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Time-Variant TEC Estimation with Fully Polarimetric GEO-SAR Data

W. Guo, J. Chen, W. Liu and C.S. Li

A time-variant total electron content (TEC) estimation method with fully polarimetric geosynchronous SAR (GEO-SAR) data is proposed based on inner aperture Faraday rotation angle estimation and an accurate TEC inversion model. With a long integration time and sensitivity to ionosphere effects, the fully polarimetric GEO-SAR data are utilized for estimation with high accuracy for both the time-variant TEC and the time interval. Superiority of the proposed method over conventional ionospheric sounding methods is verified by simulation results.

Introduction: Due to the increasing importance of achieving real-time global observations, such as geography detection, soil moisture monitoring and biomass measuring, geosynchronous synthetic aperture radar (GEO-SAR) has received a lot of attentions recently. GEO-SAR can realize sustained observation for a specific area with a long integration time (for hundreds of seconds) and a wide swath (almost one third of the earth) [1]. However, the L-band SAR signal suffers from serious ionospheric effects (including dispersion, scintillation and Faraday rotation (FR)) caused by time-variant total electron content (TEC). This sensitivity to ionospheric effects can be exploited for accurate estimation of FR angle and inversion of TEC, which will be studied for the first time in this letter for detecting the time-variant TEC. Compared with existing ionospheric sounding methods (mainly include ground-based observation, inversion with GPS occultation and topside with spaceborne radar [2-3]), TEC measurements with GEO-SAR could break the limitation of detecting coverage, accuracy and instantaneity due to limited base station layout and demand of specific detection device as payload. On the other hand, with accurate measurements of time-variant TEC, ionospheric effects can be better compensated than traditional autofocusing-based processing [4].

In this letter, a time-variant TEC estimation method with fully polarimetric GEO-SAR data is proposed based on inner aperture FR angle estimation and an accurate TEC inversion model, with detailed procedures presented. Simulations are performed to validate the effectiveness of the proposed method.

Faraday rotation: For a polarimetric SAR system, the received echo will rotate at an angle relative to the original signal when propagating through the ionosphere, known as Faraday rotation. The FR angle depends on TEC, the wave frequency and the propagation path by [5]:

$$\Omega = \frac{K_\Omega}{f^2}\int_0^h N_e \cdot B \cdot \cos\psi \cdot \sec\theta \, dh \approx \frac{K_\Omega}{f^2} \cdot \overline{B\cos\psi} \cdot TEC \qquad (1)$$

where f is the signal frequency, N_e is the electron density, B is the magnetic flux density of the Earth's magnetic field, K_Ω is a constant of value 2.365×10^4 A×m^2/kg, θ is the look angle of radar, ψ is the angle between the direction of wave propagation and the magnetic field. The approximation in (1) uses the "magnetic field factor" $\overline{B\cos\psi}$ which is normally calculated at a constant height of 400km [5].

Time-variant TEC estimation: Compared with low earth orbit SAR (LEO-SAR), GEO-SAR enjoys a long integration time, within which the TEC of background ionosphere is continuously changing. Hence, different FR angle caused by real-time TEC will be introduced into the echo signal at each azimuth time. Most users have much easier access to single looking complex (SLC) images instead of the raw data. Therefore, it is more general to use SAR images in the process. Since the SAR image has been compressed after matched filtering, decompressing should be performed before estimation of the inner aperture FR. Here the decompressing factor is given by:

$$\phi_{decompress} = -\frac{4\pi}{\lambda} \cdot R \cdot \left(\sqrt{1 - \left(\frac{f_a \cdot \lambda}{2V_{ref}} \right)^2} - 1 \right) \qquad (2)$$

where λ is the wavelength, f_a is the azimuth frequency, V_{ref} is the effective radar velocity and R is the reference range.

Modified by $\phi_{decompress}$ in the frequency domain, equivalent echoes of the four polarimetric channels are derived as:

$$S(t)^{**}_{echo} = IFFT\left(FFT\left(S(t)^{**} \right) \cdot e^{j\phi_{decompress}} \right) \qquad (3)$$

where the subscript "**" represents HH, HV, VH or VV, $S(t)^{**}$ and $S(t)^{**}_{echo}$ denote the SLC images and equivalent echoes of four polarimetric channels, respectively, t is azimuth time for the synthetic aperture, and FFT represents fast Fourier transform along the azimuth direction while IFFT for inverse fast Fourier transform.

