A Review of Ionospheric Effects in Low-Frequency SAR Data

Signals, Correction Methods, and Performance Requirements


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Collaborating Organizations:
Outline

• An Introduction to the Topic:
  – Interaction of the Ionosphere with Traversing Microwave Signals
  – Spatio-Temporal Structure of Ionospheric Delay
    • Current Ionospheric Conditions
    • Temporal Variability
    • Descriptors for Small-Scale Spatial Structure
  – Examples of Ionospheric Effects on SAR, PolSAR and InSAR Data
  – Requirements and Methods for Ionospheric Correction

• An Introduction to the Session
Signal Propagation through the Ionosphere

EUV radiation of the sun ionizes neutral atoms and molecules

Typical vertical profiles of the plasma density

Refractive Index:

\[ N_{\text{iono}} = (n_{\text{iono}} - 1) \cdot 10^6 = -K \cdot 10^3 \frac{n_e}{f^2} \]

Two-way phase shift of frequency \( f \) due to the ionosphere (nadir looking Radar):

\[ \phi(f) = -2\pi f \frac{2}{10^6} \int_0^H \frac{N_{\text{iono}}(f, h)}{c} \, dh \approx 2\pi \frac{2K}{cf} \text{TEC} \]

TEC = Total Electron Content

@ L-band: ~ 2 phase cycles
@ C-band: ~ .5 phase cycles
@ X-band: ~ .3 phase cycles
Temporal Variability of the Ionosphere

1. 11-year solar cycle
2. Seasonal cycle: high @ equinox; low @ solstice
3. Solar day: 27 day solar rotation

CODE GIM time series from 01-Jan-1995 to 13-Feb-2005
Current Ionospheric Activity

- Beginning of Solar Cycle 24 December 2008
- Sun spot count increased late in 2009
- Maximum of cycle 24 expected for March 2013 with a sun spot count of ~90 (fewest since cycle 16 (1923 - 33)
- Intensity of geomagnetic storms during cycle 24 could be elevated by large breach in Earth's magnetic field (discovered by THEMIS)
Ionospheric Turbulence - Scintillations

- Ionosphere rather smooth over large areas of the globe
- Turbulence (rapid (second-scales) fluctuations of signal amplitude, phase, polarisation caused by local (sub-km-scales) concentration / lack of ionisation):
  - Effects mainly occur at both equatorial (±20° lat) and high latitudes (above 60° lat)
  - Equatorial scintillation is observed during approx. 8 pm to 2 am local time
  - Auroral scintillation more irregular and can occur at any time during the day

The global geographic distribution of ionospheric scintillation (From (Aarons, 1982))
Most small scale variability can be described as featureless noise like signal → stationary and scale-invariant → can be described by power spectra, structure functions, covariance functions, and fractal dimensions.

**Can be used for data analysis, statistical modeling, signal representation, and simulation**

A Suitable model for small-scale turbulence spectra?

\[
P_\varphi (\kappa) \propto \left[ 1 + \kappa_{0 \perp}^{-2} \left( \kappa_\perp^2 + a^2 \kappa_z^2 \right) \right]^{-\nu/2}
\]

- Scaling factor
- Spectral index
- Anisotropy factor

\[
\kappa_\perp = \kappa_x^2 + \kappa_y^2
\]

\(\kappa_x, \kappa_y, \kappa_z = \) coordinates of spatial wavenumbers related to earth’s magnetic field
Small Scale Spatial Variability
Example Spectrum of Auroral Scintillations

- Indicates:
  - Total power of signal
  - Distribution of power over spatial scales
- Spectral Index:
  - Large → smooth signal
  - Small → noisy signal
- Spectral Indices between ~2 and ~5 have been observed
- Conversion to covariance functions through cosine FT

\[ C_\varphi (r) = \int \cos(2\pi fr) P_\varphi (f) \, df \]
Ionospheric Effects on SAR, InSAR, PolSAR
Taylor Expansion of Phase Delay

\[
\Delta \psi = -\frac{4\pi 40.28}{c_0 f_0} TEC + \frac{4\pi 40.28}{c_0 f_0^2} TEC \cdot (f - f_0) - \frac{4\pi 40.28}{c_0 f_0^3} TEC \cdot (f - f_0)^2
\]

Advance of signal phase
Delay of signal envelope
ionospheric induced chirp rate change \(\delta \phi_r(f)\)
Ionospheric Effects on SAR, InSAR, PolSAR
Taylor Expansion of Phase Delay

\[ \Delta \psi = -\frac{4\pi}{c_0} \frac{40.28}{f_0} TEC + \frac{4\pi}{c_0} \frac{40.28}{f_0^2} TEC \cdot (f - f_0) - \frac{4\pi}{c_0} \frac{40.28}{f_0^3} TEC \cdot (f - f_0)^2 \]

- **Potential effects on SAR:**
  - Reduction of geolocation accuracy in azimuth
  - Image deformation
  - Reduction of image focus in azimuth
- **Potential effects on InSAR:**
  - Phase ramps in range direction
  - Ionospheric phase screens
  - Local or global decorrelation

