Ionospheric Effects on SAR, InSAR, and SAR Polarimetry – Theory and Experiences with ALOS/PALSAR

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Outline

• SAR and the Ionosphere

• Ionospheric Effects on L-band Data:
  – Quad-Pol Data:
    Faraday Rotation Effects
  – Single-Pol Data:
    • Analysis of Azimuthal Image Distortions
      – Mapping Distortions from Image Pairs and Single Images
    • Ionosphere Induced Doppler Centroid Distortions
  – Dual-Pol
    • Data HH/HV Correlation in Dual-pol SAR Data

• Conclusions and Outlook
Formation of the Ionosphere

EUV radiation of the sun ionizes neutral atoms and molecules.

Typical vertical profiles of the plasma density:

\[ N_{\text{iono}} = (n_{\text{iono}} - 1) \cdot 10^6 = -K \cdot 10^5 \frac{n_e}{f^2} \]
Faraday Rotation in Quad-Pol L-band SAR
Faraday Rotation

• Basic effect:
  – Faraday Effect (1846): When a linearly polarized light wave is incident on a medium with an externally applied longitudinal magnetic field, the plane of polarization of this light wave undergoes a rotation.

• Function of:
  – Earth’s Magnetic Field (intensity and direction relative to propagation) \( B \)
  – TEC \( \propto \nu' \)
  – Carrier frequency
  – Signal path through TEC and magnetic field \( d' \)

\[
\Omega = \frac{K}{f^2} B \cos \theta \sec \chi \cdot TEC
\]
Faraday Rotation Effects on SAR

- Rotates energy from co-pol channels into cross-pol channels
  - Darker images, reduced signal-to-noise ratio, increased cross-talk, ...
  - Scattering matrix asymmetric
- More severe for L- and P-Band than for X- and C-Band
- Currently at solar low
  - Low TEC values dominate
  - Likely to continue for next 3 years
  - Events can still be dramatic

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

high TEC \( \approx 100 \times 10^{16} \)
medium TEC \( \approx 40 \times 10^{16} \)
low TEC \( \approx 10 \times 10^{16} \)
FR Estimation from Quad-Pol Imagery

- Measured Scattering matrix of a sufficiently calibrated SAR system
  \[
  \begin{bmatrix}
  M'_{hh} & M'_{vh} \\
  M'_{hv} & M'_{vv}
  \end{bmatrix} = \begin{bmatrix}
  \cos \Omega & \sin \Omega \\
  -\sin \Omega & \cos \Omega
  \end{bmatrix} \cdot \begin{bmatrix}
  S_{hh} & S_{vh} \\
  S_{hv} & S_{vv}
  \end{bmatrix} \cdot \begin{bmatrix}
  \cos \Omega & \sin \Omega \\
  -\sin \Omega & \cos \Omega
  \end{bmatrix}
  \]

- Direct estimation from scattering matrix (Freeman, 2004):
  \[
  \Omega = \frac{1}{2} \tan^{-1} \left[ \frac{(M'_{vh} - M'_{hv})}{(M'_{vv} + M'_{hv})} \right]
  \]

- Estimation from circular basis (Bickel & Bates, 1965):
  \[
  \begin{bmatrix}
  Z_{11} & Z_{12} \\
  Z_{21} & Z_{22}
  \end{bmatrix} = \begin{bmatrix}
  1 & j \\
  j & 1
  \end{bmatrix} \cdot \begin{bmatrix}
  M'_{hh} & M'_{vh} \\
  M'_{hv} & M'_{vv}
  \end{bmatrix} \cdot \begin{bmatrix}
  1 & j \\
  j & 1
  \end{bmatrix}
  \]
  \[
  \Omega = \frac{1}{4} \arg(Z_{12}Z_{21}^*)
  \]
FR Estimation Examples

- Geomagnetic north pole
  - Mean: $m_W = 3.80^\circ$
  - Std: $s_W = 0.42^\circ$

- Small scale ionospheric disturbances
Extracting Spatial Variation of TEC

Faraday rotation along azimuth for Case Study

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FR Estimation Examples

- North of Gakona, Alaska
  - Mean: $m_W = 3.00^\circ$
  - Std: $s_W = 0.77^\circ$

- Small scale ionospheric disturbances
Ionosphere Induced Azimuthal Image Distortions

Mapping TEC from Single-Pol Data
TEC Variations from and Azimuth Shifts

- Azimuth gradients in TEC cause azimuth shifts in SAR images
- Shifts reach up to 130 meters
- Cause problems in coregistration and interferometry
- Shifts can be used to map TEC variations

Ionospheric disturbance and azimuth shift

Azimuth position [km]

Phase in raw data [rad]

Azimuth shift [m]
Azimuthal DTEC from Single SAR Image

- **Sub-look processing:**
  - Split SAR image in two sub-look (i.e. lower frequency and higher frequency image)
  - Relative shifts between looks corresponds to **second derivative of TEC**
  - Double integration of shifts results in TEC
Azimuth Shifts – Comparison with FR Maps

