Remote sensing of sea ice

Ice concentration/extent
Age/type
Drift
Melting
Thickness

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Remote Sensing Methods

- **Passive**: senses shortwave (visible), thermal (infrared) or microwave radiation emitted by Earth
  - SSMI/AMSR: microwave 19-89 GHz, V and H polarization
    - Global ice coverage (25 km resolution)
  - AVHRR: optical & thermal (5 bands)
    - Ice coverage, ice temperature, ice drift (1 km resolution)
  - MODIS: optical & thermal (36 bands)
    - Ice coverage & processes, melt (250 m resolution)
- **Active**: actively transmits microwave (radar) or shortwave
  - Radar (e.g. Radarsat, Quikscat) C- & Ku-band (5-13 GHz)
    - Ice types, surface roughness, ice drift, ice melt (3-75 m resolution)
  - Altimeters (laser and radar; e.g. ICESat, CryoSat)
    - Ice freeboard & thickness (300 m resolution, one-dimensional)
Microwave Remote Sensing

- Can “see” through clouds and snow
- Independent of daytime/solar radiation

- **Passive**: Low spatial resolution, but daily, global coverage
- **Active** (radar): High spatial resolution, narrow swaths

- Exclusive use of polar orbiting satellites
Satellite-measured surface brightness temperature $T_b$

$$T_b = \varepsilon \, T_0$$

$\varepsilon$: Emissivity

$T_0$: Surface temperature

- Water: low emissivity
- Multiyear ice: intermediate emissivity
- First-year ice: high emissivity
- Varies with frequency and polarization

H- and V-pol emissivity at 50° incidence angle (Spreen et al., 2008)
Brightness temperature of the Arctic Ocean

- September 2007 – April 2008
- **Advanced Microwave Scanning Radiometer** (higher spatial resolution 6.25 km)
- Died on October 4, 2011
The ice cover is composed of ice floes and is discontinuous, often with a gradual transition to open water.

Ice coverage is normally given as ice concentration, in $1/10$s or $\%$.

<table>
<thead>
<tr>
<th>Ice Concentration</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$&lt;1/10$</td>
<td>Open water/ Eau libre</td>
</tr>
<tr>
<td>$1-3/10$</td>
<td>Very open drift/ Banquise très lâche</td>
</tr>
<tr>
<td>$4-6/10$</td>
<td>Open drift/ Banquise lâche</td>
</tr>
<tr>
<td>$7-8/10$</td>
<td>Close pack/Drift Banquise serrée</td>
</tr>
<tr>
<td>$9/10$</td>
<td>Very close pack/ Banquise très serrée</td>
</tr>
<tr>
<td>$9+/10$</td>
<td>Very close pack/ Banquise très serrée</td>
</tr>
<tr>
<td>$10/10$</td>
<td>Compact/Consolidated ice Banquise compact/consolidée</td>
</tr>
</tbody>
</table>
Retrieval of ice concentration:
“NASA Team Algorithm”

Ice/water mixture

\[ T_{B,ij} = C_w T_{B,W,ij} + C_{FY} T_{B,FY,ij} + C_{MY} T_{B,MY,ij} \]

Polarization ratio

\[ PR[18] = \frac{T_{b[18V]} - T_{b[18H]}}{T_{b[18V]} + T_{b[18H]}} \]

Gradient ratio

\[ GR[37V/18V] = \frac{T_{b[37V]} - T_{b[18H]}}{T_{b[37V]} + T_{b[18H]}} \]

\[ C_{FY} = \frac{F_0 + F_1 PR + F_2 GR + F_3 (PR)(GR)}{L} \]

\[ C_{MY} = \frac{M_0 + M_1 PR + M_2 GR + M_3 (PR)(GR)}{D} \]

\[ D = D_0 + D_1 PR + D_2 GR + D_3 (PR)(GR) \]

\[ C_T = C_{FY} + C_{MY} \]