Certainly, if the raw data could be obtained directly, the decompressing operation can be ignored. For GEO-SAR, TEC is assumed constant within a pulse repetition time (PRT). Thus, the corresponding FR angle is considered to be constant for each azimuth time, which could be accurately estimated with the Bickel & Bates algorithm [6]. Based on (3), the equivalent circular polarized waves $Z_{12}(t)$ and $Z_{21}(t)$ are given by:

$$\begin{aligned} Z_{12}(t) &= S(t)^{HV}_{echo} - S(t)^{VH}_{echo} + j(S(t)^{HH}_{echo} + S(t)^{VV}_{echo}) \\ Z_{21}(t) &= S(t)^{VH}_{echo} - S(t)^{HV}_{echo} + j(S(t)^{HH}_{echo} + S(t)^{VV}_{echo}) \end{aligned} \qquad (4)$$

From (4), the time-variant FR angle $\hat{\Omega}(t)$ is estimated as:

$$\hat{\Omega}(t) = \frac{1}{4} angle\left\langle Z_{21}(t) \cdot Z^*_{12}(t) \right\rangle \qquad (5)$$

where angle(·) gives the angle of its complex-valued argument and <·> represents the averaging operation.

Combining (1) and (5), the time-variant TEC can be derived as:

$$TEC(t) = \frac{\hat{\Omega}(t) \cdot f^2}{K_\Omega \cdot \overline{B\cos\psi}} \qquad (6)$$

With the flow chart shown in Fig. 1 (for both SAR images and raw data), the processing procedures of the time-variant TEC measurement is summarized as:

(1) Acquisition of fully polarimetric GEO-SAR images; (2) Calculation of the decompressing factor with system parameters; (3) FFT in the azimuth direction; (4) Decompressing in the azimuth direction with the obtained decompressing factor; (5) IFFT in the azimuth direction; (6) Construction of equivalent circular polarized waves; (7) Estimation of FR angle; (8) Inversion of time-variant TEC.

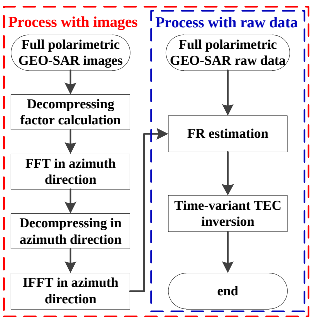


Fig. 1 Flow chart of the proposed method for time-variant TEC estimation.

Simulations and discussions: With parameters listed in Table 1, we simulate the fully polarimetric GEO-SAR images (in Fig. 2) with backscattering coefficients from AIRSAR data over Feltwell, which are free from ionospheric effects and well calibrated. The time-variant TEC for Oct. 1st 2015 (36°N, 84°W) from United States Total Electron Content (USTEC) is interpolated according to the PRF. Fig. 3 shows three time-slots of interpolated time-variant TEC (Time-slot A, B and C) used in our simulation, which represent different variation trends of TEC with concavity, monotonicity and convexity, respectively. The corresponding FR angle is added to the fully polarimetric data based on the observed scattering matrix [5].

Table 1: Simulation parameters.

Parameter	Value
Obit altitude (km)	42164.43

Look angle (°)	4
Wavelength (m)	0.24
Bandwidth (MHz)	15
PRF (Hz)	120
Azimuth resolution (m)	50
Geomagnetic field intensity (nT)	30000

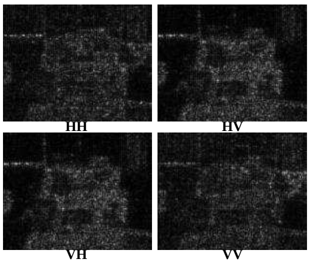


Fig. 2 Simulated fully polarimetric GEO-SAR images (HH, HV, VH and VV) with backscattering coefficients from AIRSAR data over Feltwell.

