ASSESSING FARADAY ROTATION EFFECTS IN ALOS PALSAR MISSION DATA OVER THE WESTERN HEMISPHERE

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Ionospheric Effects on Microwave Signals

- For linearly polarized SARs, ionospheric effects can be derived from Appelton-Hartree equation, describing two main signal effects:

1. **Ionosphere-induced phase shift** \( \psi_{\text{iono}}(f_0) \):

\[
\psi_{\text{iono}}(f_0) = -2\pi f_0 \frac{1}{10^6} \int \frac{N_{\text{iono}}(f_0, h)}{c} dh \approx -2\pi \frac{K}{c f_0} TEC
\]

with TEC = \( \int N_{\text{iono}}(f_0, h) dh \) is the Total Electron Content, and \( K = \frac{1}{2} \cdot \frac{e}{(4\pi^2 m \varepsilon_0)} = 40.28 \ [m^3/s^2] \)

2. **Rotation of the polarization orientation (Faraday rotation)** \( \Omega(f_0) \):

\[
\Omega(f_0) = -2\pi f_0 \frac{1}{10^6} \int \frac{N_{\text{iono}}(f_0, h)}{c} \frac{f_H}{f_0} \cos(\theta) dh \approx \frac{K}{f_0^2} B \cdot \cos(\theta) \cdot TEC
\]

with \( f_H = B e / 2\pi \) is the electron gyro frequency and \( \theta \) is angle between magnetic field and signal propagation
Impacts of the Ionosphere on SAR Performance

- Ionospheric distortions depend on the spatial variability of the ionosphere:

  - Observable SAR Distortions
    - Azimuth Defocusing
    - Azimuth geometry distortions
    - InSAR phase distortions
    - Range geometry distortions
    - Range shifts
    - Range Defocusing
    - Faraday rotation

Spatially heterogeneous Ionosphere

Polarization Distortions

Phase Distortions

UNLIKELY!
Impacts of the Ionosphere on SAR Performance

- Ionospheric distortions depend on the spatial variability of the ionosphere:

  - Observable SAR Distortions
    - Azimuth Defocusing
    - Azimuth geometry distortions

Faraday Rotation only distortion that affects every image frame independent of spatial properties of ionosphere!

→ Most relevant of all ionospheric effects
Approach to Assessment of Faraday Rotation Effects in the ALOS PALSAR Archive

• **Goal:**
  – Derive Faraday rotation for every PALSAR image frame

• **Problem:**
  – Calculation of $\Omega$ from the data requires full-polarimetric information, which is only available for small fraction of archive

• **Solution: Model-based Approach**
  – **Predict $\Omega$ frame-by-frame** using known observation geometry, GPS-derived TEC data, and geomagnetic field model

\[
\tilde{\Omega}(f_0) = \frac{K}{f_0^2} B \cdot \cos(\theta) \cdot TEC
\]

From GPS with known SAR acquisition time and location

From geomagnetic field model of image acquisition year

From Orbit geometry, satellite look angle, and thin-layer approximation of ionosphere at 400km altitude
Model Performance Analysis – Concept

• Potential limitations of approach:
  – EO satellites fly within and not above the ionosphere → GPS TEC maps overestimate $\Omega$
    → potentially location dependent bias
  – GPS TEC maps of low resolution and limited quality → increased noise in $\tilde{\Omega}$

• Method for Model validation and evaluation of limitations:
  – Selection of three test sites of different ionospheric properties
  – Estimation of $\hat{\Omega}$ from all full-pol PALSAR data over test areas using established data-driven techniques
  – Compare estimated $\hat{\Omega}$ to model-predicted $\tilde{\Omega}$
Site 1: High-latitude scenario:

- Center coordinates: 69.5N, 144.0W
- $\Omega$ ranges from 0 to $\sim 4.4^o$
- Measured $\tilde{\Omega}$ usually lower than model prediction
- Excellent correlation between $\hat{\Omega}$ and $\tilde{\Omega}$
- No bias or scale factor evident
Model Performance Analysis – Results

Site 1: High-latitude scenario:
- Center coordinates: 69.5N, 144.0W
- $\Omega$ ranges from 0 to $\sim 4.4^\circ$
- Measured $\hat{\Omega}$ usually lower than model prediction
- Excellent correlation between $\hat{\Omega}$ and $\tilde{\Omega}$
- No bias or scale factor evident

Site 2: Mid-latitude scenario:
- Center coordinates: 39.5N, 77.0W
- $\Omega$ ranges from 0 to $\sim 6.5^\circ$
- Measured $\hat{\Omega}$ usually lower than model prediction
- Excellent correlation between $\hat{\Omega}$ and $\tilde{\Omega}$
- Bias of $\sim 1^\circ$ evident
- No scaling factor
Site 1: High-latitude scenario:
- Center coordinates: 69.5N, 144.0W
- \(\Omega\) ranges from 0 to \(\sim 4.4^\circ\)
- Measured \(\hat{\Omega}\) usually lower than model prediction
- Excellent correlation between \(\hat{\Omega}\) and \(\tilde{\Omega}\)
- No bias or scale factor evident

Site 2: Mid-latitude scenario:
- Center coordinates: 39.5N, 77.0W
- \(\Omega\) ranges from 0 to \(\sim 6.5^\circ\)
- Measured \(\hat{\Omega}\) usually lower than model prediction
- Excellent correlation between \(\hat{\Omega}\) and \(\tilde{\Omega}\)
- Bias of \(\sim 1^\circ\) evident
- No scaling factor

Site 3: Southern-latitude scenario:
- Center coordinates: -43.0N, 71.0W
- \(\Omega\) ranges from -3 to \(\sim 0^\circ\)
- Measured \(\hat{\Omega}\) usually slightly higher than model prediction
- Excellent correlation between \(\hat{\Omega}\) and \(\tilde{\Omega}\)
- No significant bias of evident
- No scaling factor
Model Performance Analysis – Results

**Graph Descriptions:**

- **Low:** $Y_{\text{LOW}} = 1.0279x - 0.1931$, $R^2 = 0.9121$
- **Mid:** $Y_{\text{MID}} = 0.9341x - 1.1856$, $R^2 = 0.9753$
- **High:** $Y_{\text{HIGH}} = 0.9322x - 0.1324$, $R^2 = 0.9098$

The graph shows the relationship between measured and predicted Faraday rotation for all sites.
Studying Faraday Rotation in the ALOS PALSAR Archive over the Western Hemisphere

• Pre-processing steps:
  – $\tilde{\Omega}$ for every image frame
  – Spatial gridding of $\tilde{\Omega}$ variables in 1×1 degree grid cells
  – Split into daytime and nighttime acquisitions through frame-by-frame calculation of local sunset/sunrise times
  – For some analyses: Transformation from geographic to geomagnetic coordinates

• Conducted spatio-temporal analyses:
  – Spatial distribution of $\tilde{\Omega}$ by month and year
  – Temporal variation of $\tilde{\Omega}$ by geomagnetic latitude
  – Cumulative Distribution Functions (CDFs) by year
  – Analysis of outliers
Spatial Distribution of Faraday Rotation

- All time spatial statistical parameters
  - Mean $\tilde{\Omega}$ - nighttime
  - Max $\tilde{\Omega}$ - nighttime
  - Max $\tilde{\Omega}$ - all time
  - Std. $\tilde{\Omega}$ - nighttime
  - Skew $\tilde{\Omega}$ - nighttime
Spatio-Temporal Distribution of Faraday Rotation

- Monthly Faraday Rotation Distribution

Note: Nighttime acquisitions only!
Nighttime vs. Daytime Behavior

**Nighttime data**
- emphasizes seasonal dependence
- Mitigates solar cycle dependence

**Daytime data**
- emphasizes solar cycle dependence
- Mitigates seasonal dependence
Faraday Rotation CDFs

- CDFs used for the statistical detection of outlines
  - For the entire lifetime of the system, only 12% of images show $\Omega \geq 3^\circ$

### Maximum allowable (residual) Faraday rotation in data (defined by calibration requirements)

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<th>Polarimetric Calibration Parameter</th>
<th>Spec.</th>
<th>[deg]</th>
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<tr>
<td>Antenna Gain $\sigma_{0,HH}$</td>
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<td>8.0</td>
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<tr>
<td>Antenna Gain $\sigma_{0,HV}$</td>
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<td>Channel Amplitude Imbalance $</td>
<td>f</td>
<td>$</td>
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<td>Channel Phase Imbalance $\arg(f)$</td>
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<tr>
<td>Crosstalk $\delta$</td>
<td>-30 [dB]</td>
<td>2</td>
</tr>
</tbody>
</table>

CDF-Based Yearly Outlier Detection

- Circle per individual outlier frame
- Circle size corresponds to relative Faraday rotation
Summary and Conclusions

• A Faraday rotation analysis for ~700,000 ALOS PALSAR frames over the western hemisphere was presented

• To enable analysis, a model-based FR prediction was developed

• A performance assessment for three test sites shows good performance of the model

Some results of the Faraday rotation analysis:

- For large parts of the PALSAR lifetime, $\Omega$ was smaller than 5 degrees for 99% of the images
- Increased ionospheric activity causes 1% of the 2010 data to have $\Omega > 6.5$ degrees
- Highest $\Omega$ usually in mid latitudes
- Nighttime $\Omega$ shows seasonal dependence while daytime $\Omega$ traces solar cycle

• 12% of images have $\Omega \geq 3^\circ$
Next time, I’ll sense more remotely!!

THANK YOU FOR YOUR ATTENTION!!

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