D: based on observed \( T_b \)s
Fig. 10-2. Spectral gradient ratio versus polarization at 1.7 cm for the north polar area, February 3 to 7, 1979. The curved triangle is a representation of the algorithm used to calculate sea-ice concentration and age. Terms are listed as sea-surface temperature (K), near-surface wind (m/s), water vapor (cm), and cloud droplets (cm). The arrows indicate model calculation of $GR$ and $PR$ deviations from cold, specular, oceanic conditions [Gloersen and Cavalieri, 1986].
Ice extent vs. area

- Ice Extent: area $A_e$ enclosed by 15% ice concentration isoline
- Ice Area: Actual area covered by ice, accounting for ice concentration < 100%, i.e. $A_e \times C$
Advanced Very High Resolution Radiometer (AVHRR)

- Based on SW reflectivity and IR emission; 1 km resolution (@ nadir)
- First-of-its-kind, valuable mesoscale ice information
- Leads often appear exaggerated
MODIS: Moderate Resolution Imaging Spectroradiometer

- Sensor on NASA’s Earth Observing System (EOS) mission program
- Operated on Terra and Aqua satellites
- **GLOBAL** products
- 250 m resolution (@ nadir)
Thin ice in fjords due to enhanced ocean heat flux
Possible future polynyas?
Polynyas and primary productivity

Melling, Haas, Brossier, unpublished
Typical radar frequencies & wavelengths

- Radar waves can penetrate into matter, e.g. into snow, ice, dry sand, through vegetation

Table 9-3. RADAR Wavelengths and Frequencies Used in Active Microwave Remote Sensing Investigations

<table>
<thead>
<tr>
<th>RADAR Band Designations (common wavelengths shown in parentheses)</th>
<th>Wavelength (λ) in cm</th>
<th>Frequency (ν) in GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>K_a (0.86 cm)</td>
<td>0.75 – 1.18</td>
<td>40.0 – 26.5</td>
</tr>
<tr>
<td>K</td>
<td>1.19 – 1.67</td>
<td>26.5 – 18.0</td>
</tr>
<tr>
<td>K_u</td>
<td>1.67 – 2.4</td>
<td>18.0 – 12.5</td>
</tr>
<tr>
<td>X (3.0 and 3.2 cm)</td>
<td>2.4 – 3.8</td>
<td>12.5 – 8.0</td>
</tr>
<tr>
<td>C (7.5, 6.0 cm)</td>
<td>3.9 – 7.5</td>
<td>8.0 – 4.0</td>
</tr>
<tr>
<td>S (8.0, 9.6, 12.6 cm)</td>
<td>7.5 – 15.0</td>
<td>4.0 – 2.0</td>
</tr>
<tr>
<td>L (23.5, 24.0, 25.0 cm)</td>
<td>15.0 – 30.0</td>
<td>2.0 – 1.0</td>
</tr>
<tr>
<td>P (68.0 cm)</td>
<td>30.0 – 100</td>
<td>1.0 – 0.3</td>
</tr>
</tbody>
</table>
Backscatter as function of surface roughness

Backscatter $\sigma_0 = \frac{\text{backscattered power}}{\text{incident power}}$  

“radar reflectivity”;  
“scattering albedo”

“Lambertian scattering”
Synthetic-Aperture Radar (SAR)

- e.g. ERS, Envisat, Radarsat
- C-Band SAR
- Very high spatial resolution achieved by along-track (azimuth) synthetic-aperture (Doppler) radar processing
Radar microwave interaction with ice

(a) Multiyear:
- Low-salinity, low-loss
- Surface - volume scattering

First year:
- High-salinity
- High-loss
- Surface scattering

Open water:
- High-loss
- Surface scattering

(b) Glacier ice:
- Surface scattering

Volume scattering

Glacier ice

Lake ice

Water
FYI vs MYI microstructure & properties

- FYI: saline, low porosity $\rightarrow$ low backscatter
- MYI: desalinated by melt, porous, low density $\rightarrow$ high (volume) backscatter
Backscatter of different ice types

