Bistatic/Monostatic Synthetic Aperture Radar for Ice Sheet Measurements

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Topics

• Overview
• EM Model
• Sensor Geometry
• Antenna Array
• Position Errors
• Sandbox Tests
Overview – Motivation

• Global sea level rise threatens coastal regions
• Contributions from an ice sheet are measured by finding the mass balance of the ice sheet.
• Create ice flow model to predict mass balance
• Basal conditions needed for ice flow model
• We can drill boreholes in a few places, but not all over the Arctic and Antarctic regions – RADAR.
Overview – Basal Scattering

- The bedrock is thought to be smooth with respect to wavelength.
- Therefore it looks like a mirror at our frequencies of operation.
Data Collection Geometries

- **Monostatic Arrangement**
  - Used when the *surface is rough* and side-looking radar techniques can be employed

![Diagram showing monostatic arrangement](image)
Data Collection Geometries

- **Bistatic Arrangement**
  - Used when the *surface is smooth* and exhibits specular (mirror-like) characteristics
  - New variable: separation distance between transmitter and receiver
Overview – System Model

• Modes of operation: **monostatic and bistatic**
• Broadband operation: nearly three octaves
EM Model

• **Magnitude of Transfer Function**
  - TEM Horn Antenna Measurements
  - Radar System Transfer Function
  - Spherical Spreading
  
  \[ P_R = P_T H_T \eta_{Teff} D_T \frac{\sigma_{bs}}{4\pi R_T^2} \frac{A_R}{4\pi R_R^2} \eta_{Reff} |H_R| \]

• **Phase of Transfer Function**
  - TEM Horn Antenna Measurements
  - Radar System Transfer Function
  - Path length, phase velocity, and refraction
EM Model – TEM Horn Antenna

Magnitude Gain For Broadside

Magnitude Radiation Pattern For 4 GHz
EM Model – TEM Horn Antenna

Relative Delay For Broadside

Relative Delay Radiation Pattern For 4 GHz

Effective Relative Free Space Length (cm)

Elevation Angle (degrees)
Radar System Transfer Function

- NA Calibration and Amp/Cable Assembly
Radar System Transfer Function

• Calibration and Amp/Cable
Dielectric Half-space Model

- Three-dimensional geometry of refracted ray can be projected onto the plane of incidence (two-dimensional)

\[
y' = \sqrt{(A_x - S_x)^2 + (A_y - S_y)^2}
\]

\[
\hat{a}_{y'} = \frac{((S_x - A_x)\hat{a}_x + (S_y - A_y)\hat{a}_y)}{|(S_x - A_x)\hat{a}_x + (S_y - A_y)\hat{a}_y|}
\]

\[
\left(n_1^2 - n_2^2\right)S_{y'}^4 - 2y'(n_1^2 - n_2^2)S_{y'}^3 + \left(n_1^2(y'^2 + S_{z}^2) - n_2^2(y'^2 + T_{z}^2)\right)S_{y'}^2 - 2y'n_1^2S_{z}^2S_{y'} - y'^2n_1^2S_{z}^2S_{y'}^0 = 0
\]
Sensor Geometry

- Find the optimal transmitter position that minimizes the cross-track aperture size, \( R \).
Backscatter Characteristics

- Bistatic forward scattering characteristics are approximated with our knowledge of backscatter characteristics.

\[
\begin{align*}
\varepsilon_{\text{ICE}} &= 3.2 \\
\varepsilon_{\text{BEDROCK}} &= 8.0 \\
\end{align*}
\]
Advantage of Separation

- As the transmitter moves away from the swath, the ice surface illuminated by the forward scatter cones grows.
- In turn, the minimum required receiver movement decreases (i.e. $B < A$).
Disadvantages of Separation

- As the transmitter-receiver separation is increased, the angular resolution decreases.
- The bedrock surface subtended also increases for the same angular resolution.

\[ \rho \times \]

\[ \alpha \]

Ice

Bedrock

Nadir
Best Resolution

\[ \alpha' \]

Off-nadir
Worse Resolution

\[ \rho_x \]
Plot of Receiver Array Size

- The minimum receive aperture occurs when the transmitter position is 1580 m from the center of the swath.
- The minimum receive aperture is 47 m.

Across-track resolution: 100 m  
Ice thickness: 3 km  
Frequency: 150 MHz  
Swatch Width: 1 km  
Backscatter: 7.5 deg
Results for 3000 m thick ice

<table>
<thead>
<tr>
<th>Frequency (MHz)</th>
<th>Max forward-scatter angle (deg)</th>
<th>Tx Position (m)</th>
<th>Min. Receiver Aperture (m)</th>
<th>Min. Monostatic Aperture (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>5</td>
<td>2831</td>
<td>1323</td>
<td>799</td>
</tr>
<tr>
<td>60</td>
<td>10</td>
<td>2435</td>
<td>538</td>
<td>535</td>
</tr>
<tr>
<td>60</td>
<td>15</td>
<td>1710</td>
<td>121</td>
<td>273</td>
</tr>
<tr>
<td>60</td>
<td>20</td>
<td>0</td>
<td>66</td>
<td>32</td>
</tr>
<tr>
<td>150</td>
<td>5</td>
<td>2831</td>
<td>1125</td>
<td>762</td>
</tr>
<tr>
<td>150</td>
<td>10</td>
<td>2435</td>
<td>371</td>
<td>498</td>
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<td>15</td>
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<td>47</td>
<td>234</td>
</tr>
<tr>
<td>150</td>
<td>20</td>
<td>0</td>
<td>26</td>
<td>13</td>
</tr>
<tr>
<td>350</td>
<td>5</td>
<td>2831</td>
<td>1049</td>
<td>748</td>
</tr>
<tr>
<td>350</td>
<td>10</td>
<td>2435</td>
<td>307</td>
<td>484</td>
</tr>
<tr>
<td>350</td>
<td>15</td>
<td>1580</td>
<td>20</td>
<td>219</td>
</tr>
<tr>
<td>350</td>
<td>20</td>
<td>0</td>
<td>11</td>
<td>6</td>
</tr>
</tbody>
</table>
Monostatic Mode

