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ON AZIMUTH AMBIGUITIES SUPPRESSION FOR SHORT-BASELINE ALONG-TRACK INTERFEROMETRY: THE STEREOID CASE

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ABSTRACT

Ambiguities in short-baseline ATI interferometry need to be treated not as noise that lowers the coherence, but as a source of bias. A mathematical formulation of the interferometric ambiguity model is given, and an approach to correct ambiguities is proposed and illustrated with simulation results.

***Index Terms*—** bistatic, companion missions, Synthetic Aperture Radar. ambiguities, ATI

1. INTRODUCTION

STEREOID (Stereo Thermo-Optically Enhanced Radar for Earth, Ocean, Ice, and land Dynamics) is one of the three mission proposals selected as Earth Explorer 10 candidates. If implemented, STEREOID will dramatically augment the capabilities of the Sentinel-1 mission by flying two identical sub-500 kg- class spacecraft carrying a receive-only radar instrument as main payload that will flying in a re-configurable formation with Sentinel-1D, which will be used as illuminator. STEREOID is conceived as a multipurpose mission, that will exploit its geometric diversity to help precisely quantify small scale motion and deformation fields of the ocean surface, glaciers and ice sheets, and solid Earth, aiming at providing modellers with data required to better understand dynamic processes in these three domains.

STEREOID will alternate two flying configuration. One will be a close-formation configuration focused on single-pass cross-track interferometric measurements. In the second configuration, referred to as the stereo configuration [1], one two spacecraft, STEREOID-A, will in the order of 300 km ahead of Sentinel-1, and the other, STEREOID-B, at about the same distance behind Sentinel-1. This maximizes the line-of-sight (LoS) diversity, hereby providing the best sensitivity to motion-vectors.

One of the standard challenges of designing a companion SAR mission is to meet the promise of a light-weight solution while providing adequate sensitivity and ambiguity suppression [2]. STEREOID inherits the dual-phase-center solution proposed for SESAME [3], with two small antennas with a 4.5 m along-track separation. For cross-track or for repeat-pass interferometry, this provides adequate azimuth ambiguity suppression, while using a relatively small physical aperture.

In this paper we are interested in the observation of instantaneous velocities of the ocean surface and sea ice. Instantaneous velocities can be estimated using Doppler Centroid Anomaly techniques, or exploiting the two phase-center configuration and using Along Track Interferometry [4], or, potentially, a combination of both. Of course, using the dual-antenna system for ATI implies that we give up the azimuth ambiguity suppression capabilities of the system.

2. ATI SIGNAL MODEL

For a detailed discussion of ATI performance and system design considerations, the reader is referred to [5]. The LoS Doppler velocity estimation uncertainty, σ_{v_D}, is proportional to the the ATI phase uncertainty, σ_ϕ, and given by

$$\sigma_{v_\mathrm{D}} = \frac{\lambda_0}{2\pi} \cdot \frac{v_\mathrm{orb}}{B_\mathrm{ATI}} \cdot \sigma_\phi, \tag{1}$$

where B_ATI is the physical baseline, v_orb the orbital velocity, and λ_0 the radar wavelength. For the case of interest of a large number of looks, N_L, the ATI phase uncertainty is well approximated by

$$\sigma_\phi = \sqrt{\frac{1-\gamma^2}{2 \cdot N_\mathrm{L} \cdot \gamma^2}}, \tag{2}$$

with γ the interferometric coherence. At this point it is common to approximate the coherence as the product of several decorrelation terms associated to thermal noise,

$$\gamma_\mathrm{SNR} \approx \frac{\mathrm{SNR}}{\mathrm{SNR}+1}, \tag{3}$$

temporal decorrelation (γ_t), decorrelation due quantization and processing errors, which we will combine into γ_sys and decorrelation due to ambiguities (γ_amb) [6, 5]:

$$\gamma \approx \gamma_\mathrm{SNR} \cdot \gamma_t \cdot \gamma_\mathrm{sys} \cdot \gamma_\mathrm{amb}, \tag{4}$$

