Radar Interferometric and Polarimetric Possibilities for Determining Sea Ice Thickness

by
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January 28, 2015
PolInSAR 2015
Frascati, Italy

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Motivation
Motivation

- Sea ice thickness is a primary indicator of climate change in the polar oceans, as the thickness is a time-integrated result of both thermodynamic and dynamic processes.
- The large-scale ocean and atmospheric forcing acts on the fine-scale (a few to 10s of meters) opening and closing of the sea ice cover along fractures. The mean thickness and variance of sea thickness at km scales (50 cm uncertainty) are derived from recent spaceborne observations from the ICESat lidar and in the Arctic from sporadic upward looking sonar measurements.
- However, accurate measurements of sea ice thickness at the fine-scales at which the forcing is occurring are virtually non-existent.
- Moreover, fine spatial scale measurements are needed to support oil exploration and extraction in Arctic regions.
• In this talk we examine two potential radar interferometric means of obtaining sea ice thickness.
  – One method uses high frequency Ka-band (8.5 mm wavelength) to infer sea ice thickness by measuring elevations to the surface of the ice and to the ocean surface in nearby open leads. Data from the NASA GLISTIN radar is used to illustrate this methodology.
    • No clouds
    • Possible use on SWOT mission
  – Alternatively, we consider the use of dual frequency X-band and P-band (3 cm and 85 cm wavelengths) to exploit the differential penetration of longer versus shorter wavelengths to estimate sea ice thickness. This technique is illustrated with data collected by the Furgo Earthdata GeoSAR system.
Current methods of measuring sea ice thickness at fine spatial scales involve the use of electromagnetic induction (EM) or using ground based penetrating radars, sonar measurements or in situ obtained ice cores.

- The EM method provides mean thickness and variance and has well-known deficiencies with thicker, ridged ice.
- The penetrating radar method is designed to detect the top and bottom ice surfaces simultaneously and is able to achieve the high accuracy and spatial resolution that is desired but has not been tested on aircraft and ultimately lacks the capability to map large regions due to its narrow altimetric-like nadir swath.
- In situ ice cores although very accurate can only be made for very constrained spatial extents. Submarine based sonar measurement are temporally sporadic, although extend further back in time than satellite altimetry-freeboard based measurements.
Interferometric Mapping
Electromagnetic Versus Interferometric Penetration

**Electromagnetic Penetration**

- Electromagnetic penetration is a measure of how deep radar waves penetrate into a volume.
- Penetration depends on the effective dielectric constant and the wavelength and is independent of baseline.

\[
P(z) = P_0 e^{\eta z}
\]

\[
\eta = -\frac{2\pi \text{Im}(\sqrt{\varepsilon})}{\lambda} = -\frac{2\pi \varepsilon_r \sqrt{1 + \left(\frac{\varepsilon_i}{\varepsilon_r}\right)^2} - 1}{\lambda}
\]

\[
\eta = \frac{2\tilde{\eta}}{\cos \theta}
\]

\[
P_d = \frac{-\lambda}{2\pi \text{Im}(\sqrt{\varepsilon})}
\]

**Interferometric Penetration**

- Interferometric penetration is a measure of the elevation bias from the top of the scattering media as measured by an interferometer.
- Penetration depends on the wavelength, the scattering as function of height in the volume and the baseline length.

\[
\gamma_v = \frac{h_s}{h_i} \frac{\int \sigma(z) e^{ik_z z} dz}{\int \sigma(z) dz}
\]

\[
k_z = \frac{\partial \phi}{\partial z} = \frac{2\pi pb \cos(\theta - \alpha)}{\lambda \rho \sin \theta} = \frac{2\pi pb \cos(\theta - \alpha)}{\lambda h_p \tan \theta}
\]

\[
h_p = \frac{\text{arg}(\gamma_v)}{k_z}
\]
Simple 3-Layer Model

A simple model for the sea ice scattering is an exponential attenuating volume with surface scattering at the air/ice interface and at the ice/water interface that can be used to assess basic sensitivities.