Advance of signal phase
Delay of signal envelope
Ionospheric induced chirp rate change \( \delta \phi_r(f) \)
TEC variability will affect image quality if:
- if its correlation length is less than the synthetic aperture length & standard deviation of the phase fluctuation is significant

Effect rare – more likely at low carrier frequencies and high azimuth bandwidth

Distorted PSF due to extreme auroral disturbances
(From (Quegan and Lamont, 1986))
Ionospheric Effects on SAR, InSAR, PolSAR
TEC Gradients and Image Deformation

- Sensitivity:
  - Synthetic aperture length \( T \approx 2.26 \text{sec} \rightarrow L \approx 16 \text{km} \)
  - \( \Delta \phi_{0.5 \text{TECU}} \approx 2\pi \)
  - Width of signature: 4km

\[
\frac{\partial \Delta \phi_{0.5 \text{TECU}}}{\partial T} = \frac{1}{2.26 \text{sec}} \cdot \frac{4 \text{km}}{16 \text{km}} \approx \frac{1}{0.56} \approx 2 \text{Hz}
\]

\[
\Delta t = \frac{2 \text{Hz}}{FM} \approx 4.5 \text{ms} \rightarrow \Delta_{az} = \Delta t \cdot v_{sat} \approx 30 \text{m}
\]
Ionospheric Effects on SAR, InSAR, PolSAR
TEC Gradients and Image Deformation

• JPL conducted statistical analysis Auroral Zone turbulence effects on SAR:
  – Analysis shows less than 5% of SAR expected to be significantly degraded by auroral scintillation

Ionospheric Effects on SAR, InSAR, PolSAR
Ionospheric Phase Screens

- Phase Advance: $\phi(f) = -2\pi f \frac{2}{10^6} \int_0^H \frac{N_{\text{iono}}(f, h)}{c} dh \approx 2\pi \frac{2K}{cf} TEC$
Ionospheric Effects on SAR, InSAR, PolSAR
Ionospheric Phase Screens – Polar Examples
Ionospheric Effects on SAR, InSAR, PolSAR
Ionospheric Phase Screens – Equatorial Signals
Taylor Expansion of Phase Delay

\[ \Delta \psi = -\frac{4\pi 40.28}{c_0} \frac{TEC}{f_0} + \frac{4\pi 40.28}{c_0} \frac{TEC}{f_0^2} (f - f_0) - \frac{4\pi 40.28}{c_0} \frac{TEC}{f_0^3} (f - f_0)^2 \]

- **Potential effects on SAR:**
  - Global range shift of image
  - Variable range shift of image

- **Potential effects on InSAR:**
  - n/a

Advance of signal phase
Delay of signal envelope
Ionospheric induced chirp rate change \( \delta \phi_r(f) \)
Ionospheric Effects on SAR, InSAR, PolSAR

Taylor Expansion of Phase Delay

- Blurring due to ionospheric induced chirp rate change
- Change of the phase gradient of the range chirp ⇒ range defocus
- Second order Taylor Series expansion of the ionospheric phase delay:

\[
\Delta \psi = -\frac{4\pi}{c_0} \frac{40.28}{f_0} TEC + \frac{4\pi}{c_0} \frac{40.28}{f_0^2} TEC \cdot (f - f_0) - \frac{4\pi}{c_0} \frac{40.28}{f_0^3} TEC \cdot (f - f_0)^2
\]

Advance of signal phase
Delay of signal envelope

Wide Bandwidth (80MHz) L-band SAR

Effect very small in L-band even for wide bandwidth systems
Faraday Rotation

- Faraday Rotation changes polarimetric angle with which a system observes the earth surface

\[ \Omega = \frac{K}{f^2} B \cos \theta \sec \chi \cdot \text{TEC} \]

- Currently -10° - 10° in L-band but increase to ~25° expected at solar max.
- In P-band, \( \Omega \) may be subject to wrapping

- Effects on InSAR:
  - Strong differences in FR in acquisitions of an InSAR pair cause decorrelation due to polarization mismatch
  - Only significant if \( \Delta \text{TEC} \) is larger than 30 degrees.
• SAR Data:
  – SAR data acquired April 1, 2007, 7:27:25 UTC
  – Center coordinate 62.291°N, 144.603°W
  – Full-polarimetric data set
  – Faraday rotation was estimated based on Bickel&Bates method
  – FR estimates were projected to TEC using observation geometry and magnetic field models.
  – Ionospheric disturbance detected with FR change between 0 and 5° corresponding to TEC change of 10 TECU
• Cross validation of geocoded datasets:
  
  – SkyCam data geocoded using star coordinates
  
  – SAR data geocoded to ionospheric center at 100km altitude
Example of Ionospheric Turbulence in High Latitudes

