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INTERFEROMETRIC SAR PHASE DIFFERENCE CALIBRATION: METHODS AND RESULTS

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ABSTRACT

This paper addresses the steps necessary to determine and maintain the phase calibration of a two-channel interferometric synthetic aperture radar (IFSAR). The method, setup, and accuracy of four different calibration techniques are compared. The most novel technique involves pointing the interferometric baseline at nadir and imaging a lake surface. The other techniques include measuring various flat surfaces in traditional side-looking IFSAR maps, in-flight closed-loop calibration path measurements, and static laboratory measurements. Initial results indicate that, using combinations of these measurements, it is possible to maintain the interferometric phase calibration of Sandia National Laboratories' K_u Band IFSAR to better than 3 degrees. The time variability of various parts of the calibration and requirements for recalibration are also discussed.

INTRODUCTION

Interferometric synthetic aperture radar (IFSAR) is a technique that combines radar interferometry and synthetic aperture radar (SAR) processing to produce high precision digital terrain models. The traditional SAR produces a high-resolution projection of the terrain surface into a two dimensional coordinate system. The phase difference derived from interferometry indicates the angle of arrival of the echo for each resolution cell in the SAR image.

There are many key issues in producing accurate IFSAR maps. These include: accurate motion compensation, accurate baseline length and attitude measurement, phase preserving SAR processing, two-dimensional phase unwrapping, and measurement of the absolute phase difference. In this paper we focus on determining the portion of the absolute phase difference due to the IFSAR system. First, we present the aspects of Sandia National Laboratories' (SNL) K_u Band IFSAR which are relevant to the discussion of IFSAR phase calibration. Next we describe four different calibration methods and their results. Finally we propose a measurement program which may be used to determine and maintain IFSAR phase difference calibration.

SYSTEM DESCRIPTION

IFSAR Components and Operation

The Sandia National Laboratories K_u Band IFSAR is a two-antenna elevation (across-track) interferometer operating at a nominal 15 GHz center frequency. Figure 1 shows the main

accuracy of four different calibration techniques are compared. The most novel technique involves pointing the interferometric baseline at nadir and imaging a lake surface. The other techniques include measuring various flat surfaces in traditional side-looking IFSAR maps, in-flight closed-loop calibration path measurements, and static laboratory measurements. Initial results indicate that, using combinations of these measurements, it is possible to maintain the interferometric phase calibration of Sandia National Laboratories' K_u Band IFSAR to better than 3 degrees. The time variability of various parts of the calibration and requirements for recalibration are also discussed.

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Figure 1.
Ku Band IFSAR Block Diagram.

Figure 2.
Ku Band IFSAR Antenna Mounting and Geometry

In strip-map IFSAR mode, the motion compensation system is used to continually point the boresight of the antenna, the vector perpendicular to the antenna baseline (see Figure 2), directly at a straight line lying along the desired mapping direction and passing through the scene reference point on the ground. This geometry

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Table 1 gives operating limits and nominal conditions for the major system parameters when the system is used in the IFSAR mode with the flat plate antenna.

Table 1. K_u IFSAR Operating Parameters

Parameter		Min	Nom	Max
Center Frequency	GHz	14.7	15.0	15.3
Baseline	m		0.2	
Incidence Angle	deg	0.	45.	65.
Range	m	2000.	5000.	16000.
Tx. Bandwidth	MHz	60.	180.	180.
Height/Phase Scale	m/deg		0.5	

IFSAR Processing

The processing used to form digital terrain elevation data (DTED) from the IFSAR returns is shown in Figure 3. First, data from the real-time motion compensation subsystem is used to stabilize the phase of the radar returns to the desired trajectory of the aircraft and resample the data into a constant ground wavenumber frame (Fellerhoff, 1992). This step is followed by complex image formation on the two individual channels of data (Burns, 1994) and IFSAR phase estimation. Next comes the unwrapping of the IFSAR phase (Ghiglia, 1994). At this point, the system phase calibration factor is applied. Finally, a conversion from the range, azimuth, IFSAR phase coordinate system to a (relative) x, y, z coordinate system is performed. The knowledge of the baseline position and attitude is applied during this coordinate conversion.

