CALIBRATION OF TOPSAR CROSS-TRACK INTERFEROMETRIC DATA PROCESSED WITH THE IFPROC PROCESSOR

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1 Introduction

C-band
cross track interferometry

The NASA/JPL airborne SAR (AIRSAR) system can collect cross track interferometric data for topographic mapping applications (TOPSAR) at both C- and L-Band. Articles published in the peer-reviewed literature have shown statistical errors of 1 to 5 m using 1991 and 1992 C-Band data and larger systematic errors [Zebker et al., 1992; Madsen et al., 1993; and Madsen et al., 1995]. Recent studies have shown improved systematic errors due to improved aircraft position and attitude measurements, improved processing techniques, and improved interferometric calibration [Yoha et al., 1995][1]. In this paper, we will present our technique of calibrating TOPSAR data processed with the IFPROC interferometric processor. First, we will review the relevant system configuration features and state the parameters that need to be calculated. Next, we will go over our calibration method and procedure. We will conclude with suggestions that will improve future calibrations of TOPSAR data and mention our future work.

2 Configuration and Modes

Since the NASA/JPL airborne SAR (AIRSAR) system is described elsewhere [Lou et al., 1996], here we will only the review the features relevant for cross-track interferometric calibration. Mounted on the DC-8 are a pair of left-looking C-Band antennas, one located above the other on the fuselage. The antennas are separated by 2.5 m with a roll angle of 65° and a baseline yaw angle of $-0.5°$. Further aft are a pair of L-Band antennas. The L-Band antennas are separated by 1.9 m with a roll angle of 69° and a yaw angle of $-2°$.

Cross-track interferometric data is processed in one of four modes. The data channels used for each processing mode are given in Table 1. A data channel is identified by a three-letter mnemonic indicating its frequency (C or L), the location of the transmit antenna used (Top or Bottom), and the location of the antenna used for reception (Top or Bottom). Although used in calibration, the TOP-Bot modes are not generally used operationally because the signal-to-noise ratio is better using the TOPSAR modes and both modes use a single transmitter and have the same effective baseline. AIRSAR data can be collected with a 20 or 40 MHz bandwidth. We will limit our discussion in this paper to the TOPSAR 40 MHz bandwidth data.

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[1] This reference is currently available at `http://www.consrv.ca.gov/geosar/geo1.html`

Processing Mode	Channels Used	Data Collection Mode	Effective Baseline
C-Band TOPSAR	CTT, CTB	XTI2P or XTI1P or XTI2 or XTI1	2.5 m
C-Band TOP-Ping	CTT, CBB	XTI2P or XTI1P	5.0 m
C-Band TOP-Bot	CBT, CBB	XTI2P or XTI1P	2.5 m
L-Band TOPSAR	LTT, LTB	XTI2P or XTI2	1.9 m
L-Band TOP-Ping	LTT, LBB	XTI2P	3.9 m
L-Band TOP-Bot	LBT, LBB	XTI2P	1.9 m

Table 1: Cross-track interferometric processing modes

3 Parameters to Calibrate

In our calibration of the TOPSAR data, we determine the following parameters:

- time delays for all eight interferometric channels,
- the physical baseline length, physical baseline roll angle, and the physical baseline yaw angle for each frequency,
- the differential phase for the single transmit and ping-ponged modes and for each frequency, and
- phase screens for each mode and frequency.

In practice, the determination of the time delays is divided up into determining the differential time delay between pairs of channels processed interferometrically and determining a common range delay for each frequency. The reason for this is that the differential time delays can be measured much more accurately.

Other calibration parameters are needed in addition to the ones listed above. The yaw and pitch angle biases for the embedded GPS(Global Positioning System)/INU(Inertial Navigation Unit) used to measure the aircraft orientation are important. They are determined in an earlier calibration stage and will not be discussed here. Also additional parameters are needed for polarimetric and radiometric calibration. These parameters and methods for calculating them have been described elsewhere [Freeman, 1992 and van Zyl, 1990].

4 General Method

The calibration parameters are determined by fitting the errors in the imaged corner reflector positions using the known sensitivity of the target position to calibration parameter errors. In this section we will present the error dependences for the relevant variables and show how they fit into our calibration method. For simplicity, the 3-D planar earth equations will be presented. In practice we also apply the spherical earth corrections.

The sensitivity of the target position to platform position is given by

$$\frac{\partial \vec{T}}{\partial P_s} = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} \tag{1}$$

$$\frac{\partial \vec{T}}{\partial P_c} = \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix} \tag{2}$$

$$\frac{\partial \vec{T}}{\partial P_h} = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \tag{3}$$

where P_s, P_c, and P_h are the three components of the aircraft position, $\vec{P}$, in the along track direction, in the across track direction, and in height, respectively. $\vec{T}$ is the target position, ρ is the range to the target, and $\hat{l}_{sch}$ is the look direction to the target. The three component vector in square brackets indicates the s, c, and h components. Note that an error in the aircraft position merely translates the entire scene. This is expected since $\vec{T} = \vec{P} + \rho\hat{l}_{sch}$.

