Calibration of an Airborne Along-Track Interferometric SAR System for Accurate Measurement of Velocities

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One of the applications of synthetic aperture radar in oceanography is the study of ocean surface currents by airborne along-track interferometric SAR (along-track INSAR, ATI). There is undoubted evidence that ATI enables studies of moving processes and can give an estimate of target velocities. This paper discusses experimental and theoretical concepts for processing ATI data very accurately. Furthermore, it shows that the proposed remote sensing technique for accurate measurement of ATI phase generated from ocean surface currents is promising in terms of accuracy and spatial resolution.

INTRODUCTION

In spring 1999, a first field experiment of the German remote sensing project EURoPAK-B took place in the north of Heligoland (German Bight) covering an underwater reef to investigate the potential for measuring ocean surface currents and coastal underwater bathymetry by an airborne along-track interferometric synthetic aperture radar. The basic principle of this method is described in [1].

During this experiment, the ATI system designed by Aero-Sensing was used in along-track interferometric mode for the first time. In contrast to cross-track interferometry (XTI), ATI is sensitive to scatterer motions and not to topographic elevations. Thus the typical XTI calibration methods on the basis of corner reflector locating cannot be applied. This means that the processed effective phase is the starting point for the determination of ocean surface currents and has to be handled accurately. The final accuracy is affected by errors coming from different sources, some of them directly related to features of the SAR signal itself. Therefore some concepts for a very accurate processing of ATI data have to be developed. This includes, e.g., a correction for phase contributions resulting from the existing cross-track baseline component which depends on the squint angle during data acquisition. To minimize this effect, the exact positions of the phase centers of both antennas have to be determined very accurately. Also some other effects like a phase bias of the generated interferometric phase induced by a misregistration between two channels must be taken into account. Below, procedures for processing ATI data are discussed, and results are shown.

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AES-1 INTERFEROMETRIC RADAR

Main system parameters used for the experiment are X-band, HH polarization, and 200 MHz bandwidth. The interferometer is configured as a two-antenna single-pass interferometric SAR. In order to get an accurate aircraft motion compensation which is necessary for a precision processing, combined INS and D-GPS techniques are used which allow the determination of each antenna's absolute position with an accuracy of about 3 cm. The antennas are spatially separated by a fixed distance of 0.6 m along the flight direction of the ATI platform. Each antenna is used alternately for both signal transmission and reception so that each antenna receives the signal it has transmitted. Therefore, the effective along-track baseline is equivalent to the spatial distance between both antenna phase centers. Nominal aircraft altitude during data acquisition was 2500 m with a nominal platform velocity of around 100 m/s. Thus an ATI time lag of 6 ms results. A theoretical simulation confirmed that this time lag is a sufficiently short period for an acceptable coherence of the radar signal and on the other hand a sufficiently long period for a good resolution of measured velocities. A nominal incidence angle of 45° was selected, resulting an effective incidence angle range between 30° and 60°, which is desirable for a minimization of nonlinearities in the imaging mechanism. The ATI system parameters were selected on the basis of the recommendations given in [2].

ATI PROCESSING

For SAR processing, a range/Doppler processing algorithm including precise motion compensation is used [3]. The interferometric processor carries out the co-registration of the images, phase filtering, phase unwrapping and geocoding. For an accurate processing, robust and efficient algorithms have to be developed. In the processing chain the single look complex images (SLCs) are converted to the final geocoded coherence, amplitude, and phase, from which the interferometric velocity, surface current fields, and coastal underwater bathymetry are derived in a further step [4].

Due to the aspired accuracy of estimating the ocean surface currents, improvements of parts of the processing algorithms had to be carried out. Some typical problems and developed solutions are presented in the following subsection.