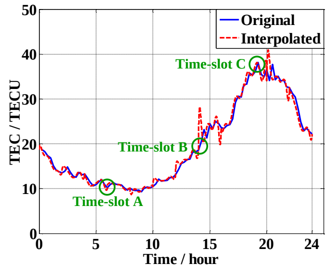


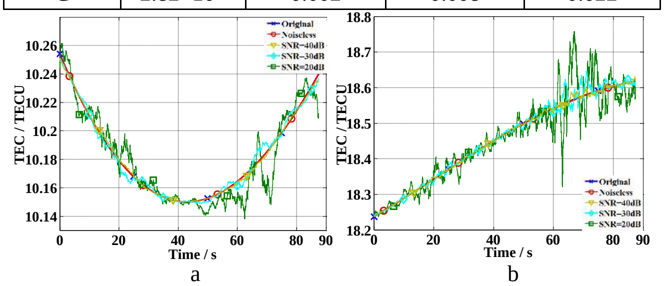
Fig. 3 Time-variant TEC (Time-slot A, B and C) used in simulation from United States Total Electron Content (USTEC) on Oct. 1st 2015 (36°N, 84°W).

As shown in Fig. 4, the estimated TEC results match the original ones very well for both of noiseless and SNR=40dB circumstances. When SNR is reduced to 30dB, some fluctuations occur due to the increasing thermal noise but without impacting TEC estimation, while the estimated curve of TEC fluctuates remarkably with SNR falling down to 20dB. It is clear that the measuring accuracy of TEC further deteriorates when the thermal noise level increases. We have calculated the standard deviation of TEC estimation error under different conditions of noise, listed in Table 2. From these results, it is clear that the measuring accuracy of TEC is better than 0.01TECU under normal SNR conditions. Even with strong thermal noise (SNR=20dB), the measuring accuracy of TEC is still better than 0.05TECU, which is much superior to those of traditional ionospheric sounding methods.

The proposed method is based on transmitted pulses of a SAR system. Since typical PRF of GEO-SAR is about hundreds of Hertz, the time interval of time-variant TEC measurement can reach the millisecond level. Taking the PRF of 120Hz used in simulation for example, the time accuracy of time-variant TEC measurement is about 0.008s.

Table 2: Standard deviation of TEC estimation error.

Time-slot	Noiseless (TECU)	SNR=40dB (TECU)	SNR=30dB (TECU)	SNR=20dB (TECU)
A	1.03×10^{-5}	0.001	0.003	0.010
B	2.46×10^{-5}	0.003	0.004	0.049
C	2.82×10^{-5}	0.002	0.008	0.022



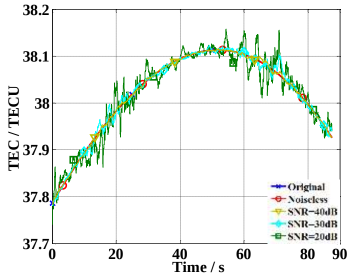


Fig. 4 Comparison of the noiseless, noisy (SNR=40dB, 30dB and 20dB) and original TEC with proposed measuring method for simulated time-variant TEC in Time-slot A, B and C.

a Time-slot A (concavity)

b Time-slot B (monotonicity)

c Time-slot C (convexity)

Conclusion: An estimation method for time-variant TEC based on fully polarimetric GEO-SAR data has been proposed. With decompression in azimuth direction, the time-variant TEC is inversed by accurate estimation of the FR within the synthetic aperture. The process is much simpler and enjoys higher measuring accuracy than conventional methods. As shown by simulations with backscattering coefficients from AIRSAR and measured time-variant TEC from USTEC, the proposed method is very effective and its estimation accuracy for time-variant TEC has reached 0.01TECU and 0.05TECU for normal and low noise SNR respectively with a time accuracy of 0.008s. In the future, the effects of polarimetric calibration errors will be studied.

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W. Guo, J. Chen and C. S. Li (School of Electronics and Information *Engineering, Beihang University, Beijing, 100191, People's Republic of* China)

E-mail: chenjie@buaa.edu.cn

W. Liu (Department of Electronic and Electrical Engineering, University of Sheffield, Sheffield S10 2TN, UK)

J. Chen and C. S. Li: also with (Collaborative Innovation Centre of *Geospatial Technology, Wuhan, 430079, People's Republic of China*)

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