PROOF OF CONCEPT OF THE MULTI-FREQUENCY ALONG-TRACK INTERFEROMETRIC SAR OCEAN WIND AND CURRENT MEASUREMENT TECHNIQUE

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LONG-TERM GOALS

The long-term goal of this work was to develop and test methods to estimate currents and wind direction from ATI SAR data at high-resolution (ideally, at the same resolution as the SAR image), and thereby provide a high-fidelity surface current information in littoral and riverine environments. Furthermore, these techniques were to be developed using technology suitable for operation from UAVs.

OBJECTIVES

- Add an L-band and an X-band ATI SAR to our airborne platform.
- Collect multi-frequency ATI SAR data in a coastal environment where terrain and vegetation are likely to affect wind forcing on the water surface.
- Develop a retrieval algorithm to estimate both surface currents and wind direction within the domain imaged.

APPROACH

The approach was to extend the method used by Kim et al. [2003] to retrieve surface currents by 1) testing different combinations of microwave frequencies, 2) using a numerical model for the Doppler bias due to sub-resolution gravity waves, and 3) using a least squares approach to estimate and remove wave orbital motion. We also used the estimate of α and a model to retrieve wind direction throughout the domain.

WORK COMPLETED

The specific tasks were:

(a) Install the L-band and X-band SlimSARs on the aircraft.
(b) Conduct a field experiment at the Deception Pass (WA) site.
(c) Process raw SAR data to form interferograms.
(d) Develop code for multi-frequency wind direction and surface current estimation.
(e) Present results at a conference

Additional task were:

(f) ASTER TIR and VNIR Imagery for CalWater2 Project (Jessup)
(g) Wave Averaged Infrared (C. Chickadel, APL-UW)

Tasks (a)-(c) and (e)-(f) were accomplished as proposed. Task (d) was modified to focus on determining system errors from the SAR that was a necessary first step. Available funds were expended before the code for the multi-frequency wind direction and surface current estimation could be completed.

RESULTS

A comprehensive system error source analysis and calibration of an airborne along-track interferometric FMCW SAR for ocean surface currents velocity retrieval was done. Starting with the observed phase errors from a stationary test site, three major error sources were analyzed and possible calibration approaches are derived. The range-dependent phase offsets were demonstrated to be introduced by the phase imbalance between receive channels and receive antennas of the transceiver. The phase undulations in the along-track direction were likely due to the uncompensated motion errors caused by inaccurate aircraft attitude and velocity measurements. After calibration, most of the system phase errors were removed which greatly improved the accuracy for surface velocity retrieval by ATI-SAR. See attached IGARSS paper for details.

IMPACT/APPLICATIONS

The system error analysis will provide improved velocity estimates in future applications.

RELATED PROJECTS

NONE

REFERENCES

Kim, D., W. Moon, D. Moller, and D. Imel (2003), Measurements of ocean surface waves and currents using L- and C-band along-track interferometric SAR, *IEEE Trans. Geosci. And Remote Sens.*, 41(12), 2821–2832, doi:10.1109/TGRS.2003.817210.

PUBLICATIONS

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SYSTEM ERROR ANALYSIS OF AN AIRBORNE ALONG-TRACK INTERFEROMETRIC FMCW SAR FOR SURFACE VELOCITY ESTIMATE

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ABSTRACT

A comprehensive system error source analysis and calibration of an airborne along-track interferometric FMCW SAR for ocean surface currents velocity retrieval is presented. Starting with the observed phase errors from a stationary test site, three major error sources are analyzed and possible calibration approaches are derived. The range-dependent phase offsets are demonstrated to be introduced by the phase imbalance between receive channels and receive antennas of the transceiver. The phase undulations in the along-track direction are likely due to the uncompensated motion errors caused by inaccurate aircraft attitude and velocity measurements. After calibration, most of the system phase errors are removed which greatly improves the accuracy for surface velocity retrieval by ATI-SAR.

