This would be correct if only topography affected the interferometric phase and the topographic phase had been completely removed by the simulation process. However, with surface deformation and other phase distortions present, a uniform coastline may not be correct. Inaccuracy in the estimated baseline can also introduce small quadratic distortions of low spatial frequency to the interferometer phase [*Zebker et al.*, 1994a]. Secular deformation rates are available at numerous GPS sites in the active region [*Owen et al.*, 1995]. These rates converted to 6-month displacements and projected into the radar line-of-site direction provide deformation ground control points for a final quadratic least squares adjustment of the phase field. Table 3 lists the GPS points used as controls. The one-sigma uncertainties for the estimates are given in parentheses. The clustering of GPS points at Kilauea causes an otherwise unconstrained quadratic fit to distort the phase field away from the control points. To place the needed constraint, supplemental control points were peppered throughout geologically inactive areas, with displacements set to zero. The points were chosen where possible in unvegetated regions. This procedure has some risk; however, it did not change the essential shape of the phase signature in the region of active deformation. In fact, conservatism in rejecting vegetated areas for control points may be responsible for the large residual phase along the northern coast.

Plate 4 depicts the L band phase field after the least squares adjustment as apparent surface displacement in units of centimeters. The radar swath has been mapped to universal time meridian (UTM) coordinates. Red (green) denotes motion away from (toward) the radar. Note also a scale interpreting the phase as topographic residuals; a topographic map derived from these data would have systematic errors as large as 600 m because of the small baseline involved. Several features of the image are noteworthy. The locations of maximum displacement away from the radar tend to appear along the coast, with the exception of a local feature associated with the Pu'u O'o lava vent (see inset in Plate 4) and the Ka'u desert southwest of Kilauea crater. Displacements at the coast southeast of Hilina Pali and at the Ka'u desert are consistent in sign with, but larger in magnitude than, the GPS secular rates predict (see Figure 2). The displacements measured in the northern coast near Hilo are not consistent with the few GPS measurements in the region, which show little or no motion. Thus the data appear to show evidence of the surface deformation signal, and other intriguing local features such as Pu'u O'o, yet artifacts in the phase confuse the interpretation.

Figure 4 plots the adjusted radar line-of-sight displacements of Plate 4 against the GPS data projected into the radar line-of-sight for two cases: where the three-dimensional GPS vector is used in the projection, and where the vertical component of the GPS vector is assumed zero. It is well known that the vertical component in GPS measurements is not nearly as well constrained as the horizontal components, consistent with Table 3 and Figure 4. Most vertical estimates are consistent with zero within their error bars. While there is likely to be a nonzero vertical component to the displacement, inclusion of it in these comparisons would require additional modeling. For consistency in computing Figure 4b, the least squares adjustment to the radar line-of-sight displacements was carried out with vertical GPS ground control displacement set to zero.

In both cases the statistical correlation between radar and GPS observations is below 0.6. In Figure 4a, the error bars in the GPS data are simply too large to give confidence in a result. While the error bars in Figure 4b are smaller, the scatter about the fitted line is still quite large, and the slope is clearly not 1, the displacement derived by radar appears to be twice the GPS estimate.

Including the neglected vertical displacement term might improve the result. For the southeast-hanging face of the fault associated with Hilina Pali, the vertical displacement of the land is clearly downward as the surface moves seaward from magma pressure and gravity. Thus the vertical GPS component is likely to be positive in the direction away from the radar, increasing the GPS-derived estimate of the projected displacement. For slip on a fault plane with 45° dip and strike normal to the radar look direction (roughly the configuration of the observations), the vertical and horizontal motions are roughly equal. Such a configuration could account for the factor of 2 discrepancy shown in Figure 4b.

In addition to the poor GPS measurement of the vertical displacement, other unknowns erode confidence in this GPS-radar consistency argument. While the error bars on the radar data are empirically determined from spatial statistics around each measurement site, little is known about the stationarity of the phase over space. The fit to the spatially distributed GPS displacements anchors the phase field on a scale of tens of kilometers; however, kilometer-scale distortions may exist from propagation effects. The magnitude of these distortions is poorly understood. An attempt to quantify these effects follows.

Plate 5 shows L and C band differential interferograms of an area near Kilauea volcano derived from data collected on October 7 and 8, 1994. The topographic signature was removed using the two-pass approach; thus, if the surface did not deform appreciably over the 1-day period, we would expect to observe a uniform phase everywhere. Note that the variability in the C band data tracks the L band changes exactly, save for a factor of about 4 (the wavelength ratio) and regions of denser vegetation, where the correlation at C band was too low to permit accurate phase retrieval. Residual topography is negligible, as the 1 day repeat baselines are very small (similar to the 6-month repeat baseline). These variations are thus due to either surface movement or to propagation through a neutral medium.

The measured rms phase residual in the image is 0.7 rad at L band. This corresponds to an excess 2-way path length of 2.6 cm. Peak-to-peak variations in the phase residual can reach as high as one cycle at L band, particularly near the coast east of Pu'u O'o (not shown in the plate). Since it is highly unlikely that the surface is undergoing such large deformation in one day without notice by any other technique or individual, we must conclude that the distortions are due primarily to variations in the atmosphere, as no other source seems likely.

