THE NASA/JPL AIRCRAFT TOPOGRAPHIC SYNTHETIC APERTURE RADAR (TOPSAR) SYSTEM FOR RAPID PRODUCTION OF DIGITAL TERRAIN MODELS

Thomas W. Thompson
Howard A. Zebker
Richard E. Carande
Paul A. Rosen
Soren N. Madsen
Scott Hensley
Ernesto Rodriguez
Jakob J. van Zyl
Timothy W. Miller

Jet Propulsion Laboratory
California Institute of Technology

Abstract

An aircraft radar interferometer, TOPSAR for TOPographic SAR, has been developed that uses a synthetic aperture radar and interferometry to rapidly produce topographic maps of the earth. In some applications, this aircraft radar interferometer system can map areas inaccessible to aerial photography because of darkness or weather. In other applications, this radar technique has the potential of replacing traditional photogrammetry which uses aerial photography. Our aircraft radar is a processor to a possible satellite system, which can produce a global digital topographic map of the earth.

The TOPSAR system is a C-band (6 cm wavelength) radar interferometer that is operated as an adjunct to the JPL Aircraft Synthetic Aperture Radar (AIRSAR) system that routinely acquires multi-polarization SAR images at P-band (70 cm wavelength), at L-band (25 cm wavelength) and at C-band. The TOPSAR/AIRSAR system flies on the DC-8 Airborne Laboratory operated by the NASA Ames Research Center. The TOPSAR system is implemented via two antennas mounted nearly vertically on the left side of the DC-8 aircraft with a 2.6 meter baseline spacing. Interferometric maps of the surface are constructed by comparing the phase differences between SAR images from the two antennas. Statistical elevation errors for the TOPSAR system range from 1-2 meters for flat land to 2-3 meters for mountainous areas.

Typical data acquisitions are for areas of 10 km across-track (i.e., in range) and up to 50 km along track (i.e., in azimuth). Analysis of radar data obtained in the Galapagos Islands (Islas Fernandina and Isabella) demonstrated that these 10 km-by-50 km topographic maps could be mosaicked together for an area of about 50 km-by-50 km. We improved the TOPSAR aircraft radar system in 1994 by installing a new tightly-coupled Global Positioning/Inertia Navigation System (GPS/INS) unit. This improved our topographic data and enabled mosaicking via dead reckoning.

These aircraft observations are a precursor for a possible earth-orbiting TOPographic SATellite (TOPSAT), which is currently in premission studies at JPL. Current studies indicate that TOPSAT could be a dual spacecraft 24-cm system or a single spacecraft 2-cm system. Current studies indicate that either spaceborne interferometric SAR system could produce topographic maps of the earth with 2 meter vertical accuracies for horizontal resolutions of 30 meters. In addition, a third flight of the Spaceborne Imaging Radar (SIR-C) on the Space Shuttle could obtain these horizontal; and vertical accuracies.

Introduction

Recent advances in locating aircrafts via the Global Positioning System (GPS) as well as the computer revolution that took place in the last decade enables a technology whereby Synthetic Aperture Radars (SARs) can produce topographic images of the earth with airborne radar systems.

Synthetic Aperture Radars (SARs) were developed following World War II as a means of providing military intelligence by producing images of surfaces toward the aircraft's horizon. This SAR technology was adopted to earth orbiting satellites in the NASA SeaSat mission that flew in 1978. Follow-on spaceborne SARs operated on the Space Shuttle as the Shuttle Imaging Radar missions in 1978, 1984, and 1994. In addition, the Europeans currently operate a spaceborne SAR on the Earth Resources Satellite (ERS-1) and the Japanese operate a spaceborne SAR on the Japanese Earth Resources Satellite (JERS-1). The Canadians will launch and operate the RadarSAT satellite later this year. One of the important advances of these satellite SARs was the development of digital processors that used digital computers to produce radar images of the earth's surface.