***Index Terms*—** Inteferometric SAR, error analysis, SAR calibration, surface velocity estimation.

1. INTRODUCTION

Airborne along-track interferometric synthetic aperture radars (ATI-SAR) have shown their promise in high-resolution mapping of surface velocity fields such as ocean surface currents and other dynamic surface features [1, 2]. ATI-SAR can estimate the radial velocity between the radar and the moving scatterer by exploring the phase difference between the received signals. Thus, any system-introduced phase errors will translate into errors in the radial velocity estimate and must be taken care of with calibration. The system phase error of airborne ATI-SAR system can result from various sources. Pinheiro et al. [3] analyzed the range-dependent phase fluctuations in the interferometric phase caused by the multipath. Our previous study [4] demonstrated the observed phase ripple in our FMCW system is caused by the phase mismatch between the receive channels. The phase imbalance between the receive antennas' phase patterns have been reported in [5] where the antenna phase pattern is mathematically derived for calibration. The effects of uncompensated motion errors on ariborne ATI phase errors due to aircraft attitude and velocity uncertainty was studied in [6]. Although each of them focus on one or a few error sources, no comprehensive phase error analysis for ATI-SAR has been summarized in the literature.

In this paper, we describe a comprehensive summary of the phase error analysis of an airborne interferometric FMCW ATI-SAR system. Starting from the observed phase error in the interferogram of a stationary farmland test site, we analyzed the error and came up with three classes of error sources that contribute to the observed error. After applying the proposed phase calibrations, significant improvement in the accuracy of the surface velocity estimate by the ATI-SAR can be achieved.

2. OBSERVED PHASE ERROR

The system employed in this study is the microASAR developed by Artemis Inc. It consists of two squinted FMCW SARs and each radar has one transmit antenna and two receive antennas mounted on the belly of an aircraft. The radial velocity u_r estimated by ATI-SAR is related to the measured interferometric phase Φ with the equation:

$$u_r = \frac{v_p}{2kB}\Phi \tag{1}$$

where k is the wavenumber, B is the baseline and v_p is the platform velocity. Any factors that contribute to the phase error will result in the error in velocity measurement.

To better illustrate the phase error of the system, we collected SAR data over a farmland area in WA of USA. Figure 1 shows the interferogram which plots the ATI phase for the imaged farmland and white color corresponds to zero phase. Ideally, the ATI phase for stationary targets should be zero. We can clearly observe the range-dependent phase ripple and non-zero phase offset over the area, ranging from 0.4 to over 1.0 radians.

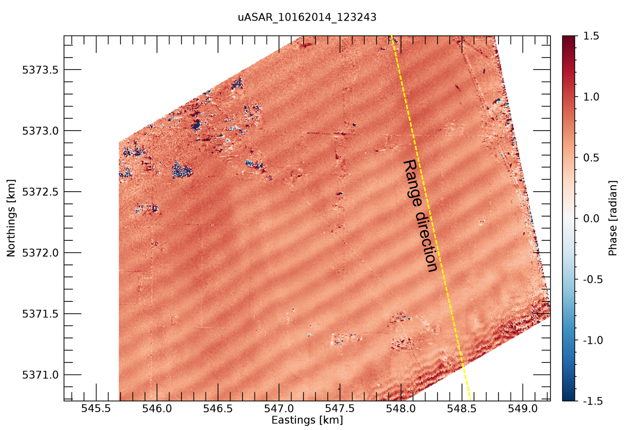

Fig. 1: Interferogram of measured ATI phase for the stationary farmland area in WA, USA. During the experiment, the aircraft was flying from the southwest to the northeast and the two squinted SARs are looking at the starboard (right) side of the platform. The yellow dashed line shows the range direction.

3. ERROR SOURCE ANALYSIS AND CALIBRATIONS

Based on the analysis of the FMCW transceiver and the time-domain backprojection imaging algorithm, we came up with three classes of error sources which may contribute to the observed phase error in Fig. 1: 1. Phase imbalance between receive channels of the transceiver, 2. imbalance between the receive antennas' phase patterns, and 3. insufficient inertial navigation system (INS) accuracy. A comprehensive and detailed analysis of each error source with possible calibration approaches are studied in this section.