It is unlikely that large variations in atmospheric pressure from point to point in the image could occur under normal circumstances, and no anomalous weather conditions were reported for the time of the observations. Hence it is more probable that what is dominating the signature in Plate 5 is natural variation in the distribution of water vapor and how that distribution changes from the time of the first observation to the time of the second. The 6-month interferogram shown to the left in Plate 5 also shows phase variations, but their spatial characteristics are quite different. The kilometer-scale random deviations attributed to water vapor in the 1-day interferogram are largely absent in the 6-month interferogram. In addition, the smoothly varying phase variations in the 6-month pair can often be associated with surface features, whereas the 1-day pair data do not show such structure. The only substantive difference between these interferograms is the acquisition time. The 6-month pair was acquired at 0200 LT (local Hawaii time), while the 1-day pair was acquired midday. The increased variability in the water vapor in the daytime points to solar-driven convection in the air mass above the island as a mechanism.

It is tempting to infer from this comparison that water vapor does not corrupt the 6-month measurements at a level sufficient to mask the deformation signal. However, little is known about the spatial distribution of water vapor. While the smaller-scale variations of water vapor seem to disappear at night, the larger-scale features, such as accumulation along the coast or colocation with vegetation, may remain. Though some of the 6-month signal is most likely deformation, it is difficult to extract.

GPS-Based Tropospheric Estimates

GPS-based estimates of the wet tropospheric delay were examined to better understand the magnitude of the delays inferred from the differential interferograms. Estimates of the wet-zenith delay from GPS and very long baseline interferometry (VLBI) data have been shown to compare favorably with those from water vapor radiometers [*Yunck*, 1993]. GPS techniques involve modeling the wet-zenith delay as a random walk process that is allowed to vary 1 cm in 1 hour or 5 cm in 24 hours. Agreement with radiometer-derived estimates ranges from 3 to 12 mm and is typically less than 10 mm.

