Topographic Mapping from Interferometric Synthetic Aperture Radar Observations

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Abstract: Interferometric synthetic aperture radar observations provide a means for obtaining high-resolution topographic maps of a region through interpretation of interference fringes. This technique, which utilizes data acquired either i) simultaneously from two slightly displaced antennas or ii) from two different recording intervals but with complete knowledge of the relative observing geometries, permits calculation of the three-dimensional coordinates of any given point in an image. The combination of height, along track, and slant range measurements is sufficient to allow rectification of the radar imagery for cartographic applications in addition to providing an accurate determination of the scene topography. We have derived topographic maps utilizing data recorded by a radar system mounted on a NASA CV990 aircraft, and processed on a general purpose digital computer. These maps consist of the height above sea level of regions approximately 11 km by 9 km in size, sampled on an 11 m grid. Uncertainties in the estimated height result from imprecise knowledge of the observational geometry, radar range bandwidth limitations, and signal-to-noise ratio considerations. For our system the error contribution from each source is approximately 3-4 m, resulting in an overall rms error of about 6 m. Analysis of a typical aircraft data set recorded over the ocean, which we can presume to be quite flat, yields a 6 m rms variation, which is consistent with the theoretically derived values. As our topographic maps represent the most accurate digital altitude data describing the imaged regions available to us, it is difficult to assess the absolute accuracy of our system. However, comparison with United States Geological Survey contour maps indicates a high degree of correlation between the two sets of altitude data.

Radar-interferometric techniques have been utilized to remove the north/south ambiguity in Earth-based observations of Venus (1), to measure lunar and Venusian topography (2,3,4), and to observe interference fringes modulated by Earth topography (5). We report here our determination of high-resolution topographic maps derived from interferometric synthetic aperture radar observations of the Earth.

Topographic maps are typically determined from stereo-pair optical photographs (6). Vertical relief causes the same terrain to appear in a slightly different projection for differing look angles, and this shift in appearance is interpreted in terms of the height of the terrain. The radar interferometric approach is related to the stereo technique in that the terrain is viewed at two different angles, however in our case the angular separation of the antennas in extremely small, on the order of a milliradian or less, as compared to tens of degrees for the optical case. Thus, the

geometrical distortion and subsequent rectification correction algorithms are much less severe in the reduction of interferometric data. Recently, stereo-pair radar imagery has also been used to produce topographic maps (7), however the methods used are extensions of the optical stereo technique rather than the interferometric approach described here.

We utilize data that were recorded using a side-looking synthetic aperture radar system mounted on a NASA CV990 aircraft, and processed at the Jet Propulsion Laboratory using a digital data processor implemented in software on a general purpose VAX 11/780 computer. The radar and processor operating characteristics are summarized in Table 1. We configure the airplane radar hardware such that a signal is transmitted by a single antenna mounted on the underside of the right wing of the aircraft; reflected energy from the ground is received by that antenna and simultaneously by a second antenna on the underside of the left wing. Data from each antenna are recorded and processed separately to yield two 10-m resolution complex (magnitude and phase) images of the illuminated terrain. Interference fringes are produced when these two data sets are combined point by point to obtain a single image whose phase at each location is the difference of the two original phases, and whose magnitude is the product of the two original magnitudes.

The radar instrument, as with most pulsed radar systems, yields the line-of-sight distance, or slant range ρ, from the antenna to the target (see Figure 1a). However, this distance is indeterminate within the slant range resolution of the radar, which depends principally on the transmitted signal bandwidth. For our system this uncertainty is approximately ±3.75 m. The interferometric technique permits in addition the determination of the distance $\rho - \rho'$ to much greater precision, typically to an accuracy of a centimeter. Application of simple geometric identities then yields the vertical distance from the antennas to the surface. This measurement, when combined with the usual along-track and slant range measurements, yields the three-dimensional position of a given point in the image. Knowledge of the location of each point then permits rectification of the image to a cartographically accurate form.

We illustrate the observational geometry in more detail in Figure 1b. Two antennas, A_1 and A_2, separated by a baseline distance B, are mounted at an angle θ with respect to horizontal. For the aircraft system we used the angle θ is very nearly zero, but it does change slightly as the aircraft rolls. The depression angle of an illuminated point is α. The path difference $\rho - \rho'$ is thus related to these angles by

$$\rho - \rho' = B \cos (\theta + \alpha) \qquad (1)$$

while the height h is

$$h = \rho \sin \alpha \qquad (2)$$

The measured phase ϕ of the interference pattern at a point is the corresponding distance $\rho - \rho'$ in wavelengths, which expressed in radians is

$$\phi = (\rho - \rho') \cdot \frac{2\pi}{\lambda} \qquad (3)$$

Combining (1), (2), and (3) we obtain an expression for h in terms of the

observational geometry B, θ and the measurable quantities ϕ and ρ, as follows:

$$h = \rho \sin \left(\cos^{-1} \frac{\phi\lambda}{2\pi B} - \theta \right) \qquad (4)$$

