

SAR POLARIMETRY AND INTERFEROMETRY

Jakob J. van Zyl

*Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena, CA 91109, USA*

1. introduction

The field of synthetic aperture radar changed dramatically over the past decade with the operational introduction of advanced radar techniques such as polarimetry and interferometry. While both of these techniques had been demonstrated much earlier, radar polarimetry only became an operational research tool with the introduction of the NASA/JPL AIRSAR system in the early 1980's, and reached a climax with the two SIR-C/X-SAR flights on board the space shuttle Endeavour in April and October 1994. Radar interferometry received a tremendous boost when the airborne TOPSAR system was introduced in 1991 by NASA/JPL, and further when data from the European Space Agency IRS-1 radar satellite became routinely available in 1991.

These advanced radar techniques are now well understood, even if all the problems are not yet solved. This paper summarizes the state-of-the-art in these two fields as of the middle of 1995, concentrating on the last three years.

2. SAR Polarimetry

Electromagnetic wave propagation is a vector phenomenon, i.e. all electromagnetic **waves** can be expressed as complex vectors. Plane electromagnetic waves can be represented by two-dimensional complex vectors. This is also the case for spherical waves when the observation point is sufficiently far removed from the source of the spherical wave. Therefore, if one observes a wave transmitted by a radar antenna when the wave is a large distance from the antenna (in the far-field of the antenna), the radiated electromagnetic wave can be adequately described by a two-dimensional complex vector. If this radiated wave is now scattered by an object, one observes this wave in the far-field of the scatterer, the scattered wave can again be adequately described by a two-dimensional vector. In this abstract way, one can consider the scatterer as a mathematical operator which takes one two-dimensional complex vector (the wave impinging upon the object) and changes that into another two-dimensional vector (the scattered wave). Mathematically, therefore, a scatterer can be characterized by a complex 2x2 scattering matrix. However, this matrix is a function of the radar frequency, and the viewing geometry.

The typical implementation of a radar polarimeter involves transmitting a wave of one polarization and receiving echoes in two orthogonal polarizations simultaneously. This is followed by transmitting a wave with a second polarization, and again receiving echoes with both polarizations simultaneously. In this way, all four elements of the scattering matrix are measured. This implementation means that the transmitter is in slightly different positions when measuring the two columns of the scattering matrix, but this distance is typically small compared to a synthetic aperture, and therefore does not lead to a significant decorrelation of the signals. The

NASA/JPL AIRSAR system pioneered this implementation for SAR systems [Zebker, *et al.*, 1987], and the same implementation was used in the SIR-C part of the SIR-C/X-SAR radars [Jordan, *et al.*, 1995].

The past three years have seen relatively little advance in the development of hardware for polarimetric SAR systems; newer implementations are simply using more advanced technology to implement the same basic hardware configurations as the initial systems. Significant advances were made, however, in the field of analysis and application of polarimetric SAR data.

2.1 Polarimetric SAR Calibration

Many of the advances made in analyzing polarimetric SAR data result directly from the greater availability of calibrated data. Polarimetric calibration usually involves four steps: cross-talk removal, phase calibration, channel imbalance compensation and absolute radiometric calibration [van Zyl, 1990]. Cross-talk removal refers to essentially correcting the cross-polarized elements of the scattering matrix for the effects of the system cross-talk that couples part of the co-polarized returns into the cross-polarized channel. Phase calibration refers to correcting the co-polarized phase difference for uncompensated path length differences in the transmit and receive chains, while channel imbalance refers to balancing the co-polarized and cross-polarized returns for uncompensated gain differences in the two transmit and receive chains. Finally, absolute radiometric calibration involves using some kind of a reference calibration source to determine the overall system gain to relate received power levels to normalized radar cross-section.

While most of the polarimetric calibration algorithms currently in use were published several years ago [van Zyl, 1990; Zebker and Lou, 1990; Gray, *et al.*, 1990; Freeman, *et al.*, 1991, Klein and Freeman, 1991] several groups are still actively pursuing the study of improved calibration techniques and algorithms. The earlier algorithms are reviewed in Zebker, *et al.* [1991] and Freeman *et al.* [1992], while Freeman [1992] provides a comprehensive review of SAR calibration in general. Some of these earlier algorithms are now routinely used to calibrate polarimetric SAR data operationally, as for example in the NASA/JPL AIRSAR and SIR-C processors [Freeman, *et al.*, 1995].

Some of the recent research deals with refining earlier algorithms. For example, Quegan [1994] recently published a unified cross-talk removal and phase calibration algorithm and derived the conditions under which the cross-talk removal algorithm previously published by van Zyl [1990] may yield inconsistent results. Sletten [1994] reported a method, based on using a rotated dihedral corner reflector, to resolve a co-polarized phase ambiguity during phase calibration. Other research deals with assessing the accuracy of the calibration algorithms as applied to SAR data. This is usually done by performing cross-calibration experiments using truck-mounted scatterometers deployed during the SAR overflights, such as the results reported by Sarabandi, *et al.* [1994]. In this experiment, the AIRSAR data were calibrated using the algorithm published by van Zyl [1990] using trihedral corner reflectors as calibration targets, and the results compared to those obtained with the University of Michigan's POLARSCAT truck-mounted scatterometer system calibrated with a reference sphere. The results show that coherent and incoherent interaction of the returns from the ground and the trihedral corner reflectors may significantly alter the

expected radar cross section of these calibration devices, resulting in inaccurate calibration. To circumvent these problems, Sarabandi [1994] introduced a calibration method that uses a known distributed target as the calibration reference. While this algorithm does not suffer from the deficiencies associated with those algorithms using point targets as references, it requires the known calibration surface to be measured with an accurately calibrated scatterometer. As in the case of algorithms involving point targets, one must also have reference surfaces that are distributed across the radar swath in order to estimate some of the range dependent calibration parameters such as the system cross-talk. Even though scatterometers can be routinely calibrated to better accuracies than SAR systems, it may not always be practical to measure enough surfaces to ensure accurate calibration across the entire range swath.