**Total Electron Content \( \Delta \text{TEC} \) along Swath**

- ~7 TECU over 700km

**Ionosphere-Induced Interferometric Phase along Swath**

1410 1400 1390 1380 1370 1360 1350 1340 1330 1320 1310 1300

Frm. 1360 missing
Methods for Ionospheric Correction

Faraday Rotation (FR) Based Correction

- FR estimation from quad-pol data
  - Freeman, 2004; Quegan, 2010
- FR estimation from HH-HV correlation
  - Nicoll & Meyer, 2008

Range Split-Spectrum Based Correction

- Distributed targets in Repeat-pass InSAR $\rightarrow \Delta_t \Delta_s TEC$
  - Rosen, 2009, 2010
- Coherent Targets in single image $\rightarrow \Delta_s TEC$
  - Papathanassiou, 2009
- Amplitude correlation of sub-looks $\rightarrow TEC$
  - Meyer & Bamler, 2005
Azimuth Autofocus Based Correction

- Contrast maximization for point targets
- Coherent AF: Phase Curvature analysis
- Incoherent AF: Sub-look co-registration (MLR)
  - several authors
  - Papathanassiou, 2008
  - Meyer & Nicoll, 2008

Hybrid Methods

- Combination of range and phase offsets in InSAR
- Two dimensional phase signature of point targets
- ...
• **Question to Answer:** How accurate does correction have to be?

• Requirements were defined such that corrected data meets calibration specs and advertised system capabilities

• Requirements for a PALSAR-like system:

  – Polarimetry: \( \sigma_{\hat{\Omega}} \leq 2^\circ \)
  – Image geolocation: \( \sigma_{\hat{\text{TEC}}} \approx 1\text{TECU} \)
  – Image geometry: \( \sigma_{\hat{\text{TEC}}} \leq 0.01\text{TECU} \)
  – Topographic Mapping from InSAR: \( \sigma_{\hat{\text{TEC}}} \leq 0.05 – 0.1\text{TECU} \)
  – Deformation mapping from InSAR: \( \sigma_{\hat{\text{TEC}}} \leq 0.005\text{TECU} \)

• Based on the developed parameters, existing ionospheric correction methods can be tested for their applicability for operational implementation

For more information:
An Introduction to the Session

• Program Session I (13:35 – 15:15):

  – **14:15**: Masanobu Shimada: “Ionospheric Streaks Appearing in PALSAR Images” (Theory & Data Analysis)

  – **14:35**: Jun Su Kim et al.: “Impact & Mitigation Strategy of Ionospheric Effects In the Context of Low-Frequency (L-/P-Band) SAR Missions Scenarios” (Theory & Correction)

  – **14:55**: Shaun Quegan et al: “Assessment of new Correction Techniques for Faraday Rotation and Ionospheric Scintillation: A BIOMASS Perspective” (Correction)
An Introduction to the Session

- Program Session II (15:40 – 17:20):

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<tr>
<th>Time</th>
<th>Presenter(s)</th>
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<tbody>
<tr>
<td>15:40</td>
<td>Ch. Carrano et al.</td>
<td>“A Phase Screen Simulator for Predicting the Impact on Small-Scale Ionospheric Structure on SAR Image Formation and Interferometry”</td>
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<tr>
<td>16:00</td>
<td>Xiaoqing Pi et al.</td>
<td>“Measurements and Corrections of Ionospheric Effects in InSAR Imagery”</td>
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<tr>
<td>16:20</td>
<td>Phillip Roth et al.</td>
<td>“Simulating and Mitigating Ionospheric Effects in Synthetic Aperture Radar”</td>
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<tr>
<td>16:40</td>
<td>Paul Rosen et al.</td>
<td>“Further Developments in Ionospheric Mitigation of Repeat-Pass InSAR Data”</td>
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<tr>
<td>17:00</td>
<td>J. Nicoll &amp; F. Meyer</td>
<td>“Faraday Rotation Detection and Correction for Dual-Polarization L-Band Data”</td>
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• Other Notable Papers on this Topic:

  – **Thursday, July 29, Session TH1.L01; Room: Sea Pearl; Time 8:20 – 9:00:**
    Giovanni Occhipinti: “Seismic and Tsunami signatures in the ionosphere: what we learn from Sumatra 2004 to Samoa 2009”

  – **Thursday, July 29, Session THP1.PI; Poster Area I; Time 9:40 – 10:45:**
    Jingyi Chen & Howard Zebker: “Estimating the Phase Signatures of the Earth’s Ionosphere Using GPS Carrier Phase Measurements”

  – **Thursday, July 29, Session THP1.PJ; Poster Area J; Time 9:40 – 10:45:**
    Ramon Brcic et al.: “Estimation and Compensation of Ionospheric Delay for SAR Interferometry”

  – **Friday, July 29, Session FR3.L09; Room: Coral 1; Time 13:35 – 15:15:**
    Albert Chen & Howard Zebker: “Reducing Ionospheric Decorrelation Effects in InSAR Data Using Accurate Coregistration”
Thanks for your attention!!