Estimation and Compensation of Ionospheric Delay for SAR Interferometry

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I. INTRODUCTION

For spaceborne SAR (Synthetic Aperture Radar) systems, the dispersive effects of the ionosphere on the propagation of the SAR signal can be a significant source of error for interferometry. While at X-band frequencies the effects are small, current and future L-band systems would benefit from ionospheric compensation. We consider two ways to estimate the ionospheric delay in SAR signals and evaluate them on L-band ALOS-PALSAR acquisitions[1].

II. PROPERTIES OF THE IONOSPHERE

The ionosphere is a region of the earth's atmosphere extending from an altitude of about 50–1000 km where solar radiation ionizes atmospheric gases. The state of the ionosphere can be summarized by the density of free electrons as quantified by the TEC (Total Electron Content) the number of free electrons contained in a cylinder with unit area passing through the atmosphere in the direction of nadir. In determining the effect of the ionosphere on a SAR signal, it is generally assumed that the ionosphere can be modeled as a thin layer at a reference altitude of 400 km. The ionosphere is a dispersive medium for electromagnetic waves and causes both a group delay and a phase advance in the signal – below the plasma frequency of ~10 MHz electromagnetic waves are reflected. The one way zenith phase and group delays are inversely proportional to frequency squared and are given by

$$d_{phase} = -K\,\mathrm{TEC}\big/ f^2 \ \text{[m] and} \tag{1}$$

$$d_{group} = K\,\mathrm{TEC}\big/ f^2 \ \text{[m]} \tag{2}$$

respectively where $K = 40.28\ \mathrm{m}^3\mathrm{s}^{-2}$. Note that the phase advance and group delay are equal in magnitude but with opposite sign. To convert to slant range geometry, these equations must be divided by the cosine of the zenith angle. The effect of the ionosphere on polarization through Faraday rotation is not considered further.

Spatially, the ionosphere can be considered homogeneous over ranges of 100s of kilometers with changes occurring only over 1000s of kilometers. At very high or low latitudes there may be a noticeable variation in azimuth. Few phenomena are known to cause disturbances on scales smaller than 100 km – one being traveling ionospheric

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[1] ALOS-PALSAR data provided thanks to Americas ALOS Data Node (AADN) and JAXA.

disturbances. Temporally, the ionosphere exhibits changes daily, seasonally and with the solar cycle. The 11 year solar cycle is the largest contributor to variation. During the current solar minimum a TECU (TEC Unit = TEC×10^{-16}) value over Europe of 5 may be considered nominal, reaching 50 during the solar maximum. When projected onto the earth's surface, the point of maximum TECU tends to lie beneath the point at which the sun is at zenith but is delayed by about 45 degrees in longitude or 3 hours. This delay represents the time it takes for incoming solar radiation to excite the atmosphere to the point of maximum ionization.

III. INFLUENCE OF THE IONOSPHERE ON SAR SIGNALS

Small TEC gradients in range and azimuth will, of course, induce a proportional gradient in the phase and group delays in range and azimuth respectively as per (1) and (2). However, even for a homogeneous TEC value over the SAR image the following effects will be seen:

- *Phase advance in range*: Due to the increase in path length / zenith angle with range, the SAR signal experiences a phase advance which increases with range. This is a source of interferometric phase error.
- *Group delay in range*: Due to the same mechanism described above, a SAR signal will also experience a group delay which increases with range. This is a source of error, e.g. when performing coregistration using speckle tracking.

Other effects include defocusing caused by a mismatch between the chirp rates of the sent and received signals – the received chirp having a different rate induced by its passage through the dispersive ionosphere. Even at L-band, the defocus effect is very small and may be neglected [1].

For the purposes of interferometry and ignoring the aforementioned coregistration issues, only the phase delay in the signal is of interest. The corresponding influence on a repeat-pass interferogram can be obtained by replacing the TEC value in (1) and (2) with the difference in TEC value between the two acquisitions, ΔTEC, and then doubling to account for the two-way delay. The interferometric phase delay represented in cycles is then

$$\Delta d_{phase} = -\frac{2K\Delta\mathrm{TEC}}{cf} \quad \text{[cycles]} \tag{3}$$

For an L-band SAR system with carrier frequency 1.27 GHz the ionosphere induced interferometric phase delay is then approximately $-2.1 \times \Delta$TECU cycles. Taking as an examples an ALOS-PALSAR acquisition with range extent 27 km and incidence angle at the scene center of 23°, the difference in interferometric phase delay as per (3) between far and near range is approximately $-3.6\times10^{-3}\times\Delta$TECU cycles. This shows that the precision needed in estimating the phase shift gradient is on the order of 10^{-3} cycles per ΔTECU. Such accuracies may be achieved by correlation based techniques over a suitably large number of samples [1][2].

In summary then, the primary effect of the ionosphere on the interferometric phase at L-band is a constant phase shift over the scene plus a small gradient in range due to a spatially constant ΔTECU. Secondary effects include small and slow variations in range and azimuth due to spatial TEC inhomogeneities.

IV. ESTIMATION OF IONOSPHERIC DELAY

According to (3), the problem of estimating the ionospheric delay is equivalent to estimating ΔTEC. Given estimates of ΔTEC for every pixel over the scene, the resulting ionospheric phase screen could be used to compensate the interferometric phase. The difficulty lies in separating the influence of the ionosphere from that of the troposphere. Two methods will be explored to achieve this. The first makes use of the fact that the ionospheric phase and group delays are sign reversed versions of each other while the tropospheric phase and group delays are equivalent. The last utilizes the inverse frequency dependence of ionospheric phase delay from (3) in comparison to the tropospheric phase delay which is directly proportional to frequency [4].