The availability of calibrated polarimetric SAR data allowed research to move from the qualitative interpretation of SAR images to the quantitative analysis of the data. This sparked significant progress in classification of polarimetric SAR images, led to improved models of scattering by different types of terrain, and allowed the development of some algorithms to invert polarimetric SAR data for geophysical parameters, such as forest biomass and surface roughness and soil moisture.

2.2 Classification of Earth Terrain

Many earth science studies require information about the spatial distribution of land cover types, as well as the change in land cover and land use with time. In addition, it is increasingly recognized that the inversion of SAR data for geophysical parameters involves an initial step of segmenting the image into different terrain classes, followed by inversion using the algorithm appropriate for the particular terrain class. Polarimetric SAR systems, capable of providing high resolution images under all weather conditions as well as during day or night, provide a valuable data source for classification of earth terrain into different land cover types.

Two main approaches are used to classify images into land cover types: 1) maximum likelihood classifiers based on Bayesian statistical analysis, and 2) knowledge-based techniques designed to identify dominant scattering.

Some of the earlier studies in Bayesian classification focused on quantifying the increased accuracy gained from using all the polarimetric information. Kong *et al.* [1988] and Lim *et al.* [1989] showed that the classification accuracy is significantly increased when the complete polarimetric information is used compared to that achieved with single channel SAR data. These earlier classifiers assumed equal *a-priori* probabilities for all classes, and modeled the SAR amplitudes as circular Gaussian distributions, which means that the textural variations in radar backscatter are not considered to be significant enough to be included in the classification scheme. van Zyl and Burnette [1992] extended the Bayesian classification to allow different *a-priori* probabilities for different classes. Their method first classifies the image into classes assuming equal *a-priori* probabilities, and then iteratively changes these probabilities for subsequent classifications based on the local results of previous classification runs. Significant improvement in classification accuracy is obtained with only a few iterations. More accurate results are obtained using a more rigorous maximum *a-posteriori* (MAP) classifier where the *a-priori* distribution of image classes is modeled as a Markov random field and the optimization of the image classes is done over the whole image instead of on a pixel-by-pixel basis [Rignot and

Chellappa, 1992] In a subsequent work, [Rignot and Chellappa, 1993] the MAP classifier is extended to include the case of multi-frequency polarimetric radar data. The MAP classifier was used by Rignot *et al.* [1994] to map forest types in the Alaskan boreal forest. In this study, five vegetation types (white spruce, balsam poplar, black spruce, alder/willow shrubs, and bog/sen/nonforest) were separated with accuracies ranging from 62% to 90%, depending on which frequencies and polarizations are used.

Knowledge-based classifiers use knowledge of dominant scattering mechanisms through an understanding of the physics of the scattering process as well as experience gained from extensive experimental measurements [Pierce, *et al.*, 1994]. One of the earliest examples of such a knowledge-based classifier was published by van Zyl [1989]. In this unsupervised classification, knowledge of the physics of the scattering process was used to classify images into three classes: odd numbers of reflections, even numbers of reflections, and diffuse scattering. The odd and even numbers of reflection classes are separated based on the co-polarized phase difference, while the diffuse scattering class is identified based on high cross-polarized return and low correlation between the co-polarized channels. While no direct attempt was made to identify each class with a particular terrain type, it was noted that in most cases the odd numbers of reflection class corresponded to bare surfaces or open water, even numbers of reflections usually indicated urban areas or sparse forests, sometimes with understory flooding present, while diffuse scattering is usually identified with vegetated areas. As such, all vegetated areas are lumped into one class, restricting the application of the results. Pierce, *et al.* [1994] extended this idea and developed a level 1 classifier that segments images into four classes: tall vegetation (trees), short vegetation, urban and bare surfaces. First the urban areas are separated from the rest by using the L-band co-polarized phase difference and the image texture at C-band. Then areas containing tall vegetation are identified using the L-band cross-polarized return. Finally, the C-band cross-polarized return and the L-band texture is used to separate the areas containing short vegetation from those with bare surfaces. Accuracies better than 90% are reported for this classification scheme when applied to two different images acquired in Michigan [Pierce, *et al.*, 1994]. Another example of a knowledge-based classification is reported by Hess *et al.* [1995]. In this study, a decision-tree classifier is used to classify images of the Amazonian floodplain near Manaus, Brazil into five classes based on polarimetric scattering properties: water, clearing, macrophyte, non-flooded forest and flooded forest. Accuracies better than 90% are reported.

2.3 Geophysical Parameter Estimation

One of the most active areas of research in polarimetric SAR involves estimating geophysical parameters directly from the radar data through model inversion. Space does not permit a full discussion of recent work. Therefore, in this section only a brief summary of recent work will be provided, with the emphasis on vegetated areas.

Many models exist to predict scattering from vegetated areas [Lang and Sidhu, 1983; Richards, *et al.*, 1987; Durden, *et al.*, 1989; Ulaby, *et al.*, 1990; Chauhan and Lang, 1991; Sun, *et al.*, 1991; Yuch, *et al.*, 1992; Wang, *et al.*, 1993; Hsu, *et al.*, 1994; Lang, *et al.*, 1994] and this remains an area of active research. Much of the work is aimed at estimating forest biomass [Dobson, *et al.*, 1992; Le Toan, *et al.*, 1992; Ranson and Sun, 1994; Beaudoin, *et al.*, 1994; Rignot, *et al.*, 1995]. Earlier works

correlated polarimetric SAR backscatter with total above-ground biomass [Dobson, et al., 1992; Le Toan, et al., 1992], and suggested that the backscatter saturates at a biomass level that scales with frequency, a result also predicted by theoretic models. This led some investigators to conclude that these saturation levels define the upper limits for accurate estimation of biomass [Imhoff, 1995], arguing for the use of low frequency radars to be used for monitoring forest biomass [Rignot, et al., 1995].