3.1. Phase Imbalance Between Receive Channels

Our previous study [4] demonstrated that the range-dependent phase fluctuations shown in Fig. 1 are caused by the mismatch in the phase response of the dual receiver channels in the FMCW SAR rather than the multipath effect studied in [3]. Note for FMCW radars, the beat signal frequency is proportional to range between radar and target. Any frequency-dependent phase mismatch between receive channels will result in the range-dependent phase fluctuations in the interferogram. Different phase calibration approaches have been derived and Fig. 2 shows the calibrated ATI phase image using the proposed joint estimate approach. We find the range-dependent phase ripple has been greatly attenuated after calibration. The standard deviation of the ripple has been reduced from 0.2 rad to 0.05 rad.

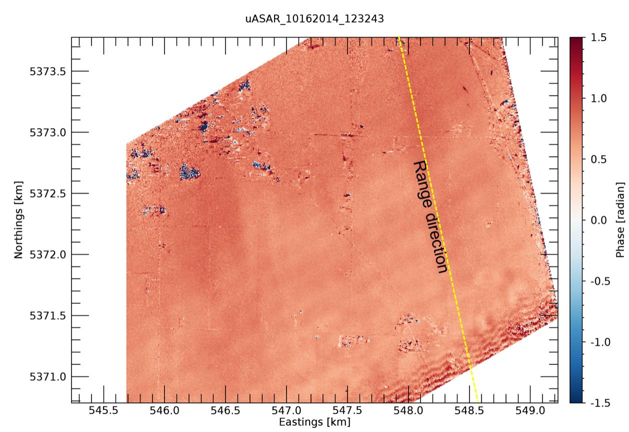

Fig. 2: Phase ripple calibrated inteferogram for the stationary farmland area in WA, USA. The yellow dashed line shows the range direction.

3.2. Phase Imbalance Between Receive Antennas

Although the range-dependent phase ripple has been greatly attenuated, we can still observe non-zero phase offset in Fig. 2. Since the phase ripple calibration experiment was done in the lab where the antennas are not installed, the residual phase offsets are likely due to the phase imbalance between the receive antennas' phase patterns. The system uses C-band patch array flat-panel as its receive antenna, which consists of a total of 16×4 patches, as is shown in Fig. 3. Due to the manufacture imperfection, the two receive antennas will have a different phase response with elevation. The mismatch between the two antennas' phase responses will result in range-dependent phase offset.

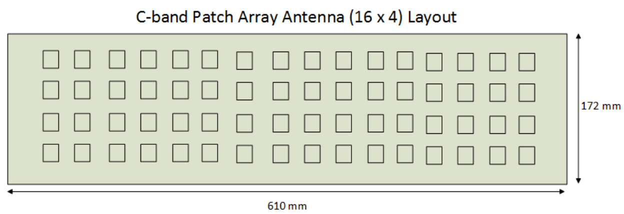

Fig. 3: Layout of C-band patch array antenna.

The calibration for the antenna phase imbalance requires the estimation of the phase mismatch between the two receive antennas' phase patterns. Bachmann et al. [5] presented a mathematical model for deriving the antenna phase pattern in an operational InSAR mission. In comparison with the complicated mathematical derivation, our study takes advantage of the collected SAR data from the stationary farmland. To estimate the imbalance between the antenna phase patterns, we made use of the ATI phase measurement in Fig. 2 rather than calculating the antenna phase pattern for each antenna. The SAR processor first calculates the elevation angle offset from boresight for each pixel in the imaged scene. We then plot a histogram of the elevation offset angles over 184 bins. For angles that fall in each bin, we first compute the coordinates for the angles (pixels) in the image. Then we go back to Fig. 2 to find the corresponding phase values. We finally compute the mean of these phases and use it as the phase imbalance between antennas for the specific elevation offset angle. The estimated antenna phase imbalance versus elevation offset angle is shown in Fig. 4. Since the estimated phase imbalance is the sample mean of phase values that fall in a specific bin, the error bar in Fig. 4 indicates the standard deviation of the sample mean.