The sensitivity of the target position to range errors is given by

$$\frac{\partial \vec{T}}{\partial \rho} = \begin{bmatrix} \cos(\beta) \\ \mu\sin(\theta) \\ -\cos(\theta) \end{bmatrix} = \hat{l}_{sch} \tag{4}$$

where

$$\mu = \sqrt{1 - \left(\frac{\cos(\beta)}{\sin(\theta)}\right)^2}, \tag{5}$$

β is the angle between the aircraft velocity and the look direction, and θ is the look angle.

The sensitivity of the target position to errors in the baseline length, the baseline roll angle, the baseline yaw angle, and the phase difference are given by

$$\frac{\partial \vec{T}}{\partial B} = \frac{\rho}{B}\left(g_{tan} + \frac{\tan(\kappa)\cos(\beta)}{g_{cos}}\right)\begin{bmatrix} 0 \\ -\cos(\theta) \\ -\mu\sin(\theta) \end{bmatrix}, \tag{6}$$

$$\frac{\partial \vec{T}}{\partial \alpha} = \rho\begin{bmatrix} 0 \\ \cos(\theta) \\ \mu\sin(\theta) \end{bmatrix}, \tag{7}$$

$$\frac{\partial \vec{T}}{\partial \kappa} = \rho\left(\tan(\kappa)g_{tan} + \frac{\cos(\beta)}{g_{cos}}\right)\begin{bmatrix} 0 \\ \cos(\theta) \\ \mu\sin(\theta) \end{bmatrix}, \tag{8}$$

and

$$\frac{\partial \vec{T}}{\partial \phi} = \left(\frac{-\lambda\rho}{a2\pi B g_{cos}\cos(\kappa)}\right)\begin{bmatrix} 0 \\ \cos(\theta) \\ \mu\sin(\theta) \end{bmatrix} \tag{9}$$

where

$$g_{tan} = \frac{\cos(\alpha)\sin(\theta)\mu - \sin(\alpha)\cos(\theta)}{\sin(\alpha)\sin(\theta)\mu + \cos(\alpha)\cos(\theta)}, \tag{10}$$

$$g_{cos} = \sin(\alpha)\sin(\theta)\mu + \cos(\alpha)\cos(\theta), \tag{11}$$

α is the baseline roll angle, B is the baseline length, and κ is the baseline yaw angle, ϕ is the phase difference, and a is 1 or 2 for single transmit or ping-ponged modes.

Since we know the derivatives, and we can measure the target position error $\Delta\vec{T}$ for each target, we can relate the measured target position errors to our calibration parameters via

$$\frac{\partial \vec{T}}{\partial \vec{P}}\Delta\vec{P} + \frac{\partial \vec{T}}{\partial \rho}\Delta\rho + \frac{\partial \vec{T}}{\partial B}\Delta B + \frac{\partial \vec{T}}{\partial \alpha}\Delta\alpha + \frac{\partial \vec{T}}{\partial \kappa}\Delta\kappa + \frac{\partial \vec{T}}{\partial \phi}\Delta\phi = \Delta\vec{T}. \tag{12}$$

Therefore using a least squares technique, we can solve for the error in the platform position $\Delta\vec{P}$, the error in the range $\Delta\rho$, the error in the baseline length ΔB, the error in the baseline roll angle $\Delta\alpha$, the error in the baseline yaw angle $\Delta\kappa$, and the error in the phase $\Delta\phi$. In practice, we use singular value decomposition to evaluate the actual errors. By adding the measured error to the initial value, we can determine the final calibration parameters.

Although the aircraft position error and range errors are included in equation (12), we normally determine these parameters using the slant plane imagery before solving for the baseline parameters. The error of the range of a target is given by

$$\frac{\partial\rho}{\partial P_s}\Delta P_s + \frac{\partial\rho}{\partial P_c}\Delta P_c + \frac{\partial\rho}{\partial P_h}\Delta P_h + \frac{\partial\rho}{\partial\tau}\Delta\tau = \Delta\rho, \qquad (13)$$

where

$$\tfrac{\partial\rho}{\partial P_s} = (\cos(\beta))^{-1}, \quad \tfrac{\partial\rho}{\partial P_c} = (\mu\sin(\theta))^{-1}, \quad \tfrac{\partial\rho}{\partial P_h} = (\cos(\theta))^{-1}, \qquad (14)$$

$\frac{\partial\rho}{\partial\tau} = 1$, and τ is the common range delay. The location error in range of each target is measured, and equation (13) is solved using singular value decomposition to determine the platform position errors and range errors.