Figure 3.
IFSAR Processing Block Diagram

Effect of Phase Calibration on Processed Data

As indicated in the introduction, the phase information derived from interferometric processing indicates a direction of arrival. This means that a phase offset behaves like a mispointing of the baseline in the DTED generation process. For our system, where the boresight is pointed at the scene reference point, equations (30) and (31) from Rodriguez, 1992 become:

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$$\delta z_{\xi} \approx r \left(\sin \theta + \tan \tau_y \right) \delta \xi \quad (1)$$

$$\delta z_{\hat{\phi}} \approx \frac{r \left(\sin \theta + \tan \tau_y \right) \delta \hat{\phi}}{kB} \quad (2)$$

From these equations, it is evident that within a scale factor, the DTED resulting from the IFSAR is affected in the same manner by a constant roll error or a constant phase difference error. The

following techniques address the measurement of sources of constant phase difference error.

NADIR LAKE MEASUREMENT & PROCESSING

The nadir-looking lake experiment involves pointing the boresight of the IFSAR straight down at a nearly still lake. The purpose of this experiment is to use the lake surface as a flat mirror to measure the path length difference for the entire IFSAR system, including the antennas. The result of the experiment is a phase difference calibration value that can be used directly in forming the digital terrain model (see Figure 3).

This technique has several advantages. The main advantage is that it measures the phase calibration difference value for the entire IFSAR system. Another significant advantage is the ease of processing and analysis of the resulting data. Also, the position of the baseline relative to the target does not need to be known to estimate the phase difference calibration value. The baseline length and roll angle do not enter into the processing directly, although they do enter into the error sources. In addition, a very good signal to noise ratio can be achieved. Finally, this experiment can be performed over naturally-occurring bodies of water and does not require special experiment setup.

One source of error in this measurement is the condition of the lake. With current processing techniques, the best results are achieved when the lake is nearly still. We have been able to achieve an rms error of less than one degree when averaging 40 azimuth measurements. Figure 4 is an example plot of raw phase difference from one such experiment. Also, we have measured a repeatability of less than one degree between different flight days (Table 2). Further study is required to identify processing techniques that may be used with less ideal lake conditions.

Figure 4.
Example of Unaveraged IFSAR Phase Calibration Data from
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Another error source is the roll error that couples in through the baseline. This phase difference will be less than 1.5 degrees for a 0.01 degree roll error for our system. In general, the unbiased portions of the measurement can be reduced by averaging data collected over a long period of time.

The constant part of the roll error is included in this measurement; however, it will be removed when the phase calibration is applied during IFSAR processing. The ability to compensate for antenna mounting biases is an additional benefit of the nadir-looking lake experiment.

Table 2. *IFSAR Phase Calibration from Nadir Lake*

Date	Phase Cal (deg)	Event
11 Oct 93	+128.0	Initial System Integration
18 Mar 94	+166.2	Major System Changes
21 Mar 94	+165.6	Another Flight
21 Mar 94	+165.7	Later on Same Day

CALIBRATION USING KNOWN SURFACES IN HEIGHT MAPS

Another method of estimating the phase difference calibration value is to generate an IFSAR map of a known area. The reason for using a known area for phase difference calibration is that any phase difference calibration error shows up directly in the resulting DTED, as explained above. The dilemma is that it is difficult to decouple errors caused by phase difference calibration from the other sources of height errors in the IFSAR map, such as range and baseline length, position, and attitude errors.

One of the simplest cases of a known surface is a flat region such as a lake shore. The advantage of a flat region is that you can use either the tilt or the height offset of the resulting image to determine the phase difference calibration error, provided you know the baseline roll accurately. For our experiments, we compared the height offset information from IFSAR and baseline position information from a GPS carrier phase (Sun, 1994) measurement to validate our phase calibration. For our known flat surface we used a rocket sled track located at Sandia National Laboratories in Albuquerque, NM. Table 3 presents the residual phase errors derived from the baseline to target height, after we have applied the phase difference calibration value derived from the nadir-looking lake experiment.

Table 3. *Residual Phase Calibration Errors from Height Offset Measurement*

Depression Angle (deg)	24.6	24.5	24.6	24.5	35	45.2
Phase Diff. Error (deg)	-5.4	-2.4	-1.4	3.1	9.8	1.8

COMPARISON TO AND LIMITATIONS OF LABORATORY MEASUREMENTS

A final method of calibrating the interferometric phase difference is to make laboratory measurements of the phases of the component subsystems and combine them. Laboratory measurements such as this are very good at measuring the phase difference over portions of the IFSAR system. Because of some real-world constraints, however, it is very difficult to use them a priori to compute total system performance. We will discuss two types of lab measurements: component measurements made with laboratory equipment, and delay-line measurements made with the

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Laboratory Measurement of Component Phase Differences

It is possible, using an automatic network analyzer and an antenna pattern range, to measure the phase difference between channels for each of the two-channel portions of an IFSAR system. This approach is subject to many error sources. First, the phase performance of a component is changed by any impedance mismatch in its connection to a succeeding component. For example, an impedance mismatch (return loss) of only -20 dB gives a maximum possible phase error of approximately 6 degrees.