Several GPS receivers were operated on Kilauea by the

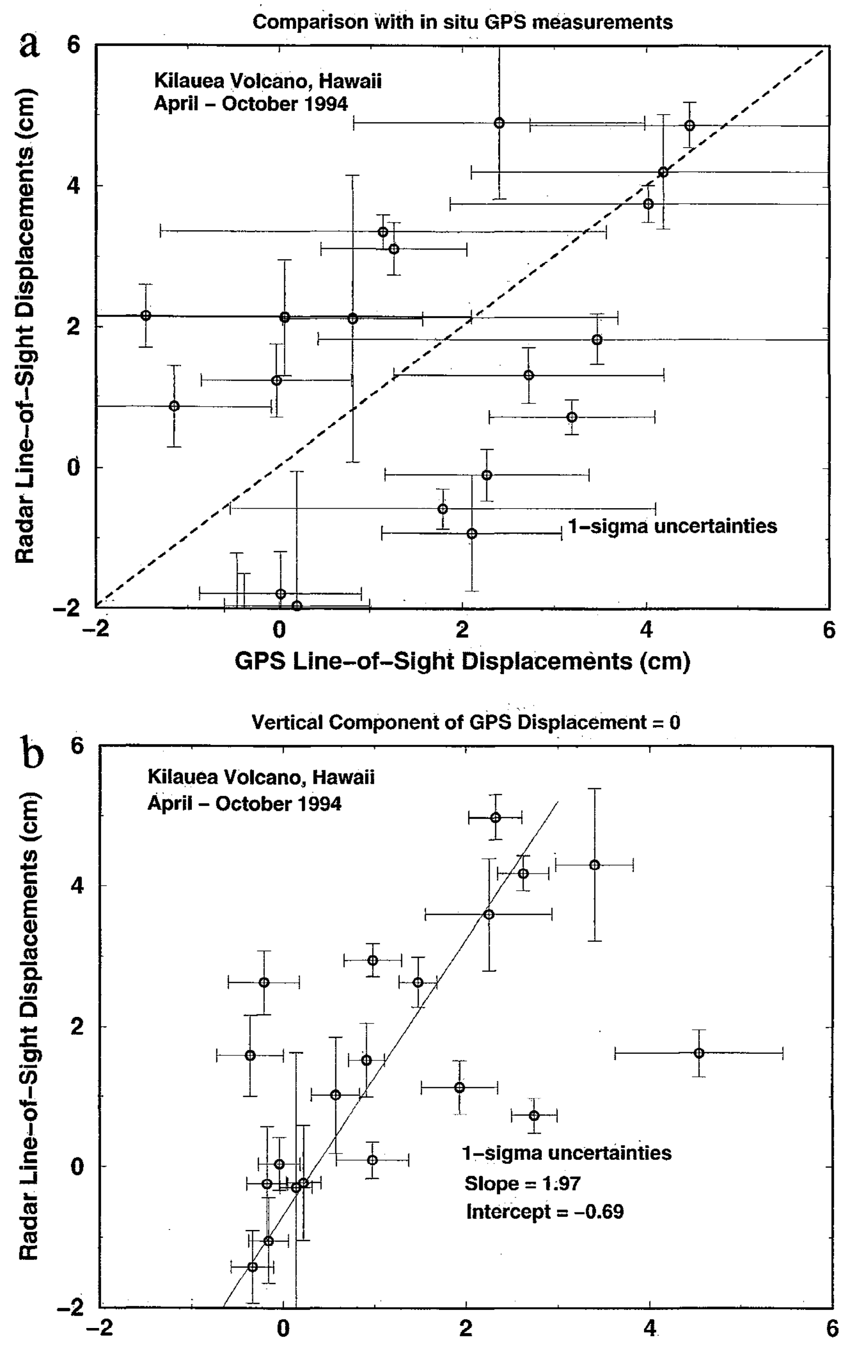

Figure 4. Comparison of radar line-of-sight apparent displacement to GPS displacements projected into the radar line-of-sight direction. (a) Using full GPS vector. (b) Assuming height component of GPS vector is zero. Dashed line in Figure 4a has slope equal to 1 but is not a fit to the data. Solid line in Figure 4b is a fit to the data.

Hawaiian Volcano Observatory of the USGS during the October shuttle overflights. These stations collected data for up to 3 days. The altitudes of the stations range from near sea level to 3000 ft.

A useful measure of the tropospheric variability is the delay difference at a station from one day to the next, as shown in Figure 5 for the KAEN station. These differences show peak-to-peak variability of 6 cm zenith delay, which maps to a two-way radar path delay exceeding 12 cm, commensurate with the peak-to-peak variability of the one-day measurements. Similarly, the rms deviations of the zenith delay is on the order of 1 cm, consistent with the rms spatial variability of the one-day radar measurements. This consistency depends on the ergodic assumption that the temporal variability of the wet troposphere seen in Figure 5 is representative of a spatial distribution that moves slowly with the wind.

Pu'u O'o Deformation Signal

Another possible explanation of the features emanating from Kilauea and hovering over Pu'u O'o is the presence of gas plumes. Water vapor and sulfur dioxide gas are frequently vented from Kilauea. Acid rain carried to the southwest by

