FURTHER DEVELOPMENTS IN IONOSPHERIC MITIGATION OF REPEAT-PASS INSAR DATA

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1. INTRODUCTION

The National Research Council (NRC) conducted a Decadal Survey of Earth Sciences [1] for NASA, and formulated a chronological plan for critical Earth Science missions to be flown over the next decade. The Survey recommended that NASA proceed with a number of missions immediately, one of which was called DESDynI (Deformation, Ecosystem Structure, and Dynamics of Ice), comprising both polarimetric a L-band radar operating as a repeat-pass interferometer and a multiple-beam lidar. These sensors will measure surface deformation for understanding natural hazards and climate and vegetation structure for understanding ecosystem health. NASA has directed the Jet Propulsion Laboratory and Goddard Space Flight Center to conduct formulation trade studies to construct a feasible design that meets these science objectives within the programmatic constraints. These studies are well under way, and key performance and technical issues are being identified and addressed.

One of the key issues with L-band radar that is factoring into these trade studies is the quality of the data in the presence of ionospheric effects. Waves propagating through the atmosphere experience a variety of effects that depend on the total electron content (TEC) and at times the orientation of the magnetic field. These effects are generally described in terms phase delay, group delay, Faraday rotation, and amplitude and phase scintillations [2]. Unlike the neutral atmosphere, which is non-dispersive (i.e. the refractive index is not a function of frequency), the ionosphere is dispersive, and significant effects in the phase and time delay can be observed across the spectrum of a radar signal. In this paper, we describe a split-spectrum method to exploit the dispersive nature of the signal to estimate the contribution of the ionosphere, with the aim to remove the effects from the data. The main limitations and error sources of this technique are described and solutions for their mitigation are suggested. Ionospheric phase delay maps derived by this technique are compared to reference data for verification. Reference phase delay maps are derived both directly from SAR data by applying alternative retrieval methods and from measurements of dense GPS networks over California (SCIGN) and Japan (GEONET).

2. IONOSPHERIC EFFECTS ON INTERFEROMETRIC PHASE

For the purpose of this paper, we are interested in addressing the effects of the ionosphere on the signal phase as it would appear in a SAR interferogram. In radar interferometry, two complex SAR images s_1 and s_2 are cross-correlated to form an interferogram $s_1 s_2^*$ (where * denotes complex conjugation), the phase of which represents the differential path delay between the two observations [3]. The differential two-way path delay is typically a combination of topographic parallax, any motion of the ground in between observations, and a refractive delay introduced by the atmosphere or the ionosphere:

$$\Delta\phi = \frac{4\pi}{\lambda}\frac{B_\perp}{r'}z + \frac{4\pi}{\lambda}\delta r_g + \frac{4\pi}{\lambda}\delta r_{atm} + \frac{4\pi}{\lambda}\delta r_{ion} \tag{1}$$

In Eq. 1, the first term is the simplified phase term proportional to the topography, where $B_\perp$ is the interferometric baseline, r' is a scaled version of the range, λ is the wavelength of the radar, and z is the topographic height. The second term represents the phase delay introduced if the ground moves by a distance projected into the radar line of sight (range direction) of δr_g. The third term represents the phase delay introduced if the neutral atmosphere produces a path delay difference between the two observations of δr_{atm}, and the fourth term represents the contribution due to the ionosphere for an equivalent ionospheric path delay difference between the two observations of δr_{ion}. As noted, the refractive index of the neutral atmosphere is non-dispersive, so δr_{atm} is a function of the integrated column of molecules along the radar paths at two different times and does not vary with wavelength at the wavelengths of interest. However, the ionospheric path delay difference δr_{ion} does, and can be described as

$$\Delta\phi_{ion} = \frac{4\pi}{\lambda}\delta r_{ion} = \frac{4\pi}{\lambda}\frac{K}{f^2}\Delta T_e = 4\pi\frac{K}{c^2}\lambda\Delta T_e \tag{2}$$

where here and in Eq. 1, the wavelength is taken to be the free-space wavelength. In Eq. 2, K = 40.28 $m^3 s^{-2}$ and ΔT_e is the total electron content – the path integral of the electron density – along the radar line of sight. In Eqs. 1 and 2, the inherent difference in wavelength dependence between non-dispersive and dispersive components of the interferometric phase can be seen. Since the dispersive and non-dispersive components have different wavelength dependencies, it is possible to separate the effects by observing at multiple wavelengths. This is exploited routinely in GPS corrections of the ionospheric contributions, as well as a variety of other fields. For SAR applications, this property was used in testing the presence of dispersive effects in surface scattering from vegetation and rough lava [4].