More recent work suggests that some spectral gradients and polarization ratios do not saturate as quickly and may therefore be used to extend the range of biomass levels for which accurate inversions could be obtained [Ranson and Sun, 1994]. Rignot, et al. [1995] showed that inversion results are most accurate for mono-species forests, and that accuracies decrease for less homogeneous forests. They conclude that the accuracies of the radar estimates of biomass are likely to increase if structural differences between forest types are accounted for during the inversion of the radar data.

Such an integrated approach to retrieval of forest biophysical characteristics is reported in Ranson et al. [1995] and Dobson et al. [1995]. These studies first segment images into different forest structural types, and then use algorithms appropriate for each structural type in the inversion. Furthermore, Dobson et al. [1995] estimates the total biomass by first using the lidar data to estimate tree basal area and height and crown biomass. The tree basal area and height are then used in allometric equations to estimate the trunk biomass. The total biomass, which is the sum of the trunk and crown biomass values, is shown to be accurately related to allometric total biomass levels up to 25 kg/m^2 , while Kasischke et al. [1995] estimates that biomass levels as high as 34 to 40 kg/m^2 could be estimated with an accuracy of 15-25% using multipolarization C, L, and P-band SAR data.

Research in retrieving geophysical parameters from non-vegetated areas is also an active research area, although not as many groups are involved. One of the earliest algorithms to infer soil moisture and surface roughness for bare surfaces was published by Oh et al. [1992]. This algorithm uses polarization ratios to separate the effects of surface roughness and soil moisture on the radar backscatter, and an accuracy of 4% for soil moisture is reported. More recently, Dubois et al. [1995] reported a slightly different algorithm, based only on the co-polarized backscatters measured at L-band. Their results, using data from scatterometers, airborne SARs and spaceborne SARs (SIR-C) show an accuracy of 4.2% when inferring soil moisture over bare surfaces. Shi and Dozier [1995] reported an algorithm to measure snow wetness, and demonstrated accuracies of 2.5%.

3. SAR Interferometry

SAR interferometry refers to a class of techniques where additional information is extracted from SAR images that are acquired from different vantage points, or at different times. Various implementations allow different types of information to be extracted. For example, if two SAR images are acquired from slightly different viewing geometries, information about the topography of the surface can be inferred. On the other hand, if images are taken at slightly different times, a map of surface velocities can be produced. Finally, if sets of interferometric images are combined, subtle changes in the scene can be measured with extremely high accuracy.

in this section, we shall first discuss so-called cross-track interferometers used for the measurement of surface topography. This will be followed by a discussion of along-track interferometers used to measure surface velocity. The section is ended with a discussion of differential interferometry used to measure surface changes and deformation. We shall not repeat the theory of radar interferometry here; as it has previously been described by *Graham* [1974], *Zisk* [1972a, 1972b], *Zebker and Goldstein* [1986], and *Massonnet and Rabaute* [1993]. Instead, we shall concentrate on implementations, and point out the areas where more research is needed.

3.1 Radar Interferometry for Measuring Topography

SAR interferometry was first demonstrated by *Graham* [1974], who demonstrated a pattern of nulls or interference fringes by vectorially adding the signals received from two SAR antennas; one physically situated above the other. Later, *Zebker and Goldstein* [1986] demonstrated that these interference fringes can be formed after SAR processing of the individual images if both the amplitude and the phase of the radar images are preserved during the processing. For details of the theory of radar interferometry, the reader is referred to *Rodriguez and Martin* [1992].

SAR interferometers for the measurement of topography can be implemented in one of two ways, in the case of single-pass interferometry, the system is configured to measure the two images at the same time through two different antennas usually arranged one above the other. The physical separation of the antennas is referred to as the baseline of the interferometer. In the case of repeat-track interferometry, the two images are acquired by physically imaging the scene at two different times using two different viewing geometries.

So far all single pass interferometers have been implemented using airborne SARs [*Zebker and Goldstein*, 1986; *Zebker et al.*, 1992; *Faller and Meier*, 1995]. Most of the research has gone into understanding the various error sources and how to correct their effects during and after processing. As a first step, careful motion compensation must be performed during processing to correct for the actual deviation of the aircraft platform from a straight trajectory [*Madsen, et al.*, 199?]. As mentioned before, the single-look SAR processor must preserve both the amplitude and the phase of the images. After single-look processing, the images are carefully co-registered to maximize the correlation between the images. The so-called interferogram is formed by subtracting the phase in one image from that in the other on a pixel-by-pixel basis.

Once the images are processed and combined, the measured phase must be unwrapped. During this procedure, the measured phase, which varies only between 0 and 360° , must be unwrapped to retrieve the original phase by adding or subtracting multiples of 360° . The earliest phase unwrapping routine was published by *Goldstein et al.* [1988]. In this algorithm, areas where the phase will be discontinuous due to layover or poor signal-to-noise ratios are identified by branch cuts, and the phase unwrapping routine is implemented such that branch cuts are not crossed when unwrapping the phases. Extensions and refinements of this technique were proposed by *Lin et al.* [1992]. Phase unwrapping remains one of the most active areas of research, and many algorithms remain under development, but have not yet appeared in the open literature.

Even after the phases have been unwrapped, the absolute phase is still not known. This is required to produce a height map that is calibrated in the absolute sense. One way to estimate this absolute phase is to use ground control points with known elevations in the scene. However, this human intervention severely limits the case

with which interferometry can be used operationally. *Madsen et al.* [1993] reported a method by which the radar data itself is used to estimate this absolute phase. The method breaks the radar bandwidth up into an upper and lower halves, and then uses the differential interferogram formed by subtracting the upper half spectrum interferogram from the lower half spectrum interferogram to form an equivalent low frequency interferometer to estimate the absolute phase. Unfortunately, this algorithm is not robust enough in practice to fully automate interferometric processing. This is one area where significant research is needed if the full potential of automated SAR interferometry is to be realized.