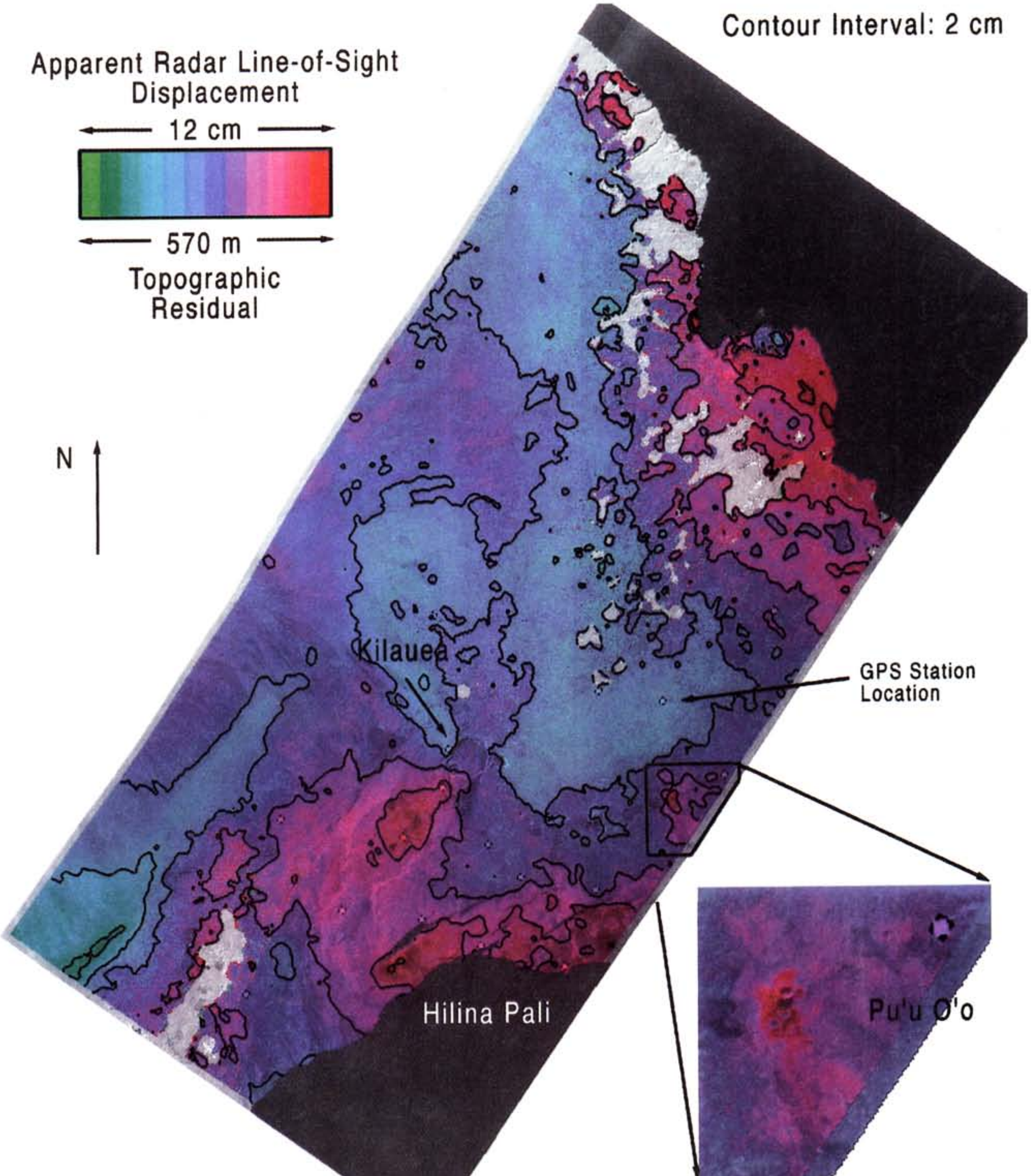

Plate 4. Apparent surface displacement at L band in map coordinates. Color scale represents one cycle of interferometric phase and can be interpreted as ~12 cm peak-to-peak displacement of the surface along the radar line-of-sight direction, or residual topography of 570 m, peak-to-peak. Red corresponds to motion away from the radar, blue to no motion, and green to motion toward the radar. Signatures southwest of Kilauea caldera and at Pu'u O'o appear to be associated with surface features, independent of topography.

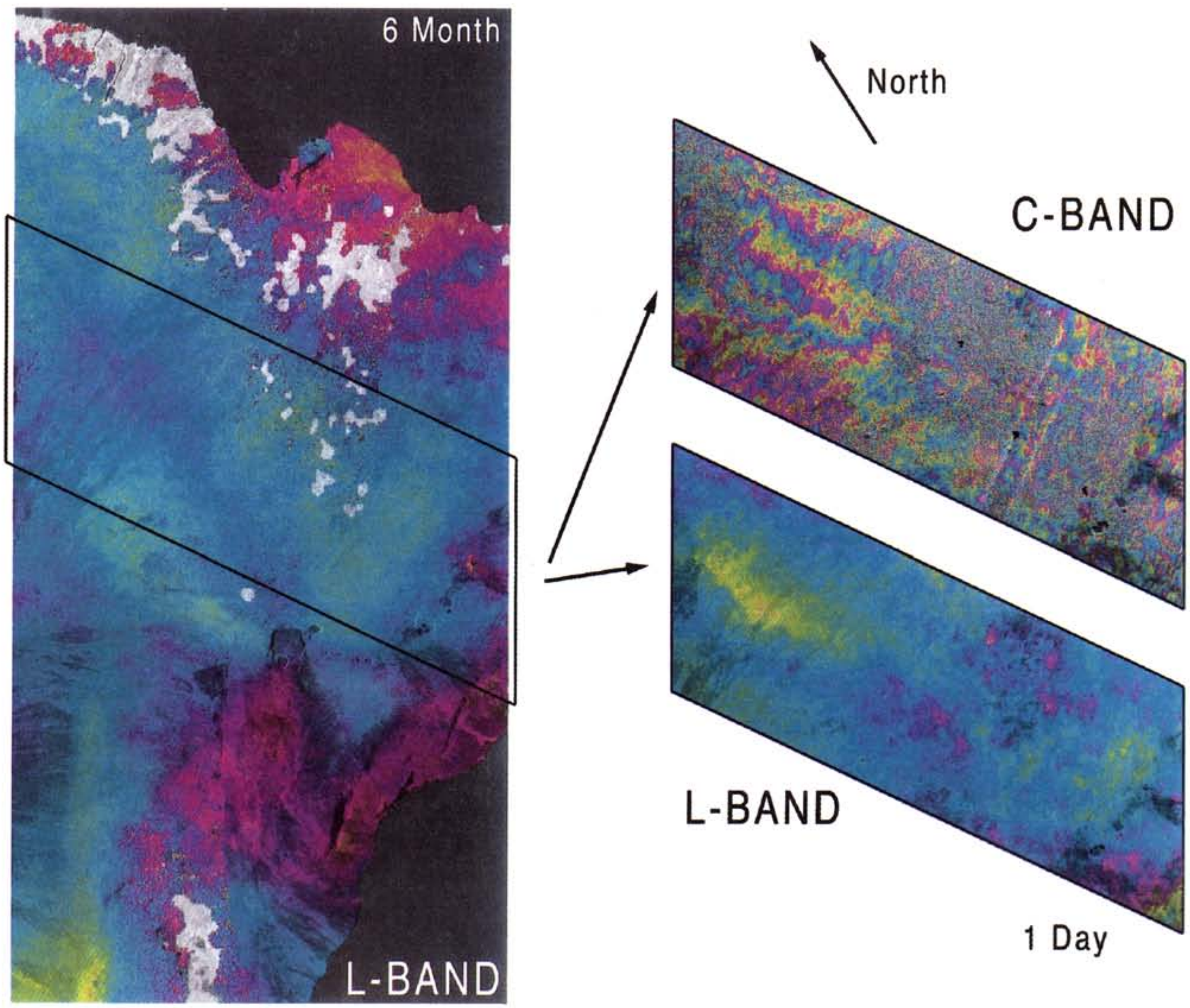

Plate 5. L and C band differential interferograms (at right) for 1-day repeat orbits, October 7 and 8, 1994, compared to L band 6-month interferogram (at left). Six-month interferogram phase was anchored to GPS ground control points. C band interferogram suffers from tropospheric effects, as well as severe decorrelation even at a 1-day observation separation. Phase variance is larger in the 1-day observations, and scale size of tropospheric effects differs from 6-month data.

