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Fully polarimetric synthetic aperture radar indices for scintillation observation

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Abstract

Low frequencies synthetic aperture radar (SAR) are invariably affected by the dispersive ionospheric layer. Amplitude scintillations arising from ionospheric irregularities damage SAR data in the form of azimuthal stripes, especially at low latitudes. In the absence of good ground-based networks of Global Navigation Satellite System (GNSS) receivers, SAR can act as a supplementary technique with wider coverage to study scintillations. The paper highlights the use to full polarimetric SAR data to differentiate between disturbed and quiet days with respect to scintillations. Two indices are developed from radar measurements, namely total power index (TPI) and depolarization power index (DPI) are formulated. All four polarization channel intensities are utilized for TPI while the depolarization power is computed from the volume scattering power (P_v) of model-based decomposition. L-band Advanced Land Observing Satellite (ALOS-2)/Phased Array-type L-band Synthetic Aperture Radar (PALSAR-2) data utilized in the study identify the region of intense scintillation with the peak of anomaly crest using the indices. The indices are less sensitive to the variation in the ionospheric conditions outside the peak scintillation region. Weakening of the scintillation strength or inappropriate SAR geometry beyond this region can be plausible explanations for it.

1. Introduction

Global change research poses significant challenge to the scientific community where researchers have grappled with the challenges of data requirements. In this pursuit, they have identified the utility of satellite remote sensing techniques as a major source of consistent and continuous data for earth observation at varying spatial and temporal scales. Microwave remote sensing, and synthetic aperture radar (SAR), in particular, is a potential technique for uninterrupted such studies. The fully polarimetric SAR (POLSAR), another category of SAR remote sensing, has proven to be quite a useful technique that has been widely used. The polarimetric information obtained from the data can directly be related to several target properties enabling in precise target identification and classification [1].

POLSAR data is relatively less affected by the tropospheric weather. However, low frequency SAR, both amplitude and phase, are severely affected by the ionosphere. Signal transmission of SAR sensors, operating at P-band (~ 500 MHz) and L-band (~ 1.3 GHz) [2], is hampered by the layer of Earth's atmosphere, ionized by solar and cosmic radiations. The effects of ionosphere on SAR are of dual nature. Presence of free electrons (caused by ionization) in the background ionosphere cause signal phase delays [3], signal attenuation, shift of polarization orientation (Faraday rotation) [4], while sudden variations in electron densities manifest as signal defocusing, loss of image contrast, as well as streaks (caused as a result of diffraction) [5]. Termed as scintillations, these ionospheric irregularities caused by fluctuations of electron densities, significantly degrade SAR data.

Scintillations affect SAR phase and amplitude depending on the size of the ionospheric irregularities pertaining to the Fresnel zone size ($\sqrt{\lambda Z}$) [6]. The diffraction pattern from the interaction of signal waveform with irregularities (size smaller than Fresnel scale) appear as prominent stripes in SAR data, when the sensor flies over the low-latitude. In high latitude, phase scintillations (irregularity size larger than Fresnel scale) are frequent.

The tropics are a storehouse of natural resources and, SAR, with advantages such as all-weather capability, day-night acquisition ability and additional information content from optical data, makes it a popular remote sensing tool among researchers. Low frequency SAR sensors suitable for forest and biomass monitoring, a promising application for global climate change predictions, are prone to scintillations hindering their application [7]. The paper utilizes full-polarimetric SAR data to develop two measurement indices that help to identify scintillation-affected SAR data. These measures are particularly useful in areas with sparse coverage of Global Navigation Satellite System (GNSS) based scintillation monitoring receivers. One such scintillation event captured by the Phased Array-type L-band Synthetic Aperture Radar (PALSAR) onboard Advanced Land Observing Satellite (ALOS)-2 is explained and the results are discussed.

The layout of the paper is as follows. The full polarimetric SAR data acquisition is explained in Section 2. Evidence of occurrence of the particular scintillation event is also presented. The new measurement indices are presented in Section 3 followed by the results in Section 4. The paper is summarized in Section 5.