A. Co-registration

Phase errors occured during data processing that were caused by misregistration of the SLCs. This behavior imposes strong limitations on the performance of the interferometric techniques because the phase bias resulting from this effect can reach high values in typical situations for airborne platforms. In a general airborne case of a squinted image geometry and squint processing, the system's impulse response function is characterized by a linear phase ramp that causes an interferometric phase bias $\delta\Phi$ if both channels are not perfectly registered [5]:

$$\delta\Phi = \tfrac{4\pi}{\lambda}\,\delta x\left(1-\cos\beta\right) \qquad (1)$$

where δx is the existing misregistration and β the squint angle. This effect can not be considered as negligible, since δx depends on the motion of the scatterers in case of ATI data. Subsequent co-registration errors were corrected using theoretical co-registration parameters which can be computed from the imaging geometry of the illuminated scene if the underlying topography as well as the exact positions of both antennas are well known, which is the case for the AeS-1 system in ATI mode.

B. Theoretical Determination of the Antenna Phase Center

For obtaining high precision ATI data, the real phase centers have to be well known. Therefore the two antennas of the ATI system are mounted on a rigid steel beam. On this beam the inertial navigation system (INS) is mounted also. For the data processing, the distances between the measurement center of the INS and the phase centers of each antenna have to be known. When determining them, some inaccuracies can occur which place the phase center of an antenna at a wrong position. The existing variation between the actual and nominal position may cause a phase ramp or phase offset as undesirable contribution to the ATI.

To eliminate this contribution from the ATI phase the phase modification has to be determined by changing the actual phase center position of one antenna. Thereby it has to be changed only in two directions which are perpendicular to the ATI baseline. The third direction, which is the azimuth direction, does not to be taken into account because the contribution to the phase is negligible. With the assumption that the relationship between phase and resulting difference of the range distance is approximately linear, the phase modification per millimeter for both directions can be determined. With this information, it is possible to find the optimal position of the antenna phase center for an accurate ATI data processing.

C. "Flat-Earth" Phase Contribution

Theoretically, ATI does not contain a "flat-earth" phase contribution which results from any cross-track baseline component. This is the case if both antennas follow exactly the same track during data acquisition. However, this collinear condition is not met if positions of the phase centers are not exactly aligned with the flight direction or if the illumination takes place with a significant antenna squint angle (which is the general case), so that different ideal tracks for both antennas are calculated in order to guarantee optimal aircraft motion compensation. Accordingly, a phase contribution arising from the corresponding cross-track baseline component is introduced. This "Flat-Earth" contribution has to be eliminated to remove all phase effects that do not origin from scatterer motions.

If the scene contains land without significant topography, the "Flat-Earth" contribution can be removed easily by adjusting the phase over the stationary targets. However, some of the tracks cover only ocean surface so that an accurate system calibration has to be carried out. Using the precisely known imaging geometry, the expected "Flat-Earth" phase was calculated for the stationary targets and compared to the actually measured one. Any difference which can arise e.g. from the not perfectly known baseline was used to adjust the corresponding system parameters. With these adjustments the system supplies offset-free phases also for tracks without stationary targets.

D. Phase Unwrapping

For an exact determination of the ATI phase, an along-track baseline (respectively time lag) is selected which covers the expected interferometric velocities within a 2π range. However, some areas, e.g. those including breaking waves, show phase values exceeding the range of 2π. These local targets give rise to high backscattered power with a Doppler bandwidth corresponding to a phase range wider than the expected domain. Therefore, the phase has to be unwrapped for a better and accurate processing and a correct interpretation. The phase unwrapping may cause errors within areas of low coherence which becomes apparent by a 2π wrap-around in the phase image. The left image of Fig. 1 shows an example for an unwrapping error. These mentioned areas have to be converted into the given and expected 2π interval. Therefore, a procedure was developed that distinguishes between phase values exceeding the 2π range, e.g. breaking waves, and phase unwrapping errors. This procedure uses morphological operators from digital image processing, e.g. threshold, conjunction, erosion, and dilation. The threshold operator is applied to extract a reduced set of structures that includes phase values exceeding the 2π domain. The other mentioned operators are first used to eliminate areas which are corrupted by noise. In a second step, the binary image produced by the threshold from the phase image is reconstructed. The extracted structures are overlaid to the input phase image and corrected by $\pm 2\pi$. As one can see in Fig. 1 this method for the correction of the phase unwrapping errors works very well and reliable for ATI data acquired over ocean areas.