with the ambiguity decorrelation term typically expressed as

$$\gamma_\mathrm{amb} \approx \frac{\mathrm{DTAR}}{\mathrm{DTAR}+1}, \tag{5}$$

and DTAR the Distributed Target to Ambiguity Ratio. This assumes that ambiguities, like thermal noise, are interferometrically incoherent, which is not the case. Considering that ambiguities are, in fact, interferometrically coherent, (4) should we rewritten as

$$\gamma = \gamma_\mathrm{SNR} \cdot \gamma_\mathrm{sys} \cdot \left| \frac{I_s + \sum_i \alpha_i I_{a,i}}{P_s + \sum_i \alpha_i P_{a,i}} \right|, \tag{6}$$

where I_s and P_s stand for the expected value of the noise-free interferogram and intensity (power) for the signal of interest, respectively; $I_{a,i}$ and $P_{a,i}$ correspond to the interferogram and intensity of the i-th ambiguity; and the coefficients α_i quantify the ambiguity rejection for the i-th ambiguity (thus, in the case of constant σ_0, we would have $\mathrm{DTAR} = 1/\sum_i \alpha_i$). Temporal decorrelation and interferometric phases would be included in the terms I_s/P_s and $I_{a,i}/P_{a,i}$.

From (6) we can deduce that the effect of ambiguities on the interferometric coherence will depend on their relative interferometric phase, as recognized in [7]. The interferometric phase will be that of the term

$$\hat{I}_s = I_s + \sum_i \alpha_i I_{a,i}, \tag{7}$$

which will be generally biased with respect to the phase of I_s. Ambiguities are partially defocused. However, since energy is conserved, this defocusing can be ignored at interferogram level as long as it small compared to the size of the spatial multi-looking window. The region generating an ambiguity is observed under nearly the same geometry as when this same region constitutes the area of interest. Therefore, we can express (7) as

$$\hat{I}_s(\vec{r}) = I_s(\vec{r}) + \sum_i \alpha_i I_s(\vec{r} - \Delta\vec{r}_i), \tag{8}$$

where $\vec{r}$ and $\Delta\vec{r}_i$ represent the range-azimuth position of the region of interest and the offset of the i-th ambiguity, respectively. For an azimuth invariant stripmap mode we can express this as a 2-D convolution of the desired interferogram with a FIR filter,

$$\hat{I}_s(\vec{r}) = I_s(\vec{r}) * \left(\delta(\vec{r}) + \sum_i \alpha_i \delta(\vec{r} - \Delta\vec{r}_i) \right). \tag{9}$$

2.1. Short-baseline case

Several things simplify in the short baseline case. First, if the along-track lag is very small compared to the coherence time of the surface, temporal decorrelation can be neglected: $\gamma_t \approx 1$. Second, the interferometric phases will be very small, allowing the following approximation

$$I_s = P_s e^{j\phi_s} \approx P_s \cdot (1 + j\phi_s). \tag{10}$$

Moreover the third term in (6) will be very close to 1, meaning that ambiguities will have no effect on the coherence, although they will still bias the results.

3. AMBIGUITIES SUPPRESSION

Convential approaches to minimize the impact of azimuth ambiguities involve some kind of Doppler-domain filtering, either by simply reducing the processed bandwidth or, for example, by applying a Wiener filter [8] at SLC level. Here we propose to suppress ambiguities at interferogram level.

The simplest case is the azimuth invariant case described by (9). In the wavenumber domain, the filter can be expressed as

$$H_a(\vec{k}) = 1 + \sum_i \alpha_i e^{-j\vec{k}.\cdot\Delta\vec{r}_i} \tag{11}$$

Since all the coefficients α_i are small, there exists a well behaved inverse filter, or equalizer, that would perfectly remove the ambiguities (in the expected value). However, this equalizer is a non-causal Infinite Impulse Response (IIR) filter. In the space domain, it can be implemented iteratively,

$$I_{k+1}(\vec{r}) = I_k(\vec{r}) + \Delta I_k(\vec{r}), \tag{12}$$

with

$$\Delta I_k(\vec{r}) = \begin{cases} -\sum_i \alpha_i I_0(\vec{r} - \Delta\vec{r}_i), & k = 0 \\ -\sum_i \alpha_i \Delta I_k(\vec{r} - \Delta\vec{r}_i), & k > 0 \end{cases} \tag{13}$$

and with $I_0(\vec{r})$ the uncorrected interferogram. This iterative solution is general and can be applied also to the azimuth variant case. Of course, only ambiguities that are actually imaged can be corrected for. In the case of STEREOID, the main ambiguities of concern are the first left and right azimuth ambiguities.

