OVERVIEW OF SAR POLARIMETRY AND INTERFEROMETRY

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ABSTRACT

This paper summarizes the recent work in the fields of Synthetic Aperture Radar (SAR) polarimetry and interferometry. These fields have seen very significant development during the last five years, and these fields arc now well understood.

Keywords: SAR, polarimetry, interferometry, calibration

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 interferornetry. While both of these techniques have 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 interferornetry 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 ERS - 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 fields as of the middle of 1997.

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, and one observes this wave in the far-field of the scatterer, the scattered wave can again be adequately described by a two-dimensional *complex* 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 [hat into another two-dimensional complex vector (the scattered wave). Mathematically, therefore, a scatterer can be characterized by a complex 2x2 scattering matrix, It should be remembered, however. that this scattering 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 tour elements of the scattering matrix is 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[88], and the same implementation was used in the SIR-C part of the SIR-C/X -SAR radars[29].

The past five years have seen relatively little advance in the development of hardware tor 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 involve four steps: cross-talk removal, phase calibration, channel imbalance compensation and absolute radiometric calibration[81]. Cross-talk removal refers to correcting mostly the cross-polarized elements of the scattering matrix for the effects of 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[81,89,24,11,33] several groups are still actively pursuing the study of improved calibration techniques and algorithms. The earlier algorithms are reviewed in *Zebker, et al.*[90] and *Freeman et al.* [12], while *Freeman*[13] 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'".

Some of the recent research deals with refining earlier algorithms. For example, *Quegan*[59] 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* [81] may yield inconsistent results. *Sletten*[75] 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.*[72]. In that experiment, the AIRSAR data were calibrated using the algorithm published by *van Zyl*[81] 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 reelectors may significantly alter the expected radar cross section of these calibration devices, resulting in inaccurate calibration. To circumvent these problems. *Sarabandi*[72] 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, lead to improved models of scattering by different types of terrain, and allowed the development o! 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 suit'ncc! studies require information about the spatial distribution of land cover type'i. as well as the change in land cove.r 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 cm quantifying the increased accuracy gained from using all the polarimetric information. *Kong et al.*[34] and *Lim et al.*[39] 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*[82] 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 the *a-priori* 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[63]. In a subsequent work[64], the MAP classifier is extended to include the case of multi-frequency polarimetric radar data. The MAP classifier was used by *Rignot et al.*[65] 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/fen/nonforest) were separated with accuracies ranging from 62% to 90%, depending on which frequencies and polarizations are used.

Knowledge-based classifiers use based upon determination of dominant scattering mechanisms through an understanding of the physics of the scattering process as well as experience gained from extensive experimental measurements[55]. One of the earliest examples of such a knowledge-based classifier was published by *van Zyl*[80]. 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' reelections, 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 cot-relation 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.*[55] extended this idea and developed a level 1 classifier that segments images into four classes: tail 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 [.-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 repot-ted for this classification scheme when applied to two different images acquired in Michigan[55]. Another example of a knowledge-based classification is reported by Hess *et al.*[26] In [his study, a decision-tree classifier is used to classify images of the Amazonian floodplain near Manaus, Brazil into five classes: water; clearing: macrophyte; non-flooded forest; and flooded forest based on polarimetric scattering properties, 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 form the radar data through model inversion. Space does not permit a full discussion of recent work. Thcrct'ore, in this section only a brief summary of recent work will be provided, with the emphasis on vegetated areas.

Many models exist [0 predict scattering from vegetated areas[15,62,9,79,3] 77 [86,83,27,36] and this remains an area of active research. Much of the work is aimed at estimating forest biomass[6,37,60,1,67]. Earlier works correlated polarimetric SAR backscatter with total above-ground biomass biomass[6,37] 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[28], arguing for the use of low frequency radars to be used for monitoring forest biomass[67].

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[60]. *Rignot, et al.* [67] 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.*[61] and *Dobson et al.* [7] 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*[7] estimates the total biomass by first using the radar 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 the be accurately related to allometric total biomass levels up to 25 kg/m^2, while *Kasischke et al.* [32] estimates that biomass levels as high as 34 to 40 kg/m^2 could be estimated with an accuracy of 15-2570 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*[51]. This algorithms 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.*[8] 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 4.270 when inferring soil moisture over bare surfaces. *Shi and Dozier*[74] reported an algorithm to measure snow wetness, and demonstrated accuracies of 2.57..

3. SAR INTERFEROMETRY

SAR interferometry refers to a class of techniques where additional information is extracted from SAR images that are acquired trom different vantage points, or at different times. Various implementations allow different types of information to be extracted. For example, it' two SAR images are acquired from slightly different viewing geometries, information about the topography of the surface can be inferred. On the other hand, it' 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; it has previously been described elsewhere[23,96,97,87,44] Instead, we shall concentrate on implementations, and point out the areas where more research is needed.

3. I Radar Interferometry for Measuring Topography

SAR interferometry was first demonstrated by *Graham*[23], who demonstrated a pattern of nulls or interference fringes by vectorally adding the signals received from tow SAR antennas; one physically situated above the other. Later, *Zebker and Goldstein*[87] demonstrated that these interference fringes can be formed after SAR processing of the individual images it' 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*[69].

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[87,91,10]. 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'. 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 measure phase must be unwrapped. During this procedure, the measured phase, which only varies between O and 360 degrees, must be unwrapped to retrieve the original phase by adding or subtracting multiples of 360 degrees. The earliest phase unwrapping routine was published by *Goldstein et al*[19]. 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*[40]. 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 absolute phase 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 ease with which interferometry can be used operationally. *Madsen et al.*[41] reported a method by which the radar data itself is used to estimate [his 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 interferornetry is to be realized.