After applying the estimated antenna phase imbalance for further calibration, the resulting calibrated interferogram is shown in Fig. 5. Compared with the interferogram in Fig. 2 before calibration, the calibrated results in Fig. 5 shows a significant reduction of the remaining phase offsets (about 0.6 radians). The phase values after further calibration are almost zeros for the farmland area.

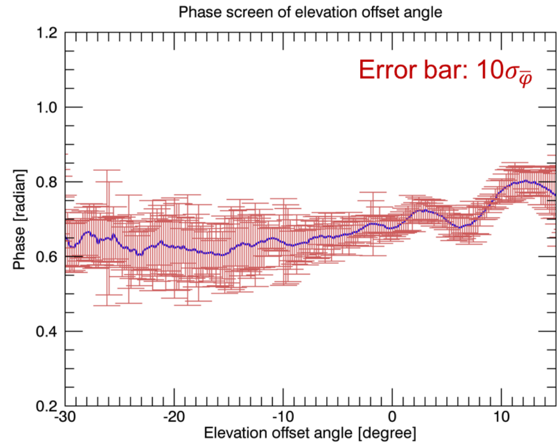

Fig. 4: Estimated antenna phase imbalance from phase ripple calibrated interferogram for farmland area in WA, USA . Error bar corresponds to10 times of the standard deviation of the sample mean of phase values in each bin.

3.3. Phase Error due to Insufficient INS Accuracy

Although the calibrations of the phase imbalance between receiver channels and receive antennas remove great amount of observed phase offsets, the remaining ATI phase for the farmland area is still not zero. Fig. 6 is the same phase plot for the farmland area after antenna phase calibration as in Fig. 5 but with smaller color scale for better visualization. We can clearly observe phase undulations in the along-track direction as alternating red and blue colors with the RMS phase value of about 0.27 rad. Our previous study [6] demonstrated that this azimuthal phase undulations are mainly due to uncompensated motion errors induced by the insufficient INS accuracy on aircraft attitude and velocity measurements. It provides the mathematical derivation of ATI phase error in terms of INS attitude and velocity uncertainties and shows that the ATI phase error is most sensitive to the errors in aircraft's yaw angle measurement. Here we performed simulations on 1001 stationary targets spread in the along-track direction to further verify the theoretical analysis. We first simulated the raw data in a SAR simulator using the measured INS data and then processed raw data in the SAR processor with the same INS data. The RMS value of the processed ATI phase for the 1001 targets in this case are very close to zero (0.037 rad). Then we added random errors to the INS attitude and velocity measurements, respectively and used the error disturbed INS data

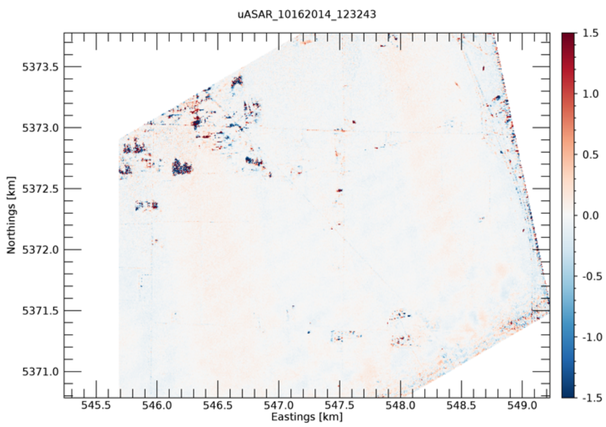

Fig. 5: Antenna phase imbalance calibrated interferogram for a farmland area in WA, USA.

to process the simulated data. From the processed results we find that the RMS phase value of the targets when only yaw error is added is about 0.21 rad, which accounts for most of the azimuthal phase undulations (0.27 rad) observed in Fig. 6. Therefore, we further demonstrated the theoretical analysis in [6] that azimutal phase undulations is due to the uncertainty in the INS attitude measurement, especially the uncertainty in the aircraft yaw angle measurement. Theoretically, we need the accuracy in yew measurement to be better than 0.08 degree to achieve less than 0.1 rad of ATI phase error.