This error is repeated at every connection between measured components -- a significant error for an IFSAR system using a scale factor of 0.5 m/degree. The second error source is the result of mechanical-to-electrical boresight mounting errors on measuring the phase performance of the antenna pair. Even with a well-calibrated antenna range it is difficult to achieve antenna boresighting to within 0.01 degrees relative to the actual mounting of the antenna on the IFSAR platform. This can contribute about 1.5 degrees to the phase calibration error. The total result of these errors is that it is very time consuming and expensive to make all the laboratory measurements necessary to calibrate the phase difference of our K_u Band IFSAR to better than 20 degrees. These measurements do, however, allow one to establish phase difference performance of individual components over temperature and time, and, by their use of multiple center frequencies, assure that the number of 2π phase wraps in the measured portions of the system are known.

Subsystem Delay-Line Measurements

Another measurement technique that lends itself to IFSAR is the delay-line calibration. For this measurement, a delay element with sufficient length and bandwidth to simulate the return of a target at a nominal range is used in place of the IFSAR antenna. In our system, this element is always installed in the radar, and is activated through a built-in switch. The delay-path phase difference measurement is automated and is performed in the air or in the lab by our on-board real-time processor. This measurement has the advantage that no connections are disturbed, so the phase measurements include all the actual effects of impedance mismatches. Therefore, it is possible to get accuracy limited only by integration time for the portion of the system which is common to the delay path. We have achieved phase difference measurements with standard deviations of less than 1 degree using this method. The major limitations of this measurement are: (1) the fact that portions of the delay path and the actual transmit-receive path are not common, and (2) since the antenna is not used, any phase errors due to the antenna or to alignment errors in mounting the antenna to the IFSAR platform are not measurable. A secondary effect, which is negligible if the data from the two channels is collected simultaneously, is drift in the phase of the delay element over time.

Table 4 shows results from delay-line phase difference measurements taken under varying conditions. The first three measurements were taken in October of 1993; the next measurement was taken after a subsystem change in March, 1994; the final measurements were taken 18 days later, when no component changes had occurred. Note that these measurements were only averaged over 40 samples -- the standard deviation could be significantly reduced by further integration.

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Table 4: Delay-Line IFSAR Phase Difference Measurements

Date	Phase Difference	Phase Diff. Std. Dev.	Event
27 Sep 93	-105.7	0.23	Initial System Integration
04 Oct 93	-104.8	0.24	Another Flight
05 Oct 93	-106.8	0.11	Another Flight
09 Mar 94	68.0	0.96	Major System Changes
21 Mar 94	65.1	N/A	Another Flight
21 Mar 94	66.3	N/A	Later Same Day

CONCLUSIONS

We have examined the accuracy of various techniques for measuring the phase difference calibration factor for Sandia National Laboratories' K_u Band interferometric synthetic aperture radar system. We have developed a schedule for performing the various measurements that allows us to maintain the phase difference calibration of the system to approximately three degrees. Table 5 shows the types of measurements, their purpose, and their absolute phase difference measurement accuracy (one standard deviation at 15.0 GHz). As mentioned above, the lab and antenna range measurements have very good ability to measure temporal changes in individual components, even though their absolute measurement accuracy is poor. Table 6 outlines the system events that require the various measurements to be repeated.

Table 5: Phase Calibration Measurements

Measurement Step	Phase Accuracy	Measurement Purpose
Lab & Antenna Range	~ 20.	Determine Performance Changes vs Time & Temperature, Validate Other Measurements
Nadir Lake	< 1.0	Determine Phase Calibration Factor
Height Offset	< 3.0	Verify Phase Calibration Factor, Check Entire System Performance
Delay Line	< 1.0	Monitor Performance of Time-Variant Components

Table 6: Phase Difference Calibration Measurement Times

Measurement Step	Integrate System	Install System	Flight Begin	Flight End
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21 Mar 94	65.1	N/A	Another Flight
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Table 6: Phase Difference Calibration Measurement Times

Measurement Step	Integrate System	Install System	Flight Begin	Flight End
Lab & Antenna Range	X			
Nadir Lake	X	X		
Height Offset	X	X		
Delay Line	X	X	X	X

Note that all techniques have been performed at multiple center frequencies to detect and remove path length differences of greater than a wavelength. Application of multiple frequencies to the system-induced portion of the phase difference is directly analogous to previous techniques used for unambiguous determination of pointing-induced phase difference (Madsen, 1992).

ACKNOWLEDGMENTS

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