Absolute phase determination is followed by height reconstruction. Once the elevations in the scene are known, the entire digital elevation map can be geometrically rectified. For the NASA/JPL TOPSAR interferometer, *Madsen et al.* [1993] reported accuracies ranging between 2.2 m r.m.s. for flat terrain and 5.5 m r.m.s. for terrain with significant relief.

An alternative way to form the interferometric baseline is to use a single channel radar to image the same scene from slightly different viewing geometries. This technique, known as repeat-track interferometry, has been mostly applied to spaceborne data starting with data collected with the L-band SEASAT SAR [*Goldstein, et al., 1988; Li and Goldstein, 1990; Prati and Rocca, 1990; Prati et al., 1990; Zebker and Villasenor, 1992; Prati and Rocca, 1995*]. Other investigators used data from the L-band SIR-B [*Gabriel, et al., 1989*], the C-band ERS-1 radar [*Gatelli, et al., 1994; Zebker, et al., 1994a*], and more recently the L-band SIR-C [*Stofan, et al., 1995*] and the X-band X-SAR [*Moreira, et al., 1995*]. Repeat-track interferometry has also been demonstrated using airborne SAR systems [*Gray and Farris-Manning, 199?*].

Two main problems limit the usefulness of repeat-track interferometry. The first is due to the fact that, unlike the case of single-pass interferometry, the baseline of the repeat-track interferometer is not known accurately enough to infer accurate elevation information from the interferogram. *Zebker et al. [1994a]* shows how the baseline can be estimated using ground control points in the image. The second problem is due to differences in scattering and propagation that result from the fact that the two images forming the interferogram are acquired at different times. One result is temporal decorrelation, which is worst at the higher frequencies [*Zebker and Villasenor, 1992*]. This problem more than any other limits the use of the current operational spaceborne single-channel SARs for topographic mapping, and led to proposals for dedicated interferometric SAR missions to map the entire globe [*Moccia and Vetralla, 1992; Zebker, et al., 1994*].

3.2 Along Track Interferometry

In some cases, the temporal change between interferometric images contains much information. One such case is the mapping of ocean surface movement. In this case, the interferometer is implemented in such a way that one antenna images the scene a short time before the second antenna, preferably using the same viewing geometry. *Goldstein and Zebker [1987]* described such an implementation in which one antenna is mounted forward of the other on the body of the NASA DC-8 aircraft. In a later work, *Goldstein, et al. [1989]* measured ocean currents with a velocity resolution of 5 to 10 m/s. Along-track interferometry was used by *Marom et al. [1990]* and *Marom et al. [1991]* to estimate ocean surface current velocity and wavenumber spectra. This technique was also applied to the measurement of ship-generated internal wave velocities by *Thompson and Jensen [1993]*.

in addition to measuring ocean surface velocities, *Carande [1994]* reports a dual baseline implementation, implemented by alternately transmitting out of the front and aft antennas, to measure ocean coherence time. He estimated typical ocean coherence times for L-band to be about 0.1 s. *Shemer and Marom [1993]* proposed a method to measure ocean coherence time using only a model for the coherence time and one interferometric SAR observation.

3.3 Differential Interferometry

One of the most exciting applications of radar interferometry is implemented by subtracting two interferometric pairs separated in time from each other to form a so-called differential interferogram. In this way surface deformation can be measured with unprecedented accuracy. This technique was first demonstrated by *Gabriel et al. [1989]* using data from S1 (ASAT) data to measure millimeter-scale ground motion in agricultural fields. Since then this technique has been applied to measure centimeter- to meter- scale co-seismic displacements [*Massonnet, et al., 199?; Massonnet, et al., 1994; Zebker, et al., 1994c; Peltzer, et al., 1994; Peltzer and Rosen, 1995; Massonnet et al., 1995*] and to measure centimeter-scale volcanic deflation [*Massonnet and Feigl, 1995*]. The added information provided by high spatial resolution co-seismic deformation maps was shown to provide insight into the slip mechanism that would not be attainable from the seismic record [*Peltzer, et al., 1994; Peltzer and Rosen, 1995*].

Differential SAR interferometry has also led to spectacular applications in polar ice sheet research by providing information on ice deformation and surface topography at an unprecedented level of spatial details. *Goldstein et al. [1993]* observed ice stream motion and tidal flexure of the Rutford Glacier in Antarctica with a precision of 1 mm per day and summarized the key advantages of using SAR interferometry for glacier studies. *Joughin et al. [1995]* studied the separability of ice motion and surface topography in Greenland and compared the results with both radar and laser altimetry. *Rignot et al. [1995]* estimated the precision of the SAR-derived velocities using a network of in-situ velocities, and demonstrated, along with *Joughin et al. [1995]*, the practicality of using SAR interferometry across all the different melting regimes of the Greenland Ice Sheet. Large-scale applications of these techniques is expected to yield significant improvements in our knowledge of the dynamics, mass balance and stability of the world's major ice masses.

One confusing factor in the identification of surface deformation in differential interferograms is due to changing atmospheric conditions. In observing the earth, radar signals propagate through the atmosphere, which introduces additional phase shifts that are not accounted for in the standard geometrical collations describing radar interferometry. Spatially varying patterns of atmospheric water vapor changes the local index of refraction, which, in turn, introduces spatially varying phase shifts to the individual interferograms. Since the two (or more) interferograms are acquired at different times, the temporal change in water vapor introduces a signal that could be on the same order of magnitude as that expected from surface deformation, as discussed by *Goldstein [1995]*. Another limitation of the technique is temporal decorrelation. Changes in the surface properties may lead to complete decorrelation of the images and no detectable deformation signature [*Zebker, et al., 1994c*].

