Reducing Uncertainty in Ice Thickness Estimation from Space-borne and Airborne Altimetry

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Dedicated to Seymour Laxon and Katharine Giles

Uncertainty in Estimating Sea Ice Thickness


Photo Credit: Larry Connor


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Context

Major Motivation and Goals:

- **Measure** seasonal, interannual, and decadal change

  in Arctic & Southern Ocean sea ice thickness and volume

  - regional and basin scale (km scale)

- **Understand** nature of these change

  - regional and basin scale (km scale)

- **Improve** predictability of Arctic sea ice

  - basin scale (model validation)

  - regional and high resolution (~ m scale) (model parameterizations)

Available Data Sets

Available Altimetric Data Sets for Sea Ice:

- **NASA's polar orbiting laser altimeters**:
  GLAS (ICESat, 2003 – 2009); **ATLAS** (ICESat-2, 2016/17 – 2020)
- **Airborne Lasers**:
  ATM (OIB); **LVIS**; **MABEL; SIMPL**; Riegl lidars (NRL/NOAA)
- **ESA's polar orbiting radar altimeters**:
  RA-2 (ERS-1, 1991-2000; ERS-2, 1995 – 2003, Envisat 2002-2012);
  SIRAL (CryoSat-2, 2010 – ongoing); **SRAL** (Sentinel-3, 2014/15)
- **CNES/ISRO**: **SARAL** (Altika, 2013 – ongoing);
- **Airborne Radars: OIB/Kansas FMCW Snow Radar**; **Ku-band radar altimeter**

Primary Validation Data Sets for Sea Ice:

- **EM Bird** (electromagnetic sounding)
- **In Situ / Direct Measurements**
- **Imagery** (visible band, SAR, etc.)
- **ULS**
- **Ice Mass Balance Buoys**
- **Other remote sensing data**

Deriving Sea Ice Thickness & Resulting Data Products