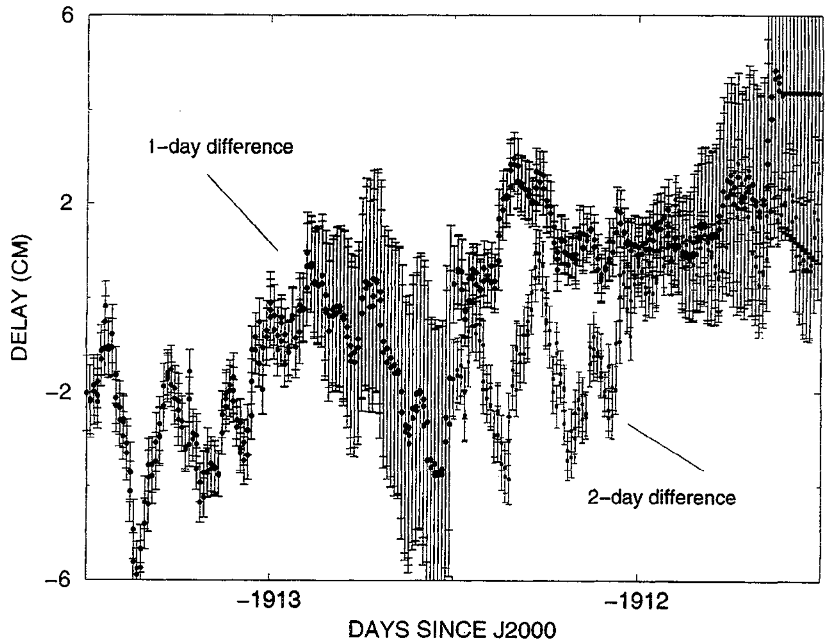

Figure 5. GPS estimate of wet tropospheric delay differences between days at a fixed GPS station. Peak-to-peak variation is 6 cm, and rms value is 1 cm. Nighttime values are unknown but are likely to be comparable in magnitude, if not in spatial structure.

trade winds contributes to the desertification of the Southwest Rift Zone, notably Ka'u desert. The shape of the differential phase signature for Kilauea is particularly clear in Plate 3, where the C band phase is fan shaped, with its tip emanating from the edge of the caldera toward the southwest. Pu'u O'o is also venting gas in this period of activity. Assuming that the atmosphere is at 50% relative humidity, that the plume is 100% water vapor, and that it has expanded to nearly the same temperature and pressure as the background atmosphere, the plume must displace only about 10% of the atmospheric column to yield a signal of 2.5 rad. Thus a plume present on one observation and not the other could also be responsible for some of the observed signals.

For the signature at these locations to be due to gas plumes, it must represent a difference in the atmospheric refractivity from April to October. Both signatures imply greater radar path length, suggesting that the outgassing activity was greater in October than April. Unfortunately, records of plume activity are not kept in the detail needed to corroborate these observations.

The shape of the phase signatures is quite different. If one assumes that the prevailing winds are similar at Kilauea and Pu'u O'o, then it is unlikely that both signatures are plumes: the Kilauea phase anomaly is elongated to the southwest, while the Pu'u O'o anomaly is centered over the vent. A plausible yet entirely uncorroborated explanation that is consistent with GPS measurements is as follows. The signature at Kilauea is not due to plume activity but is actually the expected wide-area deformation signal. The signature at Pu'u O'o is either due to localized deflation of the magma reservoir beneath the vent or it is due to a nearly vertical column of gas above Pu'u O'o.

Continuing this line of argument, it is possible to rule out gas venting at Pu'u O'o by comparing the 6-month differential phase signature to several interferograms from the October 1-day repeat observations, as shown in Plate 6. Plate 6a shows the 6-month L band signature in radar coordinates. Plates 6b–6d show the L band signatures formed from 1-day, 2-day, and 3-day repeat periods. As noted above, for the signature in Plate 6a to result from venting, it must have occurred on October 4, 1994, when the second 6-month repeat image was acquired. However, the differential interferograms in Plates 6b–6d were formed from data acquired on 4 days after October 4, and these show no evidence of anomalous phase surrounding the Pu'u O'o vent. These observations imply that the signature is not related to propagation delays, but rather reflect deformation of the surface around the vent.

Careful examination of Plate 6a shows that the center of greatest deflation occurred to the south of the Pu'u O'o vent, peaking at roughly 8 cm of deflation in the radar line of sight. For purely vertical motion, this translates to roughly −14 cm peak displacement. Ground observers saw no lava breakouts at Pu'u O'o itself in the 6-month interval, and the radar observations are corroboration. Resurfacing from lava would lead to complete decorrelation of the interferogram, as measured at numerous breakouts downslope in the area in the 1-day repeat data [*Zebker et al.*, 1996]. While some decorrelation is observed around Pu'u O'o itself, it is not severe enough to be caused by resurfacing. Deflation around the vent could occur as the magma reservoir beneath is depleted through the downslope breakouts. Again, there are no corroborating measurements with the required millimeter-level sensitivity at Pu'u O'o itself taken at the time of the SIR-C overflights. Ground measurements taken at Pu'u O'o in January and August 1994 (R. Denlinger, personal communication, 1994) may prove useful in a follow-on study.