5 Calibration Procedure

Every time the antennas are remounted on the aircraft or the radar cabling is changed, the radar system needs to be recalibrated. The first step in our calibration procedure is normally to process the XTI2P mode data collected over a calibration site in all six processing modes using the previous season's calibration parameters. Because the time delays are uncalibrated, the data in the single look complex imagery of the two interferometric channels is not coregistered. As a result, no interferograms are formed. Therefore we output slant plane imagery for each channel. The differential time delays for each interferometric pair are measured by cross correlating the slant plane images of each pair of interferometric channels. Cross correlations are done throughout the image; no radar identifiable targets are required. This method is accurate to approximately 0.05 pixels. The measured time delays are cross checked by also examining the difference when the two interferometric channels view common objects in the slant plane image. The accuracy of this technique is limited to about 0.2 pixels by the ability to resolve the position of the target to a fraction of a pixel and by the number of targets to average. At our calibration site at Rosamond Dry Lake Bed, there are 13 corner reflectors distributed in a line across track. The differential time delays measured for the TOPSAR and TOP-Bot modes are compared as a way of assessing the uncertainty in the measurement since their differential time delays should be identical.

The slant plane images are also used to determine the common range delay. For each of the eight data channels, time delay is estimated by examining the location in the slant plane image where each corner reflector was imaged. From the location differences, a time delay, an aircraft cross track position error, and an aircraft height position error are solved for. Note this requires accurate platform position information which could be enhanced with regular differential GPS data collection. For each data channel, this method produces fraction of a pixel uncertainties in the time delay. We improve the uncertainty in our common range delay measure by averaging all eight data channels aircraft position errors and synthesizing the time delay measurements of the four channels of the same frequency to determine the common range delay.

Having utilized the the slant plane images to determine the time delays, the next step is to reprocess the data for the TOP-Ping modes producing the interferometric amplitude and height maps. When reprocessing the data we use a surface fitting regridding algorithm instead of IFPROC's default nearest neighbor algorithm to get better corner reflector position and height estimates. Although the TOPSAR or TOP-Bot modes could be used, the statistical height errors are the smallest for the TOP-Ping mode making it the best choice. The interferometric baseline and phase difference are measured by fitting the measured errors in the corner reflector positions using the known error dependence of these parameters as described previously. The measured baseline and time delays are now used to process data for TOPSAR mode data. The single transmit mode phase differences are then solved for using the residual corner reflector position errors.

The final step is to calculate the phase screens for each mode. This correction is applied to the data to remove the few meter across track ripples in the heights caused by multipath and/or switch leakage in the data. The phase screen is a phase offset calculated as a function of look angle. It is calculated by measuring the difference between the measured height and reference heights from a high resolution DEM over a scene. Height differences with the same look angle over the scene are averaged together. The height differences are then multiplied by the derivative of the phase as a function of height to calculate the phase offset. The offsets are written into a phase screen file for each mode. The phase screen can be inverted to solve for the location and magnitude of the multipath and/or switch leakage.

Unfortunately, we have no high resolution DEM for the Rosamond calibration site. In order to calculate the phase screen, TOPSAR and TOP-Ping data must be processed at a different calibration site, normally Camp Roberts or Avenal Ridge. This switch from site to site can lead to phase screen errors since the platform position error is different for each run.

6 Summary and Future Work

The procedure and method outlined above has been used to successfully calibrate the TOPSAR system for both 1995 and 1996 campaigns. Thousands of kilometers of strip data has been processed using these calibrations. In addition, we are continuously improving our calibration techniques. One factor limiting our calibration quality has been our relatively poor determination of the aircraft position error. The AIRSAR system is equipped with an on-board differential GPS unit that should in the future provide better aircraft position information. Another limitation has been the calibration data collected. In many ways, the Rosamond calibration site is less then ideal for interferometric calibration: the signal-to-noise ratio is low for the corner reflectors at L-Band, the terrain is flat and dark at all frequencies increasing the statistical errors in the height measurements, and there is no high resolution DEM or kinematic survey of the area. The planned kinematic survey and resurvey of the corner reflector positions should also improve the interferometric calibration.

We have three principle areas of future work. Firstly, a recently completed point target simulator should help us to verify our code, improve our calibration procedure, and quantify the calibration uncertainties. Secondly, data collected in the fall of 1996 indicates that the baseline calibration parameters may vary with aircraft height. With future data we hope to explore this further. Thirdly, far range data collected over water and other very low signal-to-noise ratio targets seems to have different multipath and/or leakage characteristics then data collected over normal targets. Continued study of existing data sets and new data should help us to better understand these effects and develop better phase screens.

7 References

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