ICESat’s Observations of Arctic Sea Ice Freeboard/Thickness and NASA’s plans for ICESat-2

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Space and the Sweden
October 20, 2009
Ice Sheet Mass Balance Primary Objective of ICESat

- Measure ice-surface elevation changes \((dH/dt)\) from repeat measurements of elevation profiles along precise repeat tracks (minimal cross-track spacing) and at orbital crossovers.

- Derive spatially averaged elevation changes \((dH/dt)\).

- Convert volume changes \((dH/dt \times \text{area})\) to mass changes \((dM/dt)\).
  - Correct for variable firn compaction (temperature driven).
  - Calculate effective density for \(dH(A(t))/dt\) due to trends in precipitation.
  - Correct for modeled bedrock motion \(dB/dt\).
ICESat-1: Geoscience Laser Altimeter System (GLAS)

- 1064 nm (red) laser beam for surface altimetry (10 cm accuracy and 2 cm precision) and clouds and aerosols (75 m)
- GPS for precision orbits (2 cm)
- Precision laser attitude system (2 arc sec, 6 m horizontal)
- ~ 65 m footprint spaced at 172 m (50 HZ PRF)
- 532 nm laser beam for thin clouds and aerosols
ICESat was designed to operate a laser continuously for 3 to 5 years

**ICESat Operating History 16.5 campaigns to date**

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**Figure 23:** Completed and Planned Campaigns

Laser stop fire anomaly
Laser accurately measures total freeboard (F), i.e. elevation of snow and ice above ocean reference level.

Sea ice thickness ($T_i$) is estimated from freeboard using estimates of snow cover and buoyancy calculations.

CRYOSAT radar altimetry will provide similar measurements mostly to snow/ice interface and ocean reference.

Obtaining sea ice thickness has been major challenge in sea ice science.

ICESat has been providing comprehensive mapping of sea ice freeboards and estimates of sea ice thickness distributions.

Thermodynamics
- Freezing
- Melting

Mechanics
- Leads from divergence
- Thermo-dynamic mode
- Deformed ice

Thermo-dynamic mode
- Open Water
- Leads from divergence
- Deformed ice
- Ridges from convergence

[Diagram showing sea ice freeboard and thickness from altimetry]
High interannual variability of sea ice thickness in the Arctic region

Seymour Laxon, Neil Peacock & Doug Smith

Figure 1. Average winter (October to March) Arctic sea ice thickness from October 1993 to March 2001 from satellite altimeter measurements of ice freeboard. Data are not available in the marginal ice zone, or above the ERS latitudinal limit of 81.5° N. Ice freeboard is converted to thickness using fixed ice, snow and water densities and regional monthly snow depth. The mean thickness excludes thin ice (less than 0.5–1 m) and open water.

Figure 2. Comparison between satellite altimeter- and submarine-derived ice thickness in the Beaufort Sea during the 1990s. Submarine thicknesses are shown for each of the 50-km segments gathered during the four missions during the 1990s. Altimeter thickness
ICESat sea ice elevations

- Illustrates 2 cm range precision of ICESat.
- Precision is important, because mean freeboard is about 30 cm.

Ron Kwok, JPL
Near-coincident ICESat and RADARSAT Data Over Arctic Sea Ice

RADARSAT image of sea ice

ICESat track

New lead with thin ice

*Reference thickness estimated using ice age from RGPS

Δt = 1.2 days

Kwok, Zwally, & Yi, GRL Aug 2004
Multiyear ice
First year ice

mean freeboard: 0.258 m
mean freeboard: 0.506 m
ICESat-1 Sea Ice Measurements

Freeboard

Feb 20-Mar 29, 2003

Mean = 0.30 m

Thickness

Mean = 1.96 m
Comparison with ice draft along submarine track (Nov 2005)

**Trends in winter sea ice thickness from ICESat**

**MY fraction**

0.0 1.0

**MY Area (10^3 km^2)**

![MY Area Graph]

**Thickness (m)**

![Thickness Graph]

- **Trend = -0.17 m/yr**
- **Ice volume** is decreasing faster than **ice area** because both **thickness** and **area** are decreasing.

(Kwok et al., 2009)
ICESat thickness estimates extend the record previously obtained by submarine sonar showing major loss in ice thickness in central Arctic Ocean.
Decline in Age and Thickness of Arctic Sea Ice


- Oldest and thickest multiyear ice has declined significantly.
- Remaining ice is thinner and more vulnerable to increasing summer melting.

Sea Ice Thickness/Age Relationship

Ice Age from tracking model

Ice thickness from ICESat

Takes about 7 years to grow 3 to 4 m multiyear ice.

Thinner ice is only 1 to 2 years old.
While the area of sea ice at the end of the summer has been declining at an increasing rate (-4.7%/yr), the thickness has been decreasing at a similar rate (-5.3%/yr) (2003 to 2007 rates).

Therefore, the volume of sea ice has been decreasing even faster (-8.8%/yr) than the area. (2003 to 2007 rates).

A large area of former perennial ice pack from the Beaufort to Laptev Seas is now a seasonal sea ice zone.

Most of the sea ice thicker than 2 m has disappeared throughout the Arctic Ocean.

Remaining perennial pack is thinner and more vulnerable to disappearance in summer.

In 2008 and 2009 sea ice AREA has rebounded some, but not THICKNESS in 2008 and ??2009??
Quantify polar ice sheet mass balance to determine contributions to sea level rise and the linkages to changing climate.

Determine seasonal changes, interannual variability, and long-term trends.

Determine topographic character of ice sheet changes to assess mechanisms driving ice change and improve predictive ice sheet models.

Estimate sea ice thickness to examine ice/ocean/atmosphere exchanges of energy, mass and moisture.

Determine seasonal changes, inter-annual variability, and long-term trends.

Measure vegetation canopy height for estimating large-scale land biomass and biomass change.
ICESat-2 Laser Measurement Options

ICESat-1

Single Beam:
1 main laser beam
(GLAS class)

CTC Option A:
Multiple laser beams
(GLAS class)

CTC Option B:
1 main laser beam (GLAS Class)
1 CTC laser split into 8 to 16 beamlets

CTC Option C:
1 CTC laser split into 8 to 16 beamlets

High-rep laser (e.g., 20 kHz) with photon-counting detectors
Airborne Scanning Lidar (Sigma Space Corp.)

-This preliminary flight image was obtained on a single overflight just after noon from an altitude of 1800 ft.
ICESat-1 (2003 – 2009?)
ICESat-2 (2015 – 2020)

Unique Laser Missions for Multidisciplinary Earth Science