We apply (4) to the interference image in order to determine the vertical distance to the antennas, which we combine with the along-track and slant range measurements to infer the three-dimensional location of each point. The data is then rectified to correct for geometrical distortions and interpolated to fit a square grid, resulting in a cartographically accurate map of the height of the illuminated terrain. The original radar amplitude image can be interpolated using the same height data, with the result that the topography and the radar reflectivity are now precisely correlated in position. This aids in interpretation of the radar brightness data itself.

Differentiation of (4) with respect to ρ, ϕ, and θ yields the sensitivity of the height measurement to uncertainties in slant range, phase estimation, and antenna orientation, respectively. Typical values for airborne geometries yield a contribution to the overall error of about 3-4 m from each source, or roughly 6 m rms error.

Another type of error results from the 2π ambiguity associated with phase measurements, in other words, a phase measurement of x radians is indistinguishable from a measurement of $x + 2n\pi$ radians, where n is any integer. We overcome this problem by examining the data using an algorithm that is sensitive to phase differences in a two-dimensional field, and tracks the relative phase over the full image. We thus "unwrap" the ambiguous $2n\pi$ at each point to obtain a single-valued function valid over the entire image. This still leaves an absolute $2m\pi$ ambiguity, where m is an undetermined integer constant, which at present we remove using <u>a priori</u> knowledge of the true height at a single point in the image. The full interferometric data set is corrected for this absolute offset before applying (4) to determine the topographic map.

We assess the accuracy of the technique by comparison of a topographic image (not shown here) with United States Geological Survey topographic maps of the same area, however our interferometer data represent the most precise digital data available to us so it is difficult to determine the absolute accuracy. The contour maps are quite detailed and provide the best assessment of performance. At present only a preliminary comparison has been completed, but we have noted a considerable degree of coincidence between the two contour maps. We have also measured the standard deviation of the heights over part of an ocean region, which we can presume to be quite flat, and obtained a 6 m rms error. This is quite consistent with the above theoretical value. We hope to improve our verification technique in the future. However, we feel that the interferometric technique is a new, viable approach to the remote determination of topographic data.

References:

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Table 1. Radar Operating Characteristics

1. Wavelength	23.5 cm
2. Resolution	Approximately 10 m by 10 m at 4 looks
3. Range bandwidth	18 MHz
4. Peak power	5 kW
5. Pulse length	4.9 μsec
6. Pulse repitition rate	1.5 per meter along track
7. Ground track velocity	200 - 300 m sec^{-1}
8. Look angle	25 - 55 degrees
9. Aircraft altitude	8 - 14 km
10. Aircraft roll error	±0.1 degree

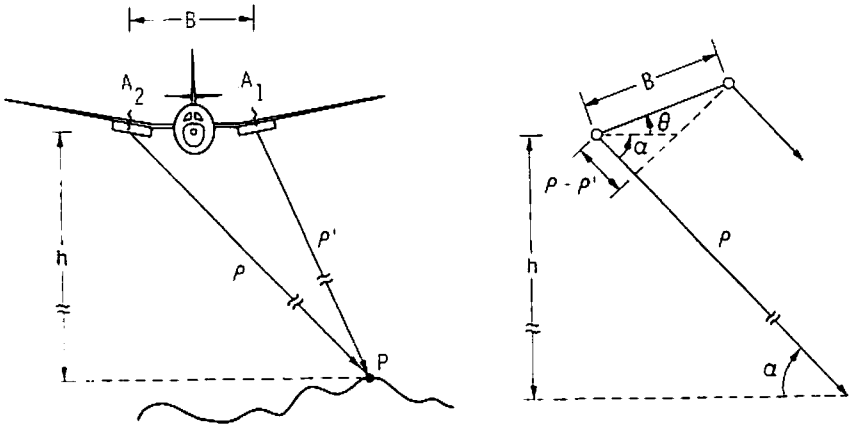

Figure 1a (left) indicates schematically the observational geometry of the interferometer. A wave is transmitted from antenna A_1 and is received simultaneously by antennas A_1 and A_2. Conventional radar measures the distance ρ to an accuracy of ±3.75, interferometric technique permits in addition the determination of $\rho - \rho'$ to about 1 cm. These two measurements, with the geometrical factors B and θ shown in detail in Figure 1b (right), are sufficient to find aircraft height h for each point in the radar image.