RESULTS AND CONCLUTIONS

Fig. 2 presents an example of a calibrated and non-calibrated phase profile. The profiles show clearly the phase resulting from land which can be seen as a stationary target between the range pixels from 50 to 500 and 1000 to 1300. In these regions the phase is nearly constant and oscillates around zero in the calibrated one. The bottom line displays the phase profile before calibration and one can see that the values in the land regions are nonrealistic. The phases of the other regions that are not in the range of zero let conclude that the scatterers have moved during the ATI time lag like the ocean surface does. With this phase information it is possible to determine the ocean surface currents in a further step [4].

An example of an actual geocoded ATI phase signature with all corrections proposed in this paper is given in Fig. 3. It shows the profile of the ATI phase over an underwater reef and acquired from two opposite illumination directions. This test site was selected because of strong current gradients resulting from the reef and corresponding radar signatures, which can be visible e.g. in the two phase profiles of Fig. 3. As one can see, they mainly differ in the sign of the phase. The reason is that in one case the line-of-sight component of the ocean surface currents is towards the radar and away from it in the other case.

These positive results are encouraging to continue this work. In a further step the algorithms for an accurate ATI processing which are presented in this paper will be applied in a second experiment of the remote sensing project EU-RoPAK-B near the German Island Sylt. Also some new algorithms will come into operation like the phase offset correction arising from different frequencies like more than one master and slave channels in X-Band and other new system parameters which will be investigated in the near future.

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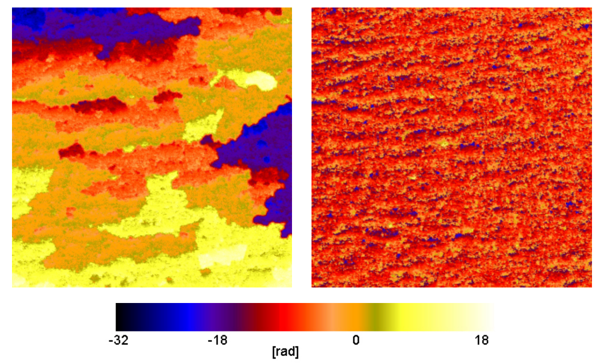

Fig. 1: Left, unwrapped phase from an ocean surface including some unwrapping errors. Right, same scene (600m × 1800m) after correction of these errors.

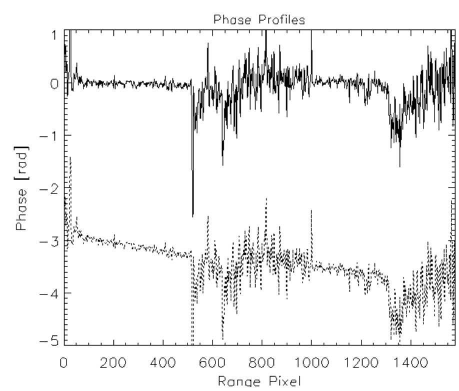

Fig. 2: Two phase profiles in range direction including some land and ocean. The upper profile shows the calibrated phase and the bottom one the non-calibrated one.

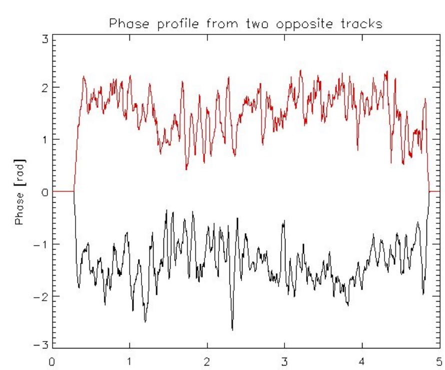

Fig. 3: Profile of actual geocoded ATI phase from the same scenario but opposite directions.