Another important advance was the augmentation of SARs with two-element interferometry whereby phase differences between radar echoes observed in two separated antennas could be used to determine the height of the surface being imaged by the radar. Two-element interferometry was demonstrated first with satellite observations where the separation between two radar observations of the earth had accurate locations determined by spacecraft orbits. The implementation of this two-element interferometry in aircraft SARs requires accurate determinations of the small but important aircraft motions. This is now being provided by Global Positioning System instrumentation.

Thus, the culmination of digital processing of SARs, coupled with two-element interferometry and accurate position determination using the Global Positioning System have produced a new technology whereby airborne radars can produce accurate elevation maps of the earth. See Zebker and Goldstein, 1986; Rodriguez and Martin, 1992; Zebker et al., 1992; Madsen et al., 1993; Madsen, Martin and Zebker, 1995; as well as Madsen and Zebker, 1995.

Locating Radar Echoes in Three Dimensions

Airborne Synthetic Aperture Radars equipped with two separated antennas can accurately locate radar echoes from the surface in three dimensions. SARs locate scattering elements on the surface in two nearly orthogonal directions by a combination of ranging and Doppler processing. (Doppler processing creates a synthetic antenna aperture by coherently adding radar echoes from many consecutive pulses). The addition of two-element interferometry permits location of echoes in a third, nearly orthogonal dimension. The geometry for locating the scattering element on the surface is shown in Figure 1.

Elements on the surface are located first in range by transmitting a pulse and measuring the time delay of the echo. The range to the scattering element, the distance between the aircraft radar antenna and the surface, is:

$$R = \frac{ct}{2} \tag{1}$$

Where R is the range, c is the velocity of light, and t is the time delay (the difference in time between transmission of the radar pulse and reception of the echo). Ranging locates the echo on a "Range Sphere" centered on the aircraft as shown in Figure 1. The accuracy of this echo location by ranging is ΔR, the width of that spherical shell. This is :

$$\Delta R = \frac{c}{2B} \tag{2}$$

where B is the bandwidth of the system. Since we normally operate TOPSAR at 8 to 10 km altitudes, range to the surface is typically 9 to 15 km, and time delay is typically 60 to 100 microseconds. Our TOPSAR bandwidth is 40 Megahertz yielding surface resolutions of about 5 meters.

Echo location by the Doppler processing that forms the synthetic antenna aperture places echoes along "Doppler Cones," which are conical shells with axes aligned with the aircraft's velocity vector as shown in Figure 1. For the broadside geometries where SARs typically operate, these conical shells are located on the surface ahead or behind the true broadside direction by:

$$F = \frac{R\lambda\Delta f}{2V} \tag{3}$$

where F is the distance ahead or behind true broadside, V is the aircraft velocity, Δf is Doppler frequency, λ is the wavelength, and R is the range. For a our aircraft radar operating at 6-cm wavelength on an aircraft traveling at 200 meter/second, F in meters is 1.5 times the Doppler in hertz. The accuracy of locating echoes in these "Doppler cones" is:

$$\Delta F = \frac{R\lambda}{2VT} \tag{4}$$

where T is the time that echoes are coherently integrated to form the synthetic aperture. For a coherent integration time of one second, ΔF can be determined with a surface resolution of about 2 meters.

When synthetic aperture radars image a relatively flat surface, these Range Spheres and Doppler Cones intersect the surface in contours that nearly parallel and perpendicular to the aircraft's ground track. Thus, SARs operating without interferometry produce images that have a photographic quality and provide good representations of the surface. For rugged surfaces, these SAR images of the surface are distorted. Higher portions of the surface are shifted toward the aircraft ground track in a foreshortening effect. That foreshortening effect can be measured directly and corrected for by augmenting the SAR with two antennas as described here.

Once echoes have been located by ranging and Doppler processing they lie in the thin intersection of the Range Spheres and Doppler Cones. The location of radar echoes along that intersection are provided by interferometry which produces a phase difference between echoes observed in two separate antennas. This phase difference is:

$$\Delta\phi = 360^\circ\left(\frac{hB}{R\lambda}\right) \tag{5}$$

where h is the distance along the Range Sphere-Doppler Cone intersection and B is the baseline formed by the two antennas. The effective baseline of our TOPSAR system is near 2 meters. Thus, one meter displacement along the Range Sphere-Doppler Cone intersection produces about 1.2 degrees of phase difference. Since interferometer phase differences can be measured to a few degrees, this establishes echo location to a few meters along the Range Sphere-Doppler Cone intersection. Note that locating echoes to 1 meter at 10 km requires baseline orientations accurate to 0.0001 radians (0.006 degrees)!