<table>
<thead>
<tr>
<th>Frame 1670</th>
<th>Frame 1680</th>
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<td>Int. Azimuth Shifts</td>
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<tr>
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<td>Azimuth Shifts</td>
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- Frame 1670: Ionospheric map from Shifts for Frame 1670
- Frame 1680: Ionospheric map from Shifts for Frame 1680
Azimuth Shifts – Comparison with FR Maps

Frame 1690

Faraday Rotation

Int. Azimuth Shifts

Azimuth Shifts

Frame 1700

Faraday Rotation

Int. Azimuth Shifts

Azimuth Shifts
Azimuth Shifts and InSAR

Image with disturbance

Interferogram

Image w/o disturbance
Azimuthal DTEC from Repeat Orbits

• Processing:
  – Calculate shifts between repeat observations
  – Relative shifts correspond to first derivative of TEC differences
  – Integration of shifts results in TEC differences
  – Different sub-looks give same results but shifted in azimuth
Ionospheric Effects on Doppler Centroid
Mapping TEC from Single-Pol Data
Ionospheric Effects on Doppler Centroid

- Ionospheric gradients cause linear phase gradients $\rightarrow$ artificial Doppler centroid

- Integration of $f_{DC}$ map results in ionospheric profile

10 pixel azimuth shift corresponds to about 20 Hz Doppler shift
Ionosphere Induced HH/HV Correlation
Mapping TEC from Dual-Pol Imagery
Ionospheric Effects on HH/HV Correlation

- Correlation between HH/HV in dual-pol datasets is linked to Faraday rotation $\rightarrow r(W)$

- If reflection symmetry $r(W=0) = 0$

- Correlation behavior is dependent on polarimetric scattering signature of target

Ionospheric Effects on HH/HV Correlation

- Correlation examples:
  - Geomagnetic North Pole
  - Surface type: Homogeneous terrain (sea ice)
  - Correlation between 0.2 and 0.6
Conclusions

- Ionospheric effects on L-band SAR are significant even at solar minimum
- Ionosphere affects L-band SAR data in various ways
- Effects correspond to theoretical expectations
- Effects may allow ionospheric mapping from single-pol, dual-pol, and quad-pol data by model inversion
- Significant small-scale ionospheric disturbances could be detected
- More image distortions are under investigation
- Quantitative analysis of ionospheric effects and error analysis is in preparation
Questions?

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FR estimation errors due to target – signal to noise

- Correlated noise has zero mean FR, so the presence of noise will bias results toward zero.
- Thermal noise
- Quantization noise (Saturation, bit clipping)
FR estimation errors due to target – signal to noise

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Washington, DC

Geomagnetic north pole

Dependence of FR on $\text{abs}(Z_{12} \cdot \text{conj}(Z_{21}))$ dB

Faraday Rotation [degrees]

$\text{abs}(Z_{12} Z_{21}^*)$

Dependence of FR on $\text{abs}(Z_{12} \cdot \text{conj}(Z_{21}))$ dB

Faraday Rotation [degrees]

$\text{abs}(Z_{12} Z_{21}^*)$
Comparison of prediction to estimation

- Offset appears to be significant
  - Most likely from small errors in cross-talk or distortion matrix
  - Need a larger distribution of data with significant FR
- Slope does not appear to be significant
  - Can have high variation even within an image

The prediction method can be used as a screening tool.

\[ y = 1.09(0.09)x + 0.5(0.2) \]
FR Correction

• Calibration and correction of FR by model inversion:

• FR Correction software allows both the correction for constant \( W \) and the correction for spatially varying \( W \)

• Faraday rotation bias has to be considered during correction
• 4 cases:
  – High signal level and no spatial FR variation
  – High signal level and spatial FR variation
  – Low signal level and no spatial FR variation
  – Low signal level and spatial FR variation
FR Correction – Spatially Constant FR

**FR statistics**

- **FR Histogram**
  - Mean res. FR in image: -0.63 ± 0.53
  - Sigma res. FR in image: 0.20 ± 0.42
- **Mean FR over Range**
- **Mean FR over Azimuth**

**Residual Faraday rotation**

- Dependence of FR on $\text{abs}(Z_{12} + \text{con}(Z_{21}))$ dB

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FR Correction – Spatially Variable FR

FR map  Fitted plane  FR statistics  Residual Faraday rotation

FR Histogram
mean res. FR in image: -0.041157
sigma res. FR in image: 0.209137

Mean FR over Range

Mean FR over Azimuth

Dependence of FR on \(\text{obs}(Z12+\text{conj}(Z21))\) dB

Residual Faraday rotation

mean magnitude [dB]: -5.88433
lower 3-sigma cutoff [dB]: -15.02588
References