Current research is only beginning to realize the full potential of radar interferometry. Even though some significant problems still have to be solved before this technique will become fully operational, the next few years will undoubtedly see an explosion in the interest and use of radar interferometry data.

Acknowledgment

This work was performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. Thanks to Dr. Eric Rignot for helpful comments to improve the manuscript.

References

- A. Beaudoin, P. LeToan, S. Goze, A. Nezry, and A. Lopez [1994], "Retrieval of Forest Biomass from SAR Data," *Int. J. Remote Sens.*, 15, pp. 2777-2796.
- R. F. Carande [1994], "Estimating Ocean Coherence Time Using Dual-Baseline Interferometric Synthetic Aperture Radar," *IEEE Trans. Geosci. Remote Sens.*, **GRS-32**, pp. 846-854.
- N. Chauhan, and R. Lang [1991], "Radar Modeling of a Boreal Forest," *IEEE Trans. Geosci. Remote Sens.*, **GIN-29**, pp. 627-638.
- M. C. Dobson, F. T. Ulaby, T. LeToan, A. Beaudoin, E. S. Kasischke, and N. Christensen [1992], "Dependence of Radar Backscatter on Conifer Forest Biomass," *IEEE Trans. Geosci. Remote Sens.*, **GRS-30**, pp. 412-415.
- M. C. Dobson, F. T. Ulaby, L. E. Pierce, P. L. Sharik, K. M. Bergen, J. Kellndorfer, J. R. Kendra, E. Li, Y. C. Lin, A. Nashashibi, K. Sarabandi, and P. Siqueira [1995] "Estimation of Forest Biophysical Characteristics in Northern Michigan with SIR-C/X-SAR," *IEEE Trans. Geosci. Remote Sens.*, **G 1 S-33**, pp. 877-895.
- P. C. Dubois, J. J. van Zyl, and T. Engman [1995], "Measuring Soil Moisture with imaging Radars," *IEEE Trans. Geosci. Remote Sens.*, **GRS-33**, pp. 915-926.
- S. L. Durden, J. J. van Zyl, and H. A. Zebker [1989], "Modeling and Observation of the Radar Polarization Signature of Forested Areas," *IEEE Trans. Geosci. Remote Sens.*, **GRS-27**, pp. 290-301.
- N. P. Faller, and E. H. Meier [1995], "First Results with the Airborne Single-Pass DO-SAR Interferometer," *IEEE Trans. Geosci. Remote Sens.*, **GRS-33**, pp. 1230-1237.
- A. Freeman, Y. Shen, and C. L. Werner [1990], "Polarimetric SAR Calibration Experiment using Active Radar Calibrators," *IEEE Trans. Geosci. Remote Sens.*, **GRS-28**, pp. 224-240.
- A. Freeman, J. J. van Zyl, J. D. Klein, H. A. Zebker, and Y. Shen [1992], "Calibration of Stokes and Scattering Matrix Format Polarimetric SAR Data," *IEEE Trans. Geosci. Remote Sens.*, **GRS-30**, pp. 531-539.
- A. Freeman [1992], "SAR Calibration: An Overview," *IEEE Trans. Geosci. Remote Sens.*, **GRS-30**, pp. 1107-1121.
- A. Freeman, M. Alves, B. Chapman, J. Cruz, Y. Kim, S. Shaffer, J. Sun, E. Turner, and K. Sarabandi [1995], "SIR-C Data Quality and Calibration Results," *IEEE Trans. Geosci. Remote Sens.*, **GRS-33**, pp. 848-857.

- A. K. Gabriel, and R. M. Goldstein [1988], "Crossed Orbit Interferometry: Theory and Experimental Results from SIR-B," *Int. J. Remote Sens.*, 9, pp. 857-872.
- A. K. Gabriel, R. M. Goldstein, and H. A. Zebker [1989], "Mapping Small Elevation Changes Over Large Areas: Differential Radar Interferometry," *J. Geophys. Res.*, 94, pp. 9183-9191.
- F. Gatelli, A. Monti-Guarnieri, F. Parizzi, P. Pasquali, C. Prati, and F. Rocca [1994], "The Wavenumber Shift in SAR Interferometry," *IEEE Trans. Geosci. Remote Sens.*, **GRS-32**, pp. 855-865.
- R. M. Goldstein, and H. A. Zebker [1987], "Interferometric Radar Measurements of Ocean Surface Currents," *Nature*, **328**, pp. 707-709.
- R. M. Goldstein, H. A. Zebker, and C. Werner [1988], "Satellite Radar Interferometry: Two-Dimensional Phase Unwrapping," *Radio Sci.*, **23**, pp. 713-720.
- R. M. Goldstein, T. P. Barnett, and H. A. Zebker [1989], "Remote Sensing of Ocean Currents," *Science*, 246, pp. 1282-1285.
- R. M. Goldstein, H. Englehardt, B. Kamb, and R. M. Frolich [1993], "Satellite Radar Interferometry for Monitoring Ice Sheet Motion: Application to an Antarctic Ice Stream," *Science*, 262, pp. 1525-1530.
- R. M. Goldstein [1995], "Atmospheric Limitations to Repeat-Track Radar Interferometry," *Geophys. Res. Letters*, 22, pp. 2517-1520.
- L. C. Graham [1974], "Synthetic Interferometer Radar for Topographic Mapping," *Proc. IEEE*, 62, pp. 763-768.
- A. L. Gray, P. W. Vachon, C. E. Livingstone, and T. I. Lukowski [1990], "Synthetic Aperture Radar Calibration using Reference Reflectors," *IEEE Trans. Geosci. Remote Sens.*, **GIN-28**, pp. 374-383.
- A. L. Gray, and P. J. Farris-Manning [1993], "Repeat-Pass Interferometry with Airborne Synthetic Aperture Radar," *IEEE Trans. Geosci. Remote Sens.*, **GRS-31**, pp. 180-191.
- L. L. Hess, J. M. Melack, S. Filoso, and Y. Wang [1995], "Delineation of Inundated Area and Vegetation Along the Amazon Floodplain with the SIR-C Synthetic Aperture Radar," *IEEE Trans. Geosci. Remote Sens.*, **GRS-33**, pp. 896-904.
- C. C. Hsu, H. C. Han, R. P. Shin, J. A. Kong, A. Beaudoin, and T. LeToan [1994], "Radiative Transfer Theory for Polarimetric Remote Sensing of Pine Forest at P-Band," *Int. J. Remote Sens.*, 14, pp. 2943-2954.
- M. L. Imhoff [1995], "Radar Backscatter and Biomass Saturation: Ramifications for Global Biomass Inventory," *IEEE Trans. Geosci. Remote Sens.*, **GRS-33**, pp. 511-518.
- R. L. Jordan, B. L. Huncyutt, and M. Werner [1995], "The SIR-C/X-SAR Synthetic Aperture Radar System," *IEEE Trans. Geosci. Remote Sens.*, **GRS-33**, pp. 829-839.