\[ \sigma(z) = \mu_i \delta(z - h_i) + e^{-\eta(h_s - z)} + \mu_s \delta(z - h_s) \]

\[ \mu_s = \text{Surface to Ice Volume Scattering Ratio} \]
\[ \mu_i = \text{Water to Ice Volume Scattering Ratio} \]
\[ \eta = \text{Attenuation in Ice (2-Way)} \]

The volumetric correlation, \( \gamma_v \), using the formula in the adjacent panel for the 3-layer volume gives:

\[ \gamma_v = \frac{e^{ik_z h_m}}{\mu_i + \mu_s + 2e^{-\eta \frac{\Delta h}{2}} \sinh \left( \frac{\eta \Delta h}{2} \right)} \left[ \mu_s e^{ik_z \frac{\Delta h}{2}} + \mu_i e^{-ik_z \frac{\Delta h}{2}} \right] + 2 \left( \frac{\eta - ik_z}{\eta^2 + k_z^2} \right) e^{-\eta \frac{\Delta h}{2}} \left[ \sinh \left( \frac{\eta \Delta h}{2} \right) \cos \left( \frac{k_z \Delta h}{2} \right) + i \cosh \left( \frac{\eta \Delta h}{2} \right) \sin \left( \frac{k_z \Delta h}{2} \right) \right] \]

The argument of the volumetric correlation provides a measure of the interferometric penetration, \( h_p \).
Ka-band Studies
GLISTIN System

- The Glacier and Ice Surface Topography Interferometer (GLISTIN not GLISTEN…) was first proposed as a spaceborne digital beamforming Ka-band space-borne mission concept. GLISTIN is a Ka-band single pass interferometer (25 cm baseline length) flown on the NASA Gulfstream III aircraft designed to measure glacier and ice topography. Ka-band (25 GHz or 8.5 mm wavelength) was chosen to minimize penetration.

- NASA’s the Earth Science Technology Office (ESTO) in 2004 initially funded for technology development of a slotted waveguide antenna beamformer along with mission studies. Later an Airborne demonstration for phenomenology and measurement concept funded in 2007 under NASA International Polar Year activities with performance upgrades to the system made in 2012.

- GLISTIN has flown a campaign to Greenland May 2009 and did a validation (land-ice) and proof-of-concept (sea-ice) 2-day campaign to Alaska April, 2013.
GLISTIN Ka-band System

Ka-band antennas installed on the NASA GIII configured for single-pass interferometry

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>IPY</th>
<th>GLISTIN-A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak transmit power (at antenna)</td>
<td>W</td>
<td>40 (TWTA)</td>
<td>80 (SSPA)</td>
</tr>
<tr>
<td>Receive Losses</td>
<td>dB</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>Ping-pong</td>
<td>No</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Height precision (30x30m posting)*</td>
<td>m</td>
<td>15°</td>
<td>0.06</td>
</tr>
<tr>
<td></td>
<td></td>
<td>31°</td>
<td>0.14</td>
</tr>
<tr>
<td></td>
<td></td>
<td>49°</td>
<td>0.50</td>
</tr>
<tr>
<td>Nominal flight altitude (AGL)</td>
<td>km</td>
<td>7</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>kft</td>
<td>24</td>
<td>41</td>
</tr>
<tr>
<td>Nominal Swath</td>
<td>km</td>
<td>6</td>
<td>11</td>
</tr>
</tbody>
</table>
- Proof of concept to see if measuring freeboard height is possible
  - Key is to determine if heights of open leads can be measured
  - Collected data at near-nadir incidence angles
  - Pertinent for the SWOT mission
- Underflew Cryosat II pass. Overflight occurred midway into first outbound leg
- Full swath overlap on reverse paths
Sensitivity Studies
Submarine Data of Sea Ice Bottom