A. Images Shifts and Interferometric Phase

As mentioned, the interaction between the SAR signal and the ionosphere affects the phase and group delays of the transmitted wave differently. The TEC contribution is therefore present in both the interferometric phase and estimated range shifts between the two acquisitions. Hence, it is possible to measure the signal delay using these two independent quantities. Even if the two achievable precisions are very different [2], it can be shown that the ionospheric delay can be estimated from a linear regression between the estimated phase and group delays. Some preliminary results demonstrating this technique are shown in Fig. 1.

B. Split Spectrum Method

The split spectrum technique splits the acquisitions' range spectrum up into two non-overlapping subbands with center frequencies $f_1 < f_2$ from which two subband interferograms are generated which simulate SAR systems with slightly different carrier frequencies. Representing the subband interferometric phases corresponding to carrier frequencies f_1 and f_2 by ϕ_1 and ϕ_2 respectively, the ionospheric component can be separated from the topographic and tropospheric components through the simultaneous solution of two linear equations [4] and is given by

$$\frac{1}{f_C}\left(\frac{1}{f_1^2}-\frac{1}{f_2^2}\right)^{-1}\left(\frac{\phi_1}{f_1}-\frac{\phi_2}{f_2}\right) \text{ [cycles]}. \qquad (4)$$

Note that the above estimate will require spatial smoothing in order to reduce phase noise as described in [1][2][3].

C. Evaluation

In the final paper we will evaluate these methods by applying them to ALOS-PALSAR datasets. We will also consider the precision and resolution of the obtained ΔTEC maps / differential ionospheric phase screens.

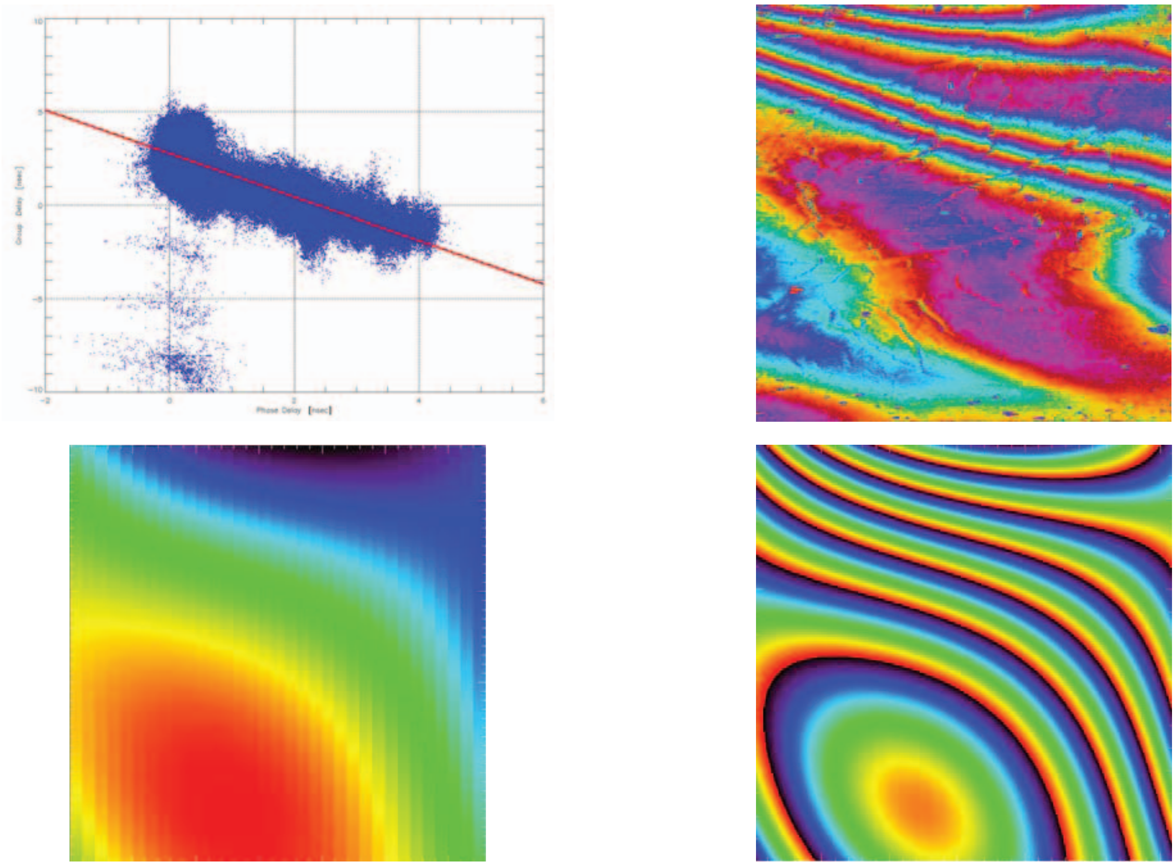

Figure 1. Estimation of ionospheric effects in an ALOS-PALSAR interferogram where the TEC was large. Anticlockwise from top right: Interferometric fringes; a scatter plot of the group delay versus phase delay showing their sign reversed relationship; a smoothed estimate of the ionospheric delay obtained by fitting a second order polynomial to the raw estimates based on the group delay = –phase delay relationship; the smoothed ionospheric delay estimate converted into interferometric fringes which compares well with the original interferometric fringes.

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