1. R. Joughin [1995], "Estimation of ice-sheet topography and motion using interferometric synthetic aperture radar," Ph.D. Thesis, University of Washington, Seattle.
1. R. Joughin, D. P. Winebrenner, and M. A. Fahnestock [1995], "Observations of ice-sheet motion in Greenland using satellite radar interferometry," *Geophys. Res. Lett.*, **22**, pp. 571-574.
- Ii. S. Kasischke, N. L. Christensen, and L. L. 130Lwgcau-Chavez, [1995], "Correlating Radar Backscatter with Components of Biomass in Loblolly Pine Forests," *IEEE Trans. Geosci. Remote Sens.*, **GRS-33**, pp. 643-659.
- J. D. Klein and A. Freeman [1991], "Quadpolarisation SAR Calibration Using Target Reciprocity," *J. Electromagnetic Waves Applications*, **5**, pp. 735-751.
- J. A. Kong, A. A. Swartz, H. A. Yueh, L. M. Novak, and R. T. Shin [1988], "Identification of Earth Terrain Cover using the Optimum Polarimetric Classifier," *J. Electromagnetic Waves Applications*, **2**, pp. 171-194.
- R. 11. Lang**, and J. S. Sidhu [1983], "Electromagnetic Backscattering from a Layer of Vegetation," *IEEE Trans. Geosci. Remote Sens.*, **GRS-21**, pp. 62-71.
- R. H. Lang, N. S. Chauhan, J. K. Ranson, and O. Kilic [1994], "Modeling P-Band SAR Returns from a Red Pine Stand," *Remote Sensing Environ.*, **47**, pp. 132-141.
- 'P. LeToan, A. Beaudoin, J. Riou, and D. Guyon [1992], "Relating Forest Biomass to SAR Data," *IEEE Trans. Geosci. Remote Sens.*, **GRS-30**, pp. 403-411.
- F. K. Li, and R. M. Goldstein [1990], "Studies of Multibaseline Spaceborne Interferometric Synthetic Aperture Radars," *IEEE Trans. Geosci. Remote Sens.*, **GRS-28**, pp. 88-97.
- H. H. Lim, A. A. Swartz, H. A. Yueh, J. A. Kong, R. T. Shin, and J. J. van Zyl [1989], "Classification of Earth Terrain using Polarimetric Synthetic Aperture Radar Images," *J. Geophys. Res.*, **94**, pp. 7049-7057.
- Q. Lin, J. F. Vesceky, and H. A. Zebker [1992], "New Approaches in Interferometric SAR Data Processing," *IEEE Trans. Geosci. Remote Sens.*, **GRS-30**, pp. 560-567.
- S. N. Madsen, H. A. Zebker, and J. Martin [1993], "Topographic Mapping Using Radar Interferometry: Processing Techniques," *IEEE Trans. Geosci. Remote Sens.*, **GRS-31**, pp. 246-256.
- M. Marom, R. M. Goldstein, E. B. Thronton, and L. Shemer [1990], "Remote Sensing of Ocean Wave Spectra by Interferometric Synthetic Aperture Radar," *Nature*, **345**, pp. 793-795.
- M. Marom, L. Shemer, and E. B. Thronton [1991], "Energy Density Directional Spectra of Nearshore Wave Field Measured by Interferometric Synthetic Aperture Radar," *J. Geophys. Res.*, **96**, pp. 22125-22134.
- D. Massonnet, and T. Rabaut [1993], "Radar Interferometry: Limits and Potential," *IEEE Trans. Geosci. Remote Sens.*, **GRS-31**, pp. 455-464.