The determination of echo phase difference in the interferometer locates echoes on a "Phase Cones", which are conical shells with axes aligned with the interferometer baseline (the line through the two elements of the interferometer). Thus, radar echoes from the surface can be located in three dimensions as shown in Figure 1 by augmenting aircraft SARs with two antennas that operate as an interferometer. Echoes can be located to an accuracy of a few meters. Once echoes have been located in three dimensions, the effects of foreshortening can be corrected for and the SAR images can be reprojected as true geometric representations of the surface. At the same time, an interferometric SAR radar system produces a topographic map (i.e., a Digital Elevation Model, DEM) of the surface.

Implementation

An radar interferometric aircraft SAR (TOPSAR for TOPographic SAR) has been implemented by the Jet Propulsion Laboratory (JPL) at a C-band wavelength as an augmentation to the JPL Aircraft Synthetic Aperture Radar (AIRSAR) system. The AIRSAR system routinely acquires multi-polarization SAR images at P-band (70 cm wavelength), at L-band (25 cm wavelength) and at C-band (6 cm wavelength). The TOPSAR/AIRSAR system flies on the DC-8 Airborne Laboratory operated by the NASA Ames Research Center (Figure 2). The TOPSAR interferometric radar system is implemented via two antennas mounted nearly vertically on the left side of the DC-8 aircraft with a 2.6 meter spacing. A block diagram of the TOPSAR/AIRSAR radar system (Figure 3) shows that several portions of the radar are shared between the TOPSAR and AIRSAR systems. Parameters for the TOPSAR/AIRSAR system are given in Table 1.

Operation of our TOPSAR System over typical terrains indicates that elevation errors for the TOPSAR DEMs are 1-2 meters for flat area and 2-3 meters for mountainous areas (see Madsen, Zebker, and Martin, 1993 and Madsen, Martin and Zebker, 1995). Horizontal resolutions are near 5 meters. Typical data acquisitions are for areas of 10 km across-track (i.e., in range) and up to 50 km along track (i.e., in Doppler). Processing of radar data obtained in the Galapagos Islands (Islas Fernandina and Isabella) and at Fort Irwin, California demonstrated that these 10 km-by-50 km topographic maps can be mosaicked together for an areas of about 50 km-by-50 km in size.

The TOPSAR aircraft radar system was improved in 1994 by installing a new tightly-coupled Global Positioning/Inertia Navigation System (GPS/INS) unit. This improved our topographic data and enabled mosaicking via dead reckoning. Absolute position location was reduced to 15 meters, aircraft velocities are known to 0.03 m/s, aircraft attitude (roll, pitch, yaw) are determined to 0.005 degrees. These accuracies have enabled the determination of echo location to the meter levels noted above.

Aircraft Radar Examples

An example of TOPSAR data is Figure 4, a perspective view of Isla Isabela, one of the Galapagos Islands located off the western coast of South America. This view was constructed by overlaying Spaceborne Imaging Radar (SIR-C) backscatter images over a Digital Elevation Model (DEM) produced by the aircraft TOPSAR system. Vertical exaggeration is 1.9; the vertical relief in this scene is 1500 meters.

As noted above, the implementation of interferometric SARs has depended upon the recent advances in aircraft location available with commercially available Global Position System devices. This implementation has been demonstrated with acquisition of topographic data for a number of research sites. Processing of data for these research areas indicate that individual images of 10-by-50 km can be produced once per day. A mosaic of several of these images takes a few days. Thus, the topographic mapping of areas up to 100-by-100 km can be produced in few weeks.

Future Directions In Spaceborne Interferometic SARs

The interferometric SAR techniques that have been demonstrated here for aircraft radars also work from spaceborne platforms. The Spaceborne Imaging Radar (SIR-C) flown in October 1994 conducted feasibility experiments that demonstrated that obtained topographic radar images of a number of sites. If a third Spaceborne Imaging Radar mission is flown, data collection would emphasize acquisition of interferometric data.