Discussion and Conclusions

In addition to the specific results pertaining to Kilauea, this study of surface deformation using SIR-C repeat-pass inter-

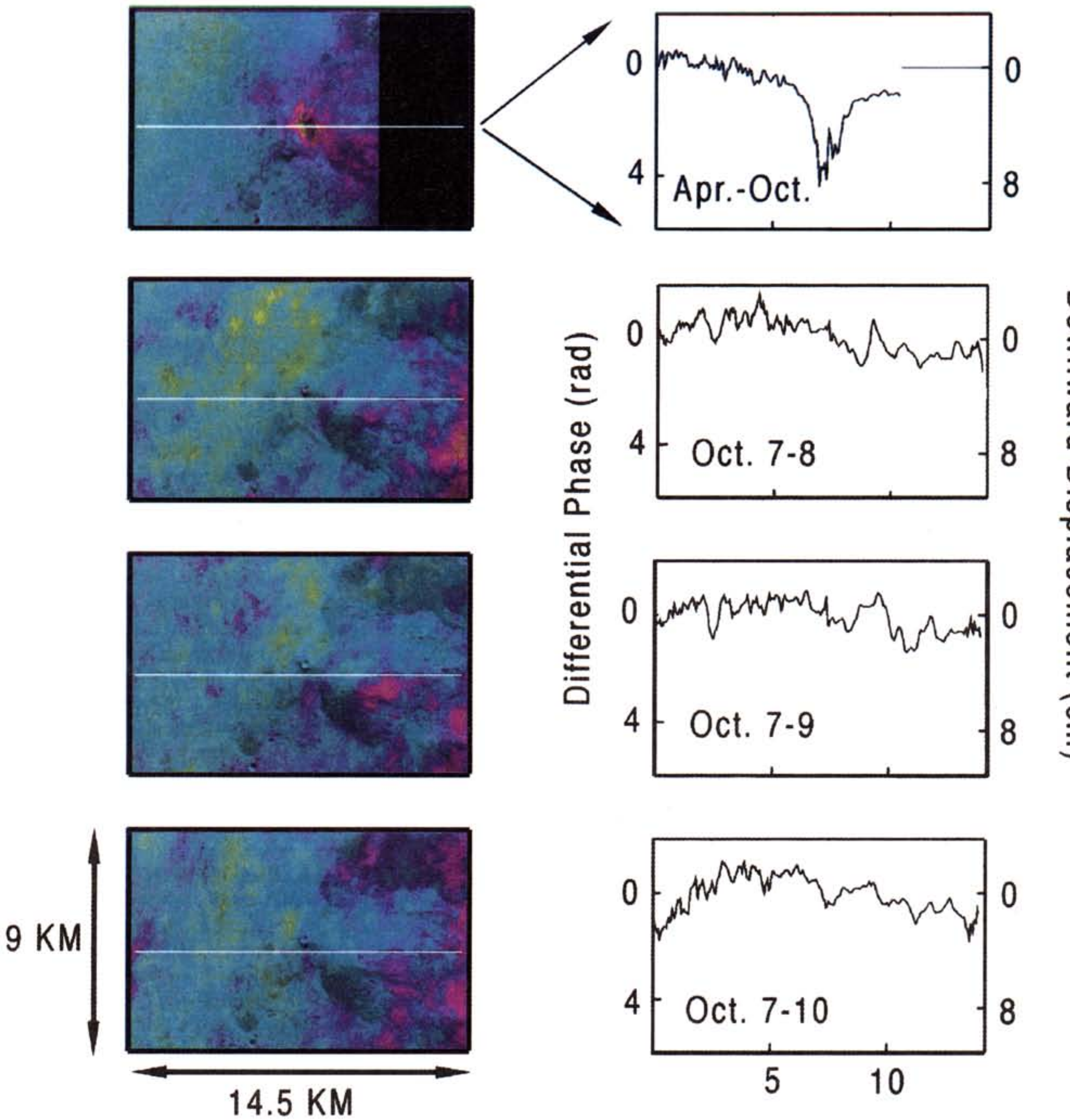

Plate 6. Comparison of Pu'u O'o phase signature at L band in (a) 6-month and (b–d) 1-day differential interferograms. Computed standard deviation of each 1-day phase profile is $\sigma = 0.42$ rad. A 6-month profile parallel to the displayed cut but south of the active area has $\sigma = 0.29$ rad. The right-hand scale of graphs is downward displacement in the radar line-of-sight direction. Vertical displacement is obtained by scaling by $1/\cos\theta_0$, where θ_0 is the incidence angle.

ferometry reflects on the capabilities and limitations of radar for measuring small-scale geophysical signals in general. The main conclusions of this work can be summarized as follows.

An area of several square kilometers surrounding the Pu'u O'o vent shows distinctive displacement away from the radar. Peak deformation was centered south of the vent itself. If the deformation is assumed to be entirely vertical, the surface is deflated by a net peak 14 cm over the 6-month interval. The signal is localized, distinctive in shape, and unique to the 6-month interferometric observations. It is very unlikely that it can be attributed to atmosphere or outgassing.