For SAR, which inherently has a wide range bandwidth, the estimation technique amounts to sub-banding each observation in range and computing individual interferograms from each sub-band. By then scaling the difference properly an estimate of the ionospheric phase difference between observations can be determined, hence the ionospheric TEC difference, and also a non-dispersive phase difference estimate can be determined.

3. ESTIMATION METHOD

Rewriting Eq. 1 in terms of non-dispersive and dispersive effects, using Eq. 2 as well,

$$\Delta\phi = \frac{4\pi}{\lambda}\delta r_{nd} + 4\pi\frac{K}{c^2}\lambda\Delta T_e \tag{3}$$

where δr_{nd} is the collection of non-dispersive terms in Eq. 1. If we divide the bandwidth of the data into two sub-bands centered at λ_1 and λ_2, then

$$\Delta\phi_1 = \frac{4\pi}{\lambda_1}\delta r_{nd} + 4\pi\frac{K}{c^2}\lambda_1\Delta T_e \tag{4}$$

$$\Delta\phi_2 = \frac{4\pi}{\lambda_2}\delta r_{nd} + 4\pi\frac{K}{c^2}\lambda_2\Delta T_e \tag{5}$$

Solving these two equations for δr_{nd} and ΔT_e,

$$\delta r_{nd} = \frac{\Delta\phi_2 - \frac{\lambda_2}{\lambda_1}\Delta\phi_1}{\frac{4\pi}{\lambda_1}\left(\frac{\lambda_1}{\lambda_2} - \frac{\lambda_2}{\lambda_1}\right)} \tag{6}$$

$$\Delta T_e = \frac{\Delta\phi_2 - \frac{\lambda_1}{\lambda_2}\Delta\phi_1}{\frac{4\pi}{\lambda_2}\frac{K}{c^2}\left(\lambda_2^2 - \lambda_1^2\right)} \tag{7}$$

Equations 6 and 7 provide the basis of the technique: by unwrapping the phase of sub-band 1, scaling by the wavelength ratio, then computing the difference between the phase of sub-band 2 and the scaled sub-band 1 phase, then unwrapping and scaling the result by the constant factor in the denominators, the non-dispersive and dispersive terms can be recovered. Note that difference in the numerator is typically very close to zero, so a formal unwrapping step is not necessary after forming the difference.

3.1 Limitations and Error Sources

The performance of split-spectrum methods for extracting ionospheric phase delay is mainly defined by the frequency separation of the upper and lower sub-band, which is limited by the available bandwidth. In L-band, the maximum available bandwidth is set to 80MHz. Within this bandwidth, the configuration of the sub-bands has to be optimized to warrant maximum separation of the band centers λ_1 and λ_2 while retaining a sufficient signal-to-noise ratio in the sub-band images. The accuracy of the estimated ionospheric phase delay $\Delta\hat{\phi}_{ion}$ for a given configuration can be further improved by spatial multi-looking. Here it is assumed that the noise in $\Delta\hat{\phi}_{ion}$ is an additive zero mean Gaussian process.

The main error sources of the technique are the estimation of the center frequencies λ_1 and λ_2 and the spatial phase unwrapping step that is required for one of the sub-bands. Estimating λ_1 and λ_2 is complicated by the weighting of the spectrum at the margin of the bandwidth that has to be known to accurately estimate the correct center. Errors in center frequency estimation will lead to an imperfect separation of δr_{nd} and ΔT_e and will also affect the scaling factor in Equation 7. The sensitivity of split-spectrum processing to the mentioned error sources will be thoroughly analyzed and expectation values for expected performance will be given.

4. VERIFICATION THROUGH COMPARISON TO REFERENCE DATA

In this section we will present a comparison among techniques that exploit the phase alone in a differential sense as described above, and other measures of ionospheric TEC, such as a polarimetric estimate of Faraday rotation for individual scenes [6]. For specific test sites a comparison of SAR based ionospheric estimates with GPS results will be performed.

5. ACKNOWLEDGMENT

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