Figure 3.4. SAR backscatter signatures as a function of ice types observed during ERS SAR ice validation experiments.
Envisat SAR image
Jan 26, 2009

• High backscatter: MYI regions
Ice information from satellite Synthetic Aperture Radar data

- Shows ice dynamics and deformation
- Retrieval of geophysical ice properties has yet to be improved

Jan-May 2007
Envisat (C-Band)
“Radarsat geophysical processor system” RGPS: Drift and Deformation

Nov 7, 1996
75.98N, -132.93E

Seasonal Ice Area

Ice Thickness (cm)
Surface roughness and melt

- Rougher ice: High backscatter; less melt ponding due to better drainage/runoff
Arctic/Antarctic contrasts:
Seasonal cycle of radar backscatter

Haas, 2001
Antarctic/Arctic contrasts:
Superimposed ice versus melt ponding

Antarctic

Arctic
Superimposed ice and ice layer formation / melt freeze cycles

- Warming and reversal of T-gradients
- Snow melting
- Meltwater percolation
- Refreezing within colder snow layers or at the colder snow/ice interface; or:
- Refreezing above slush layer by double diffusion
Effect on backscatter increase (and decreasing emissivity)

- Internal snow melt and metamorphosis
  - Grain coarsening
  - Wetting
  - $\sigma_{\text{volume}}$ increase
  - $\sigma_{\text{volume}}$ question mark

- Meltwater percolation and refreezing
  - Salt washout
  - $\sigma_{\text{volume}}$ question mark

- Superimposed ice formation

- Rough snow/superimposed ice interface
  - Fresh, bubbly superimposed ice
  - $\sigma_{\text{surface}}$ increase
  - $\sigma_{\text{volume}}$ increase

Haas, 2001
Scatterometry

- QuikSCAT radar scatterometer
- Independent of clouds or daylight
- Low spatial resolution
- Cannot easily be used for ice concentration due to variable backscatter of water
Loss and replenishment of MYI

Figure 9. Nine annual cycles of replenishment/export of Arctic Ocean multiyear ice area constructed using QuikSCAT data and Fram Strait ice export. Open circles show the approximate times of the 10 ICESat campaigns used here. The dashed vertical lines show the replenishment of the MY ice reservoir by first-year ice at the end of each summer. The two near-zero replenishment years of 2005 and 2007 are indicated. Inset shows the annual and seasonal Fram Strait ice export over the same period.

Kwok et al., 2009
Laser & radar altimetry

- ICESat (Laser, small footprint, NASA)
- CryoSat (Radar, large footprint, ESA)
- Large uncertainties due to unknown sea surface, and snow cover

Principle: \( F = h_{\text{ellip}} - D_{\text{laser}} - h_{\text{geoid}} - \Delta h \)

\( \Delta h \): Ocean dynamic topography
Sea ice thickness vs. freeboard

**Different definitions of freeboard!**

**ICESat Laser altimetry:**
Freeboard ≡ Elevation of snow surface

\[
T_i = F \frac{\rho_w}{\rho_w - \rho_i} - T_s \frac{\rho_w - \rho_s}{\rho_w - \rho_i} \approx 7
\]

**CryoSat Radar altimetry:**
Freeboard ≡ Elevation of ice surface

\[
h_i = f \frac{\rho_w}{\rho_w - \rho_i} + h_s \frac{\rho_s}{\rho_w - \rho_i} \approx 3
\]
ICESat sea ice thickness results

- Laser altimeter

Kwok et al., 2004
Sea ice freeboard measurement with SAR radar altimeter

\[ h_i = f \frac{\rho_w}{(\rho_w - \rho_i)} + \frac{h_s \rho_s}{(\rho_w - \rho_i)} \]
Fall

Spring

ICESat (2003-08)

CryoSat (2010-11)

Laxon et al., 2013

- No data during melt season
Validation

- Agreement with validation measurements within 5-8 cm (5 km mean thicknesses)
Snow – the last frontier!