- D. Massonnet, M. Rossi, C. Carmona, I. Adragna [1994], G. Peltzer, K. Freigl, and P. Rabaute [1993], "The 1-D Displacement Field of the Landers Earthquake Mapped by Radar Interferometry," *Nature*, 364, pp. 138-142.
- D. Massonnet, K. Freigl, M. Rossi, and I. Adragna [1994], "Radar Interferometric Mapping of Deformation in the Year After the Landers Earthquake," *Nature*, 369, pp. 227-230.
- D. Massonnet, and K. Freigl [1995], "Satellite Radar Interferometric Map of the Cosismic Deformation Field of the M=6.1 Eureka Valley, California Earthquake of May 17, 1993," *Geophys. Res. Letters*, 22, pp. 1541-1544.
- D. Massonnet, P. Briole, and A. Arnaud [1995], "Deflation of Mount Etna Monitored by Spaceborne Radar Interferometry," *Nature*, 375, pp. 567-570.
- A. Moccia, and S. Vetrella [1992], "A Tethered Interferometric Synthetic Aperture Radar (SAR) for a Topographic Mission," *IEEE Trans. Geosci. Remote Sens.*, **GRS-31**, pp. 103-109.
- J. Moreira, M. Schwabish, G. Fornaro, R. Lanari, R. Bamler, D. Just, U. Steinbrecher, H. Breit, M. Eineder, G. Franceschetti, D. Guedtner, and H. Rinkel [1995], "X-SAR Interferometry: First Results," *IEEE Trans. Geosci. Remote Sens.*, **GRS-33**, pp. 950-956.
- Y. Oh, K. Sarabandi, and F. T. Ulaby [1992], "An Empirical Model and an Inversion Technique for Radar Scattering from Bare Soil Surfaces," *IEEE Trans. Geosci. Remote Sens.*, **GRS-30**, pp. 370-381.
- G. Peltzer, K. Hudnut, and K. Freigl [1994], "Analysis of Cosismic Displacement Gradients Using Radar Interferometry: New Insights into the Landers Earthquake," *J. Geophys. Res.*, 99, pp. 21971-21981.
- G. Peltzer, and P. Rosen [1995], "Surface Displacement of the 17 May 1993 Eureka Valley, California, Earthquake Observed by SAR Interferometry," *Science*, 268, pp. 1333-1336.
- L. E. Pierce, F. T. Ulaby, K. Sarabandi, and M. C. Dobson [1994], "Knowledge-Based Classification of Polarimetric SAR Images," *IEEE Trans. Geosci. Remote Sens.*, **GRS-32**, pp. 1081-1086.
- C. Prati, and F. Rocca [1990], "Limits to the Resolution of Elevation Maps from Stereo SAR Images," *Int. J. Remote Sens.*, 11, pp. 2215-2235.
- C. Prati, F. Rocca, A. Monti Guarnieri, and E. Damonti [1990], "Seismic Migration for SAR Focussing: Interferometrical Applications," *IEEE Trans. Geosci. Remote Sens.*, **GRS-28**, pp. 627-640.
- C. Prati, and F. Rocca [1993], "Improving Slant Range Resolution with Multiple SAR Surveys," *IEEE Trans. Aerosp. Elec. Sys.*, 29, pp. 135-144.
- S. Quegan [1994], "A Unified Algorithm for Phase and Cross-Talk Calibration of Polarimetric Data - Theory and Observations," *IEEE Trans. Geosci. Remote Sens.*, **GRS-32**, pp. 89-99.

- K. J. Ranson, and G. Sun [1994], "Mapping Biomass of a Northern Forest Using Multifrequency SAR Data," *IEEE Trans. Geosci. Remote Sens.*, **GRS-32**, pp. 388-396.
- K. J. Ranson, S. Saatchi, and G. Sun [1995], "Boreal Forest Ecosystem Characterization with SIR-C/XSAR," *IEEE Trans. Geosci. Remote Sens.*, **GRS-33**, pp. 867-876.
- J. A. Richards, G. Sun, and D. S. Simonett [1978], "L-Band Radar Backscatter Modeling, of Forest Stands," *IEEE Trans. Geosci. Remote Sens.*, **GRS-25**, pp. 487-498.
- I. Rignot, and R. Chellappa [1992], "Segmentation of Polarimetric Synthetic Aperture Radar Data," *IEEE Trans. Image Process.*, **1**, pp. 281 -300.
- I. Rignot, and R. Chellappa [1993], "Maximum *a-posteriori* classification of Multifrequency, Multilook, Synthetic Aperture Radar Intensity Data," *J. Opt. Soc. Amer. A*, **10**, pp. 573-582,
- Ii. J. M. Rignot, C. L. Williams, J. Way, and L. Viereck [1994], "Mapping of Forest Types in Alaskan Boreal Forests Using SAR Imagery," *IEEE Trans. Geosci. Remote Sens.*, **GRS-32**, pp. 1051 -1059.
- I. Rignot, J. Way, C. William, and L. Viereck [1994], "Radar Estimates of Aboveground Biomass in Boreal Forests of Interior Alaska," *IEEE Trans. Geosci. Remote Sens.*, **GRS-32**, pp. 1117-1124.
- I. J. Rignot, R. Zimmerman, and J. J. van Zyl [1995], "Spaceborne Applications of L-Band Imaging Radars for Measuring Forest Biomass," *IEEE Trans. Geosci. Remote Sens.*, **GRS-33**, pp. 1162-1169.
- I. Rignot, K. Jezek, and H.G. Sohn [1995], "Ice flow dynamics of the Greenland Ice Sheet from SAR Interferometry," *Geophys. Res. Lett.*, **22**, pp. 575-578.
- I. Rodriguez, and J. Martin [1992], "Theory and Design of Interferometric Synthetic Aperture Radars," *IEEE Proc.*, **139**, pp. 147-59.
- K. Sarabandi, F. Ulaby, and M. Tassoudji [1990], "Calibration of Polarimetric Radar Systems with Good Polarization Isolation," *IEEE Trans. Geosci. Remote Sens.*, **GRS-28**, pp. 70-75.
- K. Sarabandi, and F. Ulaby [1990], "A Convenient Technique for Polarimetric Calibration of Single-Antenna Radar Systems," *IEEE Trans. Geosci. Remote Sens.*, **GRS-28**, pp. 1022-1033.
- K. Sarabandi, L. E. Pierce, Y. Oh, M. C. Dobson, F. T. Ulaby, A. Freeman, and P. Dubois [1994], "Cross-Calibration Experiment of J]". AIRSAR and Truck-Mounted Polarimetric Scatterometer," *IEEE Trans. Geosci. Remote Sens.*, **GRS-32**, pp. 975-985.
- L. Shemer, and M. Marom [1993], "Estimates of Ocean Coherence Time by Interferometric SAR," *Int. J. Remote Sens.*, **14**, pp. 3021-3029.