2. March 23, 2015, Scintillation Event

Ionospheric irregularities, causing to amplitude scintillations, are observed post-sunset in the equatorial region due to plasma instabilities. One such event was captured by Advanced Land Observing Satellite-2 (ALOS-2) over India on March 23, 2015 at ~ 1900 UT (corresponding to 30 min past local midnight) as the satellite flew past the region. The complex wave interaction of the SAR signal with the ionospheric irregularities cause diffraction that appear as streaks or stripes along the flight direction in SAR data. The intensity and direction of streaks depend on the local geomagnetic field as well as the geometry with which the signal intercepts the ionospheric-layer [8, 9]. A total of 26 scenes were captured by PALSAR-2 in that orbit and are utilized in the study. For comparative analysis, SAR data in the same orbit on a later date of October 31, 2016 was processed. Data on this date was less affected by scintillation. Figure 1 demonstrates the varying effect of scintillation on SAR that is not only dependent on the ionospheric conditions but also on the satellite geometry during acquisition.

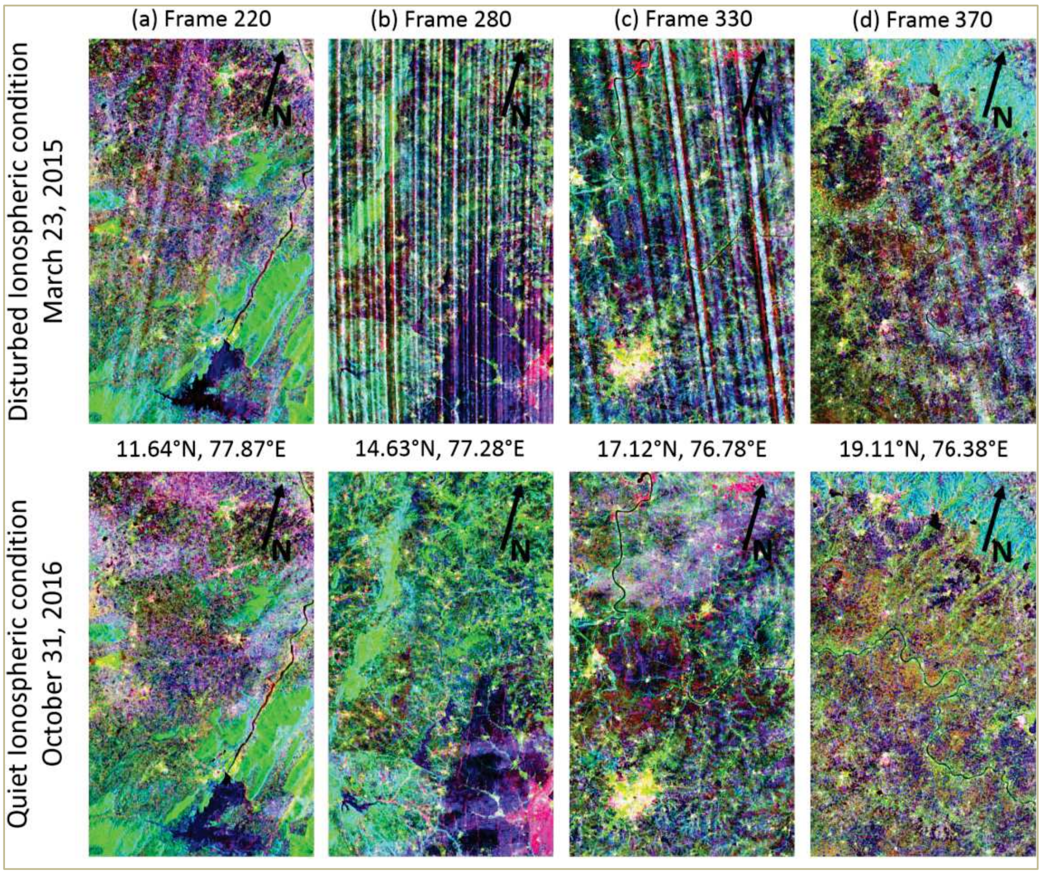

Figure 1. G4U color composite RGB images (Red: double-bounce scattering, Green: volume scattering, and Blue: surface scattering) of ALOS-2/PALSAR-2 data acquired on nights with different ionospheric activity: (top row) disturbed, and (bottom) quiet. The radar look direction is from left to right in all images with centre coordinates (latitude/longitude) of each scene. The intensity and orientation of amplitude stripes vary as the SAR ascends in latitude.

The geomagnetic conditions along with total electron content and amplitude scintillation index (S_4) measurements from four ground-based GNSS receiver set the context for the ionospheric conditions on the two dates under study. Details of the ionosphere and scintillation conditions are elaborately explained in [10] proving the potential of SAR data in characterizing amplitude scintillations.