• Required as input to the scattering model are the sea ice roughness and correlation length for the bottom and top of the sea ice.
  – Many papers describe the top of the sea ice, however little or no data are available on the bottom roughness of the sea ice.
  – We used submarine based ice topography measurements to bound the roughness and estimate the correlation length.
• Ice draft measurements gridded in 2 cm resolution cells. Courtesy of M. Doble
  – A 5x5 pixel box centered on each pixel was used to estimate the local mean and local standard deviation.
  – RMS height is close to measurement precision so this assessment only places an upper bound on surface roughness.
Sea Ice Bottom Roughness and Correlation

Graphs showing the mean height and rms height with histograms of rms height.
Scattering Model

- We have developed a scattering model of radar interferometric observations of sea ice in order to assess to ability to measure sea ice thickness under various sea conditions. We analyzed submarine based sonar draft measurements to obtain sea ice bottom characteristics used in our scattering models.
Sensitivity Analysis

- Using sea ice roughness obtained from the submarine data for the bottom layer, sea ice dielectric profiles which determine the level of attenuation of microwaves in sea ice we estimated the amount of penetration at X and P-band for a range of values about these nominal values. Above show the ratio of top/bottom scattering power.
X/P-Band GeoSAR Interferometry
GeoSAR Imaging Geometry

- GeoSAR is a dual frequency X-band and P-band radar interferometer that is flown a Gulfstream II which is owned and operated by Furgo Earthdata International. The system exploits the different penetration levels of P-band and X-band in scattering volumes such as vegetation and sea ice.
- The system operates with a wide bandwidth of 160 MHz which provides sub meter resolution.
GeoSAR System

<table>
<thead>
<tr>
<th>Interferometric Band</th>
<th>Baseline (m) SAT</th>
<th>Baseline (m) Ping-Pong</th>
</tr>
</thead>
<tbody>
<tr>
<td>P-band</td>
<td>21.6</td>
<td>43.2</td>
</tr>
<tr>
<td>X-band</td>
<td>2.7</td>
<td>5.4</td>
</tr>
</tbody>
</table>
GeoSAR Data Collections

• GeoSAR has made several campaigns dedicated to studying the ability of dual frequency radar interferometric measurements to measure sea ice thickness.
  – On April 10, 2012 the GeoSAR radar collected a series of flight lines over first year and multi-year ice in a region just north of Barrow Alaska. Several radar corner reflectors were deployed in the area for calibration. GeoSAR flight lines were arranged to overlap a helicopter EM survey of sea ice thickness. In addition to radar measurements the GeoSAR platform has a lidar that measures elevation to the top of the sea ice.
  – Then in April 2014 another collection of sea ice was made by GeoSAR, this time in the Canadian archipelago on a potentially more amenable type and thickness of sea ice to demonstrate this radar concept. Sea ice within the Canadian islands becomes largely stationary, and maintaining the same location for many months makes it thus a more accessible site for in situ measurements and flight planning. These flights were obtained over ice that was at least a few years old, of considerable thickness, and with minimum salinity, which optimizes radar penetration.
Barrow, Alaska Collection

AEM Coverage

Data Coverage

Multi looks are blurred due to ice floes.
No blurring over land.

1 Look
2 Looks
3 Looks
7 Looks
5 Looks
2 Looks
3 Looks

EM Profiler
GeoSAR Coverage
Lidar Profiler Line
Corner Reflectors
Profiles Through Ice Island

- **X-band Elevation**
- **P-band Elevation**
Conclusions and Future Work
Conclusions

- Both low and high frequency radar observations may be useful for sea ice thickness estimates.
- Coherent interferometric/polarimetric scattering from sea ice particularly at low frequencies with realistic sea ice input parameters are needed.
- NEXT STEPS: Improved model to understand how penetration depends on ice type and improved algorithms for estimating sea ice thickness.