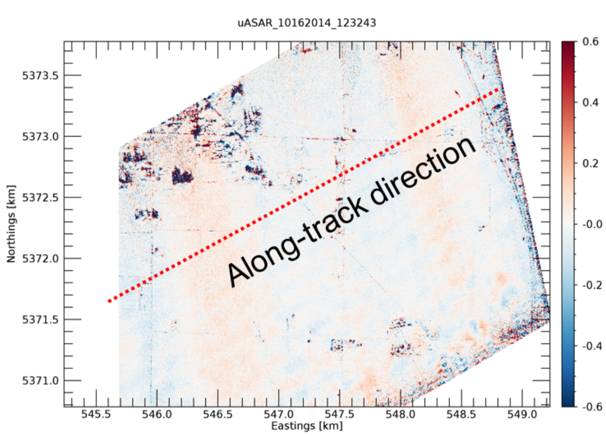

Fig. 6: Antenna phase imbalance calibrated interferogram for a farmland area in WA, USA with smaller color scale. One can clearly observe phase undulations in the flight direction.

4. CONCLUSIONS

This study presents a comprehensive system error analysis of an airborne FMCW ATI-SAR for surface velocity retrieval. It summarized three major error sources that account for the observed phase error and presented possible calibration approaches. Finally, after the proposed phase calibrations, the phase error of the system can be reduced from 1.2 rad to 0.25 rad. Based on the imaging geometry of the system, this corresponds to the reduction of the estimated surface velocity error from 70 cm/s to about 14 cm/s, indicating a significant improvement in the accuracy of the surface velocity estimates by ATI-SAR.

5. REFERENCES

[1] R. M. Goldstein and H. A. Zebker, "Interferometric radar measurement of ocean surface currents," *Nature*, vol. 328, no. 6132, pp. 707–709, 1987.

[2] G. Farquharson, H. Deng, Y. Goncharenko, and J. Mower, "Dual-beam ATI SAR measurements of surface currents in the nearshore ocean," in *2014 IEEE Int. Geosci. Remote Sens. Symp.*, 2014.

[3] M. Pinheiro, P. Prats, Scheiber R., and Fischer J., "Multipath correction model for multi-channel airborne SAR," in *Proc. IEEE Geosci. Remote Sens. Symp.*, July 2009, vol. 3, pp. 729 – 732.

[4] H. Deng, G. Farquharson, J. Sahr, Y. Goncharenko, and J. Mower, "Phase caliration of an along-track interferometric fmcw sar," *IEEE Trans. Geosci. Remote Sens.*, vol. 56, no. 8, pp. 4876–4886, 2018.

[5] Markus Bachmann, Marco Schwerdt, Gabriel Castellanos Alfonzo, and Dirk Schrank, "Phase pattern calibration for interferometric applications in spaceborne sar systems," *International Journal of Antennas and Propagation*, vol. 2013, 2013.

[6] H. Deng, G. Farquharson, M. Nalaban, A. Korovotniy, and Y. Goncharenko, "Analysis of velocity and attitude error in along-track interferometric SAR," in *IEEE Int. Geosci. Remote Sens. Symp.*, July 2017.

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14. ABSTRACT

This work is to develop and test methods to estimate currents and wind direction from ATI SAR data at high-resolution (ideally, at the same resolution as the SAR image), and thereby provide a high-fidelity surface current information in littoral and riverine environments. Furthermore, these techniques will be developed using technology suitable for operation from UAVs.

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15. SUBJECT TERMS

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