3. SAR Measurement Indices for Scintillations

Modulations to the signal waveform due to ionospheric irregularities alter the phase as well as amplitude of SAR data. The backscatter returns from scintillation-affected POLSAR data, comprising of returns from the targets on the ground as well as the interaction with the ionospheric layer, are best described by the complex 2×2 scattering matrix [S] that defines the relationship between the incident and scattered wave fields as [11]

$$E_s = \frac{e^{-jkr}}{r}\begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} E_I \qquad (1)$$

where, $\frac{e^{-jkr}}{r}$ takes into account the propagation effects in amplitude and phase with polarizations (HH, HV, VH, VV). Elements of the scattering matrix are complex and depend on signal frequency, target shape and orientation, etc. While the elements of the main diagonal represent co-polarized quantities, the off-diagonal elements account for the cross-polarized/de-polarized component. The wealth of polarimetric information contained in POLSAR data over its counterpart (i.e., single- and dual-polarized SAR sensors) assists in an improved understanding of targets. In this work, we exploit the full-polarimetric nature of ALOS-2/PALSAR-2 data for identification of scintillation conditions.

Though previous authors have used single polarization SAR data as a technique for scintillation studies [12], the potential of full-POLSAR is largely unexplored. Two indices namely, total power index (TPI) and depolarization power index (DPI) are introduced as measurement parameters in studying the ionospheric scintillation effects on SAR. TPI, defined as the normalized variance of total power, is computed from the linear summation of all four polarization channels that give the total power (per pixel) as

$$TPI = \frac{\langle TP^2 \rangle - \langle TP \rangle^2}{\langle TP \rangle^2} \quad (2)$$

where, (3)

$$TP = |S_{HH}|^2 + |S_{HH}|^2 + |S_{HH}|^2 + |S_{HH}|^2$$

In an attempt to understand if ionospheric scintillations produce depolarization of the signal, the volume scattering power (P_v) is analyzed. The scattering powers (namely odd-bounce (P_s), even-bounce (P_d), volume (P_v) and helix (P_c)) for individual pixels are computed using the General Four-Component Scattering Power Decomposition with Unitary-transformation (G4U) model [13]. The depolarization or cross-polarization of the wave due to an ensemble of randomly oriented cloud of dipoles is represented by the volume scattering power, P_v. The interaction of wave with forest canopy is the best example of such scattering phenomenon. However, depolarization is not always due to the target interaction. The wave, upon propagation within an ionized medium in a magnetic field also experiences shift in polarization. Similarly, L-band SAR signal while traversing through the ionosphere also undergo depolarization. Thus, to study the amount of depolarization occurring in SAR signals due to the ionospheric interaction, a normalized depolarization index, DPI has been developed. Defined as the normalized variance of PV, the DPI is calculated as

$$DPI = \frac{\langle P_v^2 \rangle - \langle P_v \rangle^2}{\langle P_v \rangle^2} \quad (4)$$

4. Results and Discussion

Earlier works involving SAR for scintillation studies have revolved in quantifying the scintillation intensity using several methods. One among them is the image contrast method, which is basically the normalized variance of signal amplitude, referred to as contrast (C_d) that is proportional to S_4 by N. The factor N is the number of independent amplitude samples that is stochastically added along the length of the synthetic aperture to calculate S_4. For details regarding the method and results, refer [12]. The only drawback of the image contrast method is that it deals with a single polarization. The total power index provides an additional measure of studying the scintillation phenomenon, accounting for the sum of intensities of all four polarization channel. The plot of latitudinal variation of TPI along the entire swath of SAR acquisition is shown in Figure 2.