No convincing agreement was found between the radar observations and the GPS measurements of secular motion at Kilauea. There are "hot spots" in the radar interferograms corresponding to those regions most rapidly deforming according to GPS. The sense of motion and the size of the inferred displacements also corresponds roughly with the GPS measurements. However, detailed analysis revealed the following.

1. Peak-to-peak uncertainties in the phase measurements due to wet tropospheric delay anomalies or the presence of gas plumes are likely to be as large as the displacement signature and may have structure correlated with topography or surface features.

2. The radar line-of-sight displacement is composed of horizontal and vertical displacement components. Because the GPS measurements are inaccurate in the vertical direction, it is difficult to compare the GPS and radar observations for such small motions. The large uncertainties in the GPS projected displacement do not allow a well-constrained least squares fit. Ignoring the noisy vertical component of the GPS displacement artificially reduces the uncertainties but does not improve agreement between radar and GPS observations. GPS data recently reduced at the Hawaiian Volcano Observatory have slightly smaller error in the vertical direction (R. Denlinger, personal communication, 1996). These data also were taken at roughly the same time as the SIR-C overflights in April and October. Four stations out of a total of eight match the stations in the secular rate data provided by Owen et al. used throughout this paper. From these, it was clear that the secular rates were different from the April–October displacements at the centimeter level, mostly in the horizontal components. Unfortunately, the April–October data were either too closely spaced or did not coincide with the valid radar displacements. In the end, only about four April–October GPS points were useable, and these could not constrain the baseline error component of the displacement field. The fact that the secular rates and April–October "point" displacements are so different is interesting, suggesting that the surface does not move linearly with time. A time series of imaged displacements via interferometry could be valuable in constraining spatial variability of motion, if the atmospheric distortions can be controlled.

3. GPS-derived displacement ground control points were too sparsely located and inaccurate in the vertical to correct for the quadratic phase distortions introduced by poor orbit knowledge. Residual distortion can account for some of the excess delay observed along the coast in the north. The presence of residual distortions severely limits the interpretability of small deformation signals.

The limitations posed here are not necessarily globally applicable. The atmospheric effects at Kilauea are generally an order of magnitude more severe than at nontropical sites [e.g., *Goldstein*, 1995], so these results may be viewed as a worst case. Nonetheless, it is appropriate to characterize the behavior of the effects on a more theoretical basis, and to explore strategies for reducing them. This is an area of active research. The empirical observations of delay in the 1-day repeat interferograms form a useful data set for comparison with theory. No other active volcanoes were observed by SIR-C during the 6-month interferometry observations; however, continuing reduction of ERS and especially the longer wavelength JERS 1 radar observations of volcanoes is warranted by these results.

Plume activity is yet another hazard associated with volcanoes that requires monitoring, particularly for aircraft safety. The all-weather, day-night capability of radar and its fine phase sensitivity to measuring refractive change could provide a substantial new capability in hazard assessment. The simple calculations presented here of refractivity changes due to plume activity at volcanoes, coupled with the observation of a phase signature that looks like a wind-blown plume trail at Kilauea, point to a new area of investigation for interferometry. Again, study of other volcanoes with active vents using ERS or JERS data is needed to better characterize these effects.

One of the more important lessons of SIR-C repeat-pass interferometry is the limitation imposed on topographic accuracy. Atmospheric effects can unacceptably distort the phase, resulting in large height errors, especially for short baseline observations. Care must be exercised in designing a repeat-pass topography mission to trade off the long baseline necessary for minimizing these distortions, and the short baseline required for reliable processing over a wide range of incidence angles. Furthermore, for both topography and topographic change, it is clear that decorrelation due to vegetation severely limits the usefulness of short-wavelength (C band or shorter) radars in repeat-pass interferometry.

Appendix A: Interferogram Simulation Method

Simulation of a radar interferogram requires spacecraft ephemeris information, a DEM of the region of interest, and radar operating parameters. The simulation proceeds by generating a synthetic image and height map in radar imaging coordinates. This two-dimensional coordinate system has one dimension as the distance, or "range," from the antenna to a specified point on the ground when that point was imaged by the radar, and the other dimension as the distance along track, or "azimuth," from some reference position on the orbit track when the point was imaged. Thus the radar imaging coordinates are easily computed using simple geometry given the position of the platform when a point in the DEM was imaged.

The platform position at the time a particular point is imaged is a function of the processing algorithm used to generate the SAR image. The algorithm can be made to synthesize a radar looking arbitrarily forward or backward along the orbit track direction. For Kilauea observations the radar antenna boresight was nearly orthogonal to the direction of shuttle motion, so the data were processed to fix the synthetic boresight in precisely the orthogonal direction.

For each DEM coordinate the position along the orbit track where the radar imaged that point is determined by searching iteratively through the reconstructed state vectors of the shuttle's orbit for the intersection of the plane normal to the flight direction and the DEM point. Once this position is determined, simple vector geometry allows the computation of the range from the antenna to the DEM coordinate. The height at that coordinate is then transcribed into a two-dimensional array indexed by range and along-track position.

Table 4. Coordinate Reference System Definitions

Parameter	Value	
	WGS 84	Old Hawaiian Datum
Semimajor axis	6378137.0	6378206.4
Square of eccentricity	0.00669437999015	0.0067686579
DX[a]	...	61
DY	...	−285
DZ	...	−181

[a]Datum vector offset relative to WGS 84 Cartesian coordinates.