4. RESULTS

To illustrate the effect of ambiguities on ATI we have simulated STEREOID-like data using TanDEM-X ATI data as a starting point. Starting with the TanDEM-X data set, multi-looked down to a $500\,\mathrm{m}$ resolution product, we have scaled the phase so that it corresponds to that a $4.5\,\mathrm{m}$ ATI baseline, and then added ambiguities, following (8) and considering the α coefficients and offsets calculated for STEREOID's azimuth ambiguities. The first 4 panels in Fig. 1 show, from left to right: the TanDEM-X Normalized Radar Cross Section; the estimated radial Doppler velocity, which we use as a reference; the estimated radial Doppler velocity after adding ambiguities; and the difference between the two. This simulation clearly illustrates that the errors introduced by ambiguities are significant, and that their power scales with the power of the signal of interest.

The last two panels in the figure show the residual correction after applying the correction method accounting only for the first left and right ambiguity in the correction, and accounting for the first two left and right ambiguities, respectively.

The second case illustrates how, in principle, interferometric ambiguities can nearly perfectly suppressed. The first case is more realistic, as knowledge of the α coefficients will be always imperfect, in particular for far ambiguities.

Table 1 shows the standard deviation and the maximum of the velocity error caused by ambiguities before and after correction. The improvement, considering only the first ambiguities, is more than $10\,\mathrm{dB}$.

Case	$\sigma_{\Delta v}$ [$\mathrm{m\,s^{-1}}$]	$\max\{\lvert\Delta v\rvert\}$ [$\mathrm{m\,s^{-1}}$]
Uncorrected	0.008	0.11
First ambiguity	0.002	0.033
Second ambiguity	0.0004	0.003

Table 1: Standard deviation and maximum velocity error before and after ambiguity correction.

5. OUTLOOK

The main challenge associated to the proposed approach is to accurately estimate the coefficients α_i, which will be sensitive to small antenna model errors. However, since ambiguities introduce spatial correlations in the retrieved signal, these coefficients may be estimated from the data by looking for the values that minimize these spatial correlations.

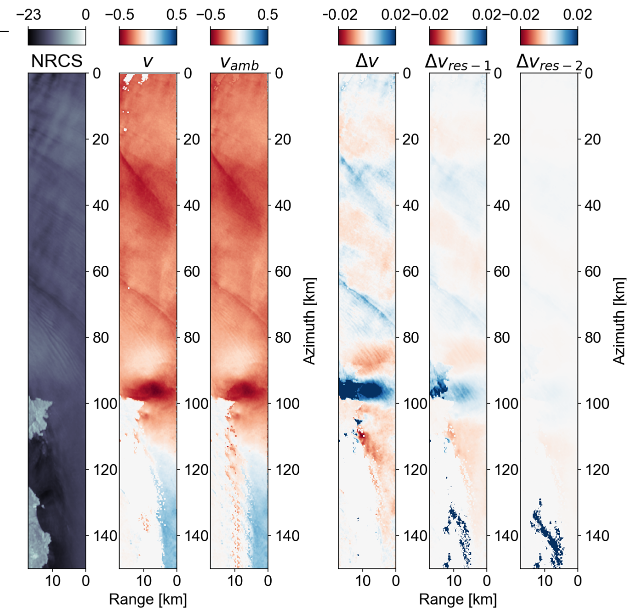

Fig. 1: Emulated results showing, from left to right: the NRCS of a TanDEM-X acquisition in front of Cap de Creus; original estimated radial Doppler velocity; degraded Doppler velocity including simulated azimuth ambiguities; velocity error due to ambiguities; residual error after proposed correction, accounting for the first ambiguity; residual error accounting for the first two ambiguities.

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