Recent premission studies for a TOPographic SATellite (TOPSAT) indicate that spaceborne SARs could produce DEMs of the earth with 2 meter vertical accuracies for horizontal cells of 30 meters width (See Zebker, et al., 1994). TOPSAT could be a dual spacecraft 24-cm system or a single spacecraft 2-cm system. The vertical and horizontal resolution of either configuration is determined by phase noise, due to signal-to-noise estimates as well as errors in determining antenna baseline attitudes. These spacecraft systems can accomplish larger (20 to 75 km) swath widths than aircraft systems.

Acknowledgement

We thank the AIRSAR Operations Group at JPL for their superb operation of the AIRSAR/TOPSAR Radar System, used in collecting data of our research areas. In addition, we thank the Medium Altitude Mission Branch at NASA Ames Research Center for their continued operation of the NASA DC-8 Airborne Laboratory, the platform for our observations.

The research described in this paper was performed at the Jet Propulsion Laboratory, California Institute of Technology under a contract with the National Aeronautics and Space Administration.

References

S. N. Madsen, H. A. Zebker, and J. M. Martin, "Topographic Mapping Using Radar Interferometry: Processing Techniques," IEEE Transactions on Geoscience and Remote Sensing, Vol. 31, No. 1, pp. 246–256, January 1993

S. N. Madsen, J. M. Martin, and H. A. Zebker, "Analysis and Evaluation of the NASA/JPL Across-Track Interferometric SAR System," IEEE Transactions on Geoscience and Remote Sensing, Vol. 33, No. 2, pp. 383–391, March 1995

S. N. Madsen and H A. Zebker, "Imaging Radar Interferometry," Chapter 17, Manual of Remote Sensing (3rd Edition), American Society of Photogrammetry, In Press, Fall 1995

E. Rodriguez and J. M. Martin, "Theory and Design of Interferometric Synthetic Aperture Radars," IEE Proceedings, Vol. 139, pp. 147–159, 1992

H. A. Zebker and R. M. Goldstein, "Topographic Mapping from Interferometric Synthetic Aperture Radar Observations," Journal Geophysical Research, Vol. 91, No. B5, pp. 4993–4999, 1986

H. A. Zebker, S. N. Madsen, , K. B. Wheeler, T. Miller, Y. Lou, G Alberti, S. Vetrella, and C. Cucci, "The TOPSAR Interferometic Radar Topographic Mapping Instrument," IEEE Transactions on Geoscience and Remote Sensing, Vol. 30, pp. 934–940, September 1992

H. A. Zebker, T. G. Farr, R. P. Salazar and T. H. Dixon, "Mapping the World's Topography Using Radar Interferometry: The TOPSAT Mission," Proceedings of the IEEE, Vol. 82, No. 12, pp. 1774–1786, December 1994

Table 1. TOPSAR System Parameters

Frequency	5.3 Ghz
Wavelength	5.7 cm
Range Bandwidth	40 MHz
Peak Power	1.0 Kwatts
Antenna Length	1.6 meters
Antenna Width	0.11 meters
Antenna Gain	25 dB
Antenna Baseline	2.6 meters
Antenna Angle	62.8 degrees
Horizontal Resolution	5 meters
Vertical Resolution	1-2 meters - Level areas 2-3 meters - Rugged areas
Altitude	typically 9 km
Platform Velocity	nominally 200-250 m/s
Image Width	10-12 Kms
Image Length	30-60 Kms
Look Angle	30-60 degrees
GPS/INS Location	±15 m
GPS/INS Velocity	±0.03 m/s
GPS/INS Attitude	±0.005°

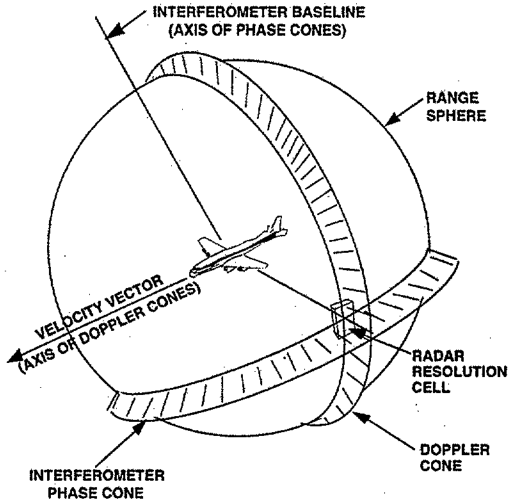

Figure 1. Geometry for three-Dimensional Echo Location

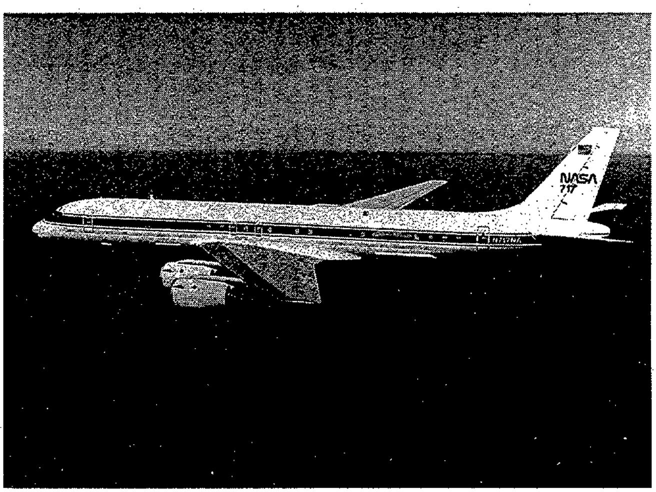

Figure 2. NASA Ames DC-8 Airborne Laboratory, the Aircraft Platform for the JPL TOPSAR/AIRSAR Radar System

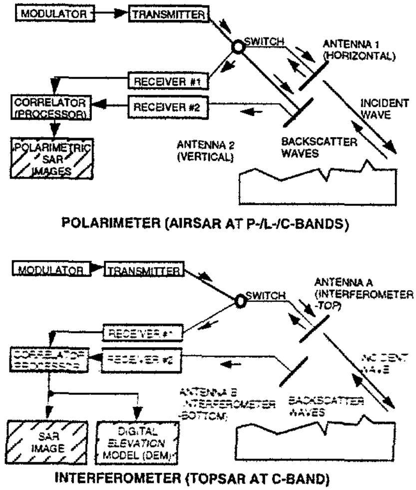

Figure 3. Block Diagram for NASA/JPL Aircraft Polarametric SAR (AIRSAR) and Interferometric SAR (TOPSAR) Radar Systems

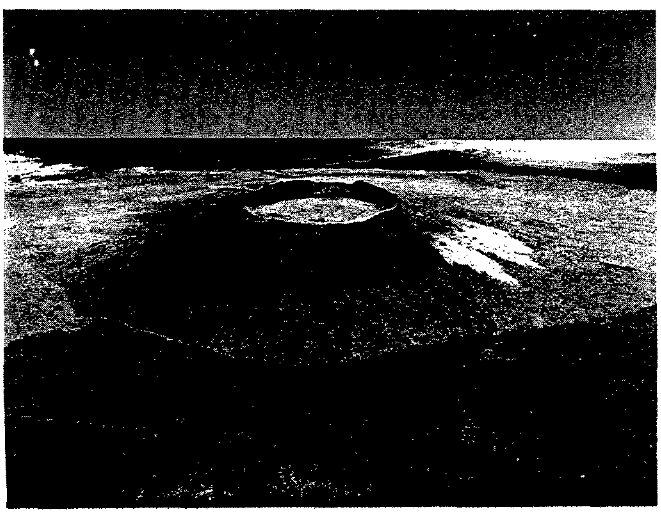

Figure 4. Example of TOPSAR Topographic Image, a Perspective View of Isla Isabela, Galapagos Island Produced from TOPSAR and Spaceborne Imaging Radar Data (JPL Photo P-43940).