After all DEM coordinates are mapped, the resulting "range-azimuth" image may be sparsely filled; the mapping from map coordinates to slant range coordinates is not regular when topography is present. The vacant image points are typically few and are filled in by interpolation.

The shuttle ephemeris vectors were specified relative to the World Geodetic System (WGS 84) datum and the DEM points in UTM coordinates of the Old Hawaiian datum. Conversion from the northing-easting values of the Old Hawaiian UTM datum to latitude and longitude followed *Snyder* [1983]. Conversion from latitude λ, longitude θ, and height above the WGS 84 ellipsoid h to rectangular coordinates (X, Y, Z) used

$$X = [r_e(\lambda) + h] \cos(\lambda) \cos(\theta) \tag{10}$$

$$Y = [r_e(\lambda) + h] \cos(\lambda) \sin(\theta) \tag{11}$$

$$Z = [r_e(1 - e^2) + h] \sin(\lambda) \tag{12}$$

where $r_e(\lambda)$ is the radius of curvature in the east direction given by

$$r_e(\lambda) = \frac{a}{[1 - e^2 \sin^2(\lambda)]^{1/2}}, \tag{13}$$

e^2 is the square of the eccentricity of the figure of the Earth, and a is the semimajor axis. WGS 84 vectors are obtained to within 5-m accuracy by adding an offset vector to the rectangular coordinates obtained above. WGS 84 and Old Hawaiian datum parameters and the datum offset values are given in Table 4. Failure to convert from UTM to rectangular coordinates properly results in distortions such as skew and higher order warping that inhibit the fine co-registration between the simulated and measured interferogram required for differential interferometry applications.

In addition to the height, the radar brightness is simulated. Radar brightness is proportional to the local incidence angle according to the surface's backscattering phase function. The local incidence angle is determined from the local slope (the numerical gradient of the DEM) and radar line-of-sight vector. A very realistic brightness image arises from assuming a $\cos^2(\ \ )$ phase function.

The orbit is not known precisely, so the simulated imagery does not align perfectly with the radar image. A straightforward brightness correlation gives the offsets required to register the simulation to the data.

Appendix B: Baseline Estimation

With the unwrapped interferogram phase and the topographic heights available in the same slant-range coordinate system, an accurate baseline can be estimated from thousands of "ground control points" through (2). The accuracy requirements on baselines for topographic mapping and deformation measurements are discussed elsewhere [*Zebker et al.*, 1994a,b].

The phase computed from the interferogram is known only modulo 2π rad, whereas the phase field representing the topography and surface change is a continuous field. It is necessary to unwrap the phase in a way that does not introduce error or phase inconsistencies [*Goldstein et al.*, 1988]. Phase unwrapping errors are difficult to characterize; however, they generally arise when the interferometric fringe rate is high or the data are very noisy. For the purposes of phase unwrapping, the interferogram was smoothed to a pixel resolution of 200 m to reduce phase noise. The fringe rate at L band is quite slow, so rapid fringe variation was not a significant problem.

The accuracy of the baseline is determined by the accuracy of the unwrapped phase and the DEM heights. The stability of the baseline estimate depends largely on the extent to which the measured image phase is related to topography. From (7), if the unwrapped phase has a component unrelated to topography of magnitude 2π rad, then the inferred topography will be in error by the ambiguity height, roughly 570 m. Such inconsistency will cause the baseline to be highly dependent on the ground control points used to derive it.

Two sets of control points were selected to determine the baseline: points covering the entire imaged area and points covering only the area north of the active deformation measured by GPS. The two baselines were quite different in length; however, their perpendicular components were roughly the same (see Table 5). This is understood from (7), which shows that the topography is determined to first order by $B_\perp$. The second-order term neglected in this equation contains the parallel baseline component:

$$\phi_2 = \frac{4\pi}{2\lambda} B_{\|0} \left(\frac{z}{\rho_0 \sin \theta_0} \right)^2, \tag{14}$$

This term varies by less than 0.1 rad over the extent of the scene's topography. The maximum topographic error induced by neglecting this term is $0.1 h_a / 2\pi \approx 10$ m, which is less than the accuracy of the USGS DEM. This implies that it is not important to know $B_{\|0}$.

This is fortunate because phase distortions exceeding about 2 rad exist in the data and primarily influence the estimate of the parallel component. At the 200-m resolution of these unwrapped phases, the statistical phase noise is negligible. However, there is deformation of the surface present in the interferogram: GPS has measured a maximum rate of surface deformation of 5 cm in 6-months. From (7), this would correspond to about 2.6 rad of phase change at L band. Other phase distortions, for example, from propagation delays in the variable atmosphere, may also exist.

Table 5. Baseline Estimates

	Entire Image	North Image
$\lvert B \rvert$, m	143.8	103.0
α, deg	176.0	−172.0
B_c, m	−143.4	−102.0
B_h, m	10.1	−14.4
$B_\perp$,[a] m	−68.0	−66.7
$B_\|$,[a] m	−126.6	−78.5

[a]Computed for $\theta = 57.6°$.

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