Absolute phase determination is followed by height reconstruction. Once the elevations in the scene are known, [he entire digital elevation map can be geometrically rectified. *Madsen et al.*[41] 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' for the NASA/JPL TOPSAR interferometer.

An alternative way to form the interferometric baseline is [o 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[19,18,56,57,92,58]. Other investigators used data from the L-band SIR-B[15], the C-band ERS-1 radar[17,93], and more recently the L-band SIR-C[76] and the ,X-band X-SAR[50]. Repeat-track interferometry has also been demonstrated using airborne SAR systems[35]

Two main problems limit the usefulness of repeat-track interferometry. The first is due to the fact [hat, unlike the case of single-pass interferometry, the baseline of the repeat-track interferometer is not known accurately enough to infer accurate elevation information form the inter ferogram. *Zebker et al*[91] show 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 results 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[92]. This problem more than any other limits the use of [he current operational spaceborne single-channel SARS for topographic mapping, and led to proposals for dedicated interferometric SAR missions to map the entire globe[49,94].

3.2 **Along Track Interferometry**

In some cases, the temporal change between interferometric image 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*[18] 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.*[20] measured ocean currents with a velocity resolution of 5 to 10 m/s. Along-track interferometry was used by *Marom et al.*[41] and *Marom et al. 43* 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*[78].

In addition to measuring ocean surface velocities, *Carande*[2] 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 O. I second. *Shemer and Marom*[73] 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 interferornetry 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.*[16] using data from SEASAT data to measure mm-scale ground motion in agricultural fields. Since then this technique has been applied to measure cm to m scale co-seismic displacements[45,46,95,53,54,48] and to measure cm-scale volcanic deflation”. 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 records’s”.

Differential SAR interferometry has also lead 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.*[21] observed ice stream motion and tidal flexure of the Rutford Glacier in Antarctica with a precision of I mm per day and summarized the key advantages of using SAR interferometry for glacier studies. *Joughin* et *al.*[31] studied the separability of ice motion and surface topography in Greenland and compared the results with both radar and laser altimetry. *Rignot et al.*[68] estimated the precision of the SAR-derived velocities using a network of in-situ velocities, and demonstrated, along with *Joughin et al.*[30,31], 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 inter ferograms 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 [he standard geometrical equations describing radar interferometry. Spatially varying patterns of atmospheric water vapor changes the local index of retraction. which, in turn, introduces spatially varying phase shifts to the individual interferograms. Since the two (or more) inter ferograms 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*[22]. 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[95].

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.

4. POLARIMETRIC INTERFEROMETRY

Towards the end of tbe second SIR-C/X-SAR mission in October 1994, the Space Shuttle Endeavour was placed in an orbit that allowed the acquisition of repeat-pass interferometric data. The temporal baseline was about 24 hours when compared to data acquired during the same mission, and about six months when compared to data acquired during the first mission flown in April 1994. In several cases data were acquired in the fully polarimetric mode of the SIR-C L- and C-band radars.

Since the data were acquired in the fully polarimetric mode on each of the two (or more) passes of the SIR-C instrument, it means that one now can investigate the effect of polarization on the elevation inferred from the repeat-pass interferometric data.

Cloude and Papathanassiou[4,5] are first group to report results using polarimetric interferometry to optimize the coherence of the radar interferograms. They show a dramatic improvement in the coherence when optimized using all the available polarization information.

By utilizing the polarization information, one can also construct polarimetric differential interferograms. This is done by using a common polarization on the first day, and two different polarizations on tbe subsequent day. *Papathanassiou and Cloude*[52] show that by using the HH polarization as tbe common polarization, and then using HH and VV polarizations on the second data take, very subtle elevation differences (on the order of a few centimeters) are measured in agricultural fields.

This powerful technique of combining polarimetry and differential interferometry opens a new possibility to fully understand scattering from vegetated surfaces. Not only can one now relate the polarization information to geophysical parameters such as biomass, but the interferometric information also help to identify the part of the canopy that is responsible for the majority of the measured radar return. Utilizing this information about where in the canopy the majority of the scattered return is measured from, one can then more easily correlate the radar return to a specific component of the biomass. Therefore, automatic biomass estimation algorithms following a similar procedure as that proposed by *Kasischke et al.*[32] can become a reality.

At tbe moment research in the area of polarimetric interferometry is limited by the limited availability of data. From space, only a few data takes are available from the SIR-C/X-SAR mission at C- and L-band. There are no fully polarimetric single pass interferometers available on airborne platforms today. A small amount of data have been acquired with the AIRSAR system flying repeat tracks. However, repeat-track airborne data are notoriously difficult to process, so very little data are available for study. This means that very little low frequency polarimetric interferometry data are available to fully investigate the utility of this powerful technique.

5. SUMMARY AND CONCLUSIONS

As shown in this summary. and the numerous works referenced here, polarimetry and interferometry are two SAR techniques that show great promise for providing quantitative geophysical information about the earth's surface and its vegetation cover. Recent results suggest that combining these two powerful techniques may provide even more ways in which the geophysical information may be extracted trom [he data

In order to t'Lilly exploit the power t)t'combining these techniques, fully polarimetric interferometric systems must be developed for operational use. Furthermore, these systems must be able to operate at the lower frequencies, including P-Band and lower. At present, it is exceedingly difficult to get permission to radiate in the frequency range below approximately 500 MHz. Getting the most out of these powerful techniques for monitoring the earth's natural resources suggest that a concerted international effort is required in order to gain access to this important part of the electromagnetic spectrum for SAR remote sensing systems.

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