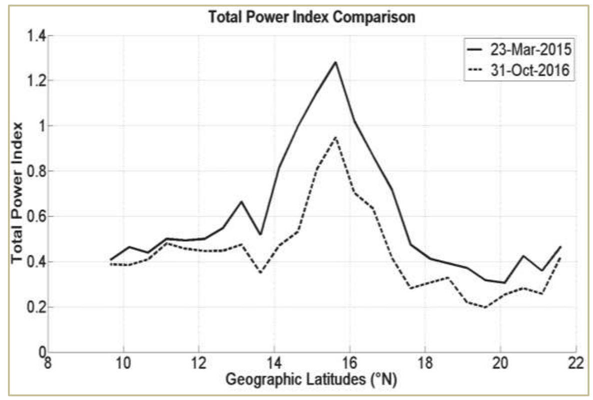

Figure 2. Plot of total power index (TPI) *versus* geographic latitude

A SAR scene (70 × 30 km in azimuth, Az, and range, Rg, directions respectively) is divided into smaller groups of 50 × 25 pixels (Az × Rg). The TPI for each sub group is calculated and their mean is computed to represent the TPI for one scene. Same process is followed for all 26 scenes in one orbit. The TPI on a relatively quiet day of scintillation activity is also shown in Figure 2. A clear demarcation can again be identified between TPI corresponding to days with varying ionospheric activities. Nevertheless, the efficacy of the index can only be further verified by comparing more number of datasets. The index peaks between 14°N and 17.5°N geographic latitudes corresponding to SAR scenes (Frame No. 260-350) where the intensity of the azimuth streaks is very severe. Although the TPI indices on disturbed- (March 23, 2015) and quiet- (October 31, 2016) days are clearly separated, the sensitivity of the index fades beyond the latitudes of 12°N and 19°N. This can be explained by two reasons that are as follows:

a) The northern crest of the equatorial anomaly, leading to the ionospheric scintillation event on March 23, 2015 was located between 14°N - 17°N (~ 5°N - 8°N geomagnetic latitude). The solar condition during the PALSAR-2 acquisition corresponds to the solar minimum condition where the peak of the anomaly region can be expected to reside.
b) The satellite geometry of the ALOS-2 with respect to the local geomagnetic field lines during acquisition can be a plausible explanation for the non-sensitivity of TPI beyond 12°N and 19°N. It has been widely discussed that scan direction of SAR sensors at the height of the ionospheric pierce point (IPP) contributes to the orientation and intensity of the amplitude stripes. As the

SAR ascends in latitude, the scintillation intensity may have weakened and is not captured by SAR or the angle between the satellite's heading angle and the magnetic field is large producing no stripes.

Furthermore, since the magnitude of P_v corresponds to the depolarization, it can be used to describe the signal depolarization effect of the SAR from interaction with target and ionospheric scintillation. The Depolarization Power Index (DPI) computes the magnitude of signal depolarization contributed by the target and the ionosphere as well. Theoretically P_v is given as [13]

$$P_v = 4|S_{HV}|^2 - 2|Im\{S_{HV}^*(S_{HH} - S_{VV})\}| \quad (5)$$

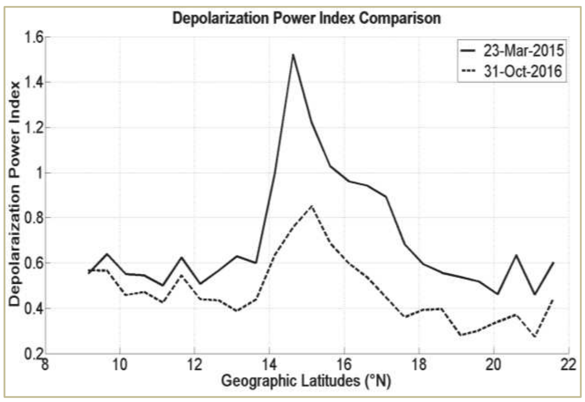

Figure 3. Plot of depolarization power index (DPI) *versus* geographic latitude

From the plot of DPI *versus* geographic latitude in Figure 3, it is apparent that considerable amount of depolarization has occurred in the scenes affected by ionospheric scintillation (denoted by the solid black line). For scenes that are not affected by the scintillation (denoted by the dotted black line), the DPI values account to the depolarization caused by target interaction only. Hence, it can be said that scintillation causes additional depolarization of SAR signal.

5. Summary

The paper attempts to define two new measurement indices for identification of SAR data affected by ionospheric scintillations. These indices are developed using radar measurements of total power (TP) and depolarization power (P_v). While SAR intensity from single signal polarization have been earlier used for estimating S_4, it is for the first time that full polarimetric information is being used to ascertain scintillations in SAR. Additional depolarization of data, due to scintillations, is also identified that further assists in demarcating variedly affected SAR data. The two indices, TPI and DPI, are simple, straightforward, and easy-to-implement techniques that demonstrate the potential of full polarimetric low frequency SAR data for ionospheric studies.

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