- J. Shi, and J. Dozier [1995], "Inferring Snow Wetness Using C-Band Data from SIR-C's Polarimetric Synthetic Aperture Radar," *IEEE Trans. Geosci. Remote Sens.*, **GRS-33**, pp. 905-914.
- M. A. Sletten [1994], "Resolution of a Phase Ambiguity in a Calibration Procedure for Polarimetric Radar Systems," *IEEE Trans. Geosci. Remote Sens. S.*, **GRS-32**, pp. 213-216.
- E. R. Stofan, D. L. Evans, C. Schmullius, B. Holt, J. J. Plaut, J. van Zyl, S. D. Wall, and J. Way [1995], "Overview of Results of Spaceborne imaging Radar-C, X-Band Synthetic Aperture Radar (SIR-C/X-SAR)," *IEEE Trans. Geosci. Remote Sens.*, **GRS-23**, pp. 817-828.
- G. Sun, D. S. Simonett, and A. H. Strahler [1991], "A Radar Backscatter Model for Discontinuous Coniferous Forest Canopies," *IEEE Trans. Geosci. Remote Sens.*, **GRS-29**, pp. 639-650.
- D. R. Thompson, and J. R. Jensen [1993], "Synthetic Aperture Radar Interferometry Applied to Ship-Generated Internal Waves in the 1989 Loch Linnhe Experiment," *J. Geophys. Res.*, 98, pp. 10259-10269.
- F. T. Ulaby, K. Sarabandi, K. McDonald, M. Whitt, and M. C. Dobson [1990], "Michigan Microwave Canopy Scattering Model," *Int. J. Remote Sens.*, **11**, pp. 1223-1253.
- J. J. van Zyl [1989], "Unsupervised Classification of Scattering Behavior Using Radar Polarimetry Data," *IEEE Trans. Geosci. Remote Sens.*, **GRS-27**, pp. 36-45.
- J. J. van Zyl [1990], "A Technique to Calibrate Polarimetric Radar Images Using Only Image Parameters and Trihedral Corner Reflectors," *IEEE Trans. Geosci. Remote Sens.*, **GRS-28**, pp. 337-348.
- J. J. van Zyl, and C. F. Burnette [1992], "Bayesian Classification of Polarimetric SAR Images Using Adaptive *a-priori* Probabilities," *Int. J. Remote Sensing*, **13**, pp. 835-840.
- Y. Wang, J. Day, and G. Sun [1993], "Santa Barbara Microwave Backscattering Model for Woodlands," *Int. J. Remote Sens.*, 14, pp. 1146-1154.
- M. Whitt, and F. Ulaby [1990], "A Polarimetric Radar Calibration Technique with Insensitivity to Target orientation," *Radio Science*, 2S, pp. 1137-1143.
- M. Whitt, F. Ulaby, P. Polatin, and V. Liepa [1991], "A General Polarimetric Radar Calibration Technique," *IEEE Trans. Ant. Prop.*, **GRS-39**, pp. 62-67.
- S. H. Yuch, J. A. Kong, J. K. Rae, R. T. Shin, and T. LeToan [1992], "Branching Model for Vegetation," *IEEE Trans. Geosci. Remote Sens.*, **GRS-30**, pp. 390-402.
- H. Zebker and R. Goldstein [1986], "Topographic Mapping from Interferometric SAR Observations," *J. Geophys. Res.*, 91, pp. 4993-4999.
- H. A. Zebker, J. J. van Zyl, and D. N. Held [1987], "imaging Radar Polarimetry from Wave Synthesis," *J. Geophys. Res.*, 92, pp. 683-701.

11. A. Zebker, and Y. I. Lou [1990], "Phase Calibration of imaging Radar Polarimeter Stokes Matrices," *IEEE Trans. Geosci. Remote Sens.*, **G 1** < S-28, pp. 246-252.
11. A. Zebker, J. J. van Zyl, S. I. Durden, and L. Norikane [1991], "Calibrated imaging Radar Polarimetry: Technique, Examples, and Applications," *IEEE Trans. Geosci. Remote Sens.*, **GRS-29**, pp. 942-961.
11. A. Zebker, S. N. Madsen, J. Martin, K. B. Wheeler, J. Miller, Y. Lou, G. Alberti, S. Vetrone, and A. Cucci [1992], "The 'T' O' SAI< interferometric Radar 'Topographic Mapping Instrument,'" *IEEE Trans. Geosci. Remote Sens.*, **GRS-30**, pp. 933-940.
11. A. Zebker, and J. Villasenor [1992], "Decorrelation in Interferometric Radar Echoes," *IEEE Trans. Geosci. Remote Sens.*, **GRS-30**, pp. 950-959.
11. A. Zebker, C. L. Werner, P. A. Rosen, and S. I. Lensley [1994a], "Accuracy of 'T' orographic Maps Derived from ERS-1 Interferometric Radar," *IEEE Trans. Geosci. Remote Sens.*, **GRS-32**, pp. 823-836.
11. A. Zebker, T. G. Farr, R. I. Salazar, and T. H. Dixon [1994b], "Mapping the World's Topography Using Radar Interferometry: The TOPSAT Mission," *Proc. IEEE*, **82**, pp. 1774-1786.
11. A. Zebker, P. A. Rosen, R. M. Goldstein, A. Gabriel, and C. L. Werner [1994c], "On the Derivation of Co-seismic Displacement Fields Using Differential Radar Interferometry: The Landers Earthquake," *J. Geophys. Res.*, **99**, pp. 19617-19634.
- S. I. Zisk [1972a], "A New, Earth-Based Radar Technique for the Measurement of Lunar Topography," *Moon*, **4**, pp. 296-306.
- S. I. Zisk [1972b], "First Radar Interferometer Measurements of the Alphonsus-Ptolemaeus-Arzachel Region," *Science*, **178**, pp. 977-980.