- For comparison.
- Using a cross-track spatially sampled monostatic array.
Monostatic vs. Bistatic

• Minimum SAR aperture required using a bistatic configuration (also compared to monostatic).
Along-track Array

- Along-track antenna array
  - Sharpens along-track beam
  - Less frequent along-track sampling
  - Sum antenna array elements together
  - SAR focusing hindered by loss of control over individual elements
Results

- This plot shows the maximum SAR resolution attainable versus aperture size.
- One tenth of a wavelength variation across the aperture was tolerated.
Position Errors

• The Radar will derive its position using the global positioning system (GPS).
• GPS’s have errors that are a significant fraction of a wavelength
• Need to answer the question: How do positioning errors effect the performance of the SAR processor?
Position Errors

- Gaussian random process
- Correlated errors created by low pass filtering
- Topcon GPS system:
  - 0.1 m standard deviation in latitude
  - 0.1 m standard deviation in longitude
  - 0.2 m standard deviation in elevation
Results for $\sigma = 0.05 \text{ m}$

100 m resolution with $\sigma = 0.05 \text{ m}$

- Zero correlation
- 10 m correlation
- 50 m correlation

SIR (dB) vs. Frequency (MHz)
Results for $\sigma = 0.1 \text{ m}$
Results for $\sigma = 0.1 \text{ m (fixed aperture)}$
Sandbox Laboratory

- Test the EM model
- Test the SAR processing algorithm
  - Ability to determine the position of a target
  - Ability to accurately determine the target’s reflectance
Measurement Setup

- Left side: measurement setup
- Right side: simulation setup
A-Scopes

Left side: measured dataset
Right side: simulated dataset
SAR Processed

Left side: measured dataset after SAR processing
Right side: simulated dataset after SAR processing
Ten Targets

![Diagram showing actual and measured positions of ten targets with a color map representing power levels.](image)
# Table of Results

<table>
<thead>
<tr>
<th>Target #</th>
<th>Diameter</th>
<th>Metal/Air</th>
<th>Signal Power</th>
<th>Position Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>12.5 cm</td>
<td>Metal</td>
<td>-35 dB</td>
<td>2 cm</td>
</tr>
<tr>
<td>2</td>
<td>10 cm</td>
<td>Metal</td>
<td>-38 dB</td>
<td>5 cm</td>
</tr>
<tr>
<td>3</td>
<td>12.5 cm</td>
<td>Metal</td>
<td>-35 dB</td>
<td>2 cm</td>
</tr>
<tr>
<td>4</td>
<td>10 cm</td>
<td>Metal</td>
<td>-42 dB</td>
<td>1.41 cm</td>
</tr>
<tr>
<td>5</td>
<td>10 cm</td>
<td>Metal</td>
<td>-40 dB</td>
<td>2.24 cm</td>
</tr>
<tr>
<td>6</td>
<td>10 cm</td>
<td>Metal</td>
<td>-42 dB</td>
<td>3.16 cm</td>
</tr>
<tr>
<td>7</td>
<td>11.5 cm</td>
<td>Air-filled</td>
<td>-53 dB</td>
<td>2.24 cm</td>
</tr>
<tr>
<td>8</td>
<td>15 cm</td>
<td>Air-filled</td>
<td>-49 dB</td>
<td>6.08 cm</td>
</tr>
<tr>
<td>9</td>
<td>11.5 cm</td>
<td>Air-filled</td>
<td>-52 dB</td>
<td>1 cm</td>
</tr>
<tr>
<td>10</td>
<td>15 cm</td>
<td>Air-filled</td>
<td>-49 dB</td>
<td>1 cm</td>
</tr>
</tbody>
</table>

- Max sidelobe is –49 dB
- Signal to sidelobe is at least 4 dB within the region of the target
Conclusions

• Transmitter Location (Sensor Geometry)
  • The transmitter position has a very large effect on the size of the bistatic array.
  • Depending on the type of scattering and thickness of the ice, the bistatic mode may or may not be faster than the monostatic mode.
  • The bistatic transmitter position that minimizes the receiver cross-track movement was found.

• Along-track Antenna Array
  • Along-track antenna array could be helpful in expediting the bistatic measurements.
  • For high-precision measurements (e.g. 10 m) its usefulness is limited unless each element can be controlled individually.
Conclusions

• Position Errors
  • Position errors can be very severe at higher frequencies. Increasing aperture length does not help position errors.
  • GPS errors need to be characterized in terms of magnitude of relative error and error correlation over time and space.

• Sandbox lab tests showed:
  • First-order EM Model gives results consistent with the measured results
  • Ability to position targets to within a few centimeters
  • Ability to distinguish targets with different reflectivities (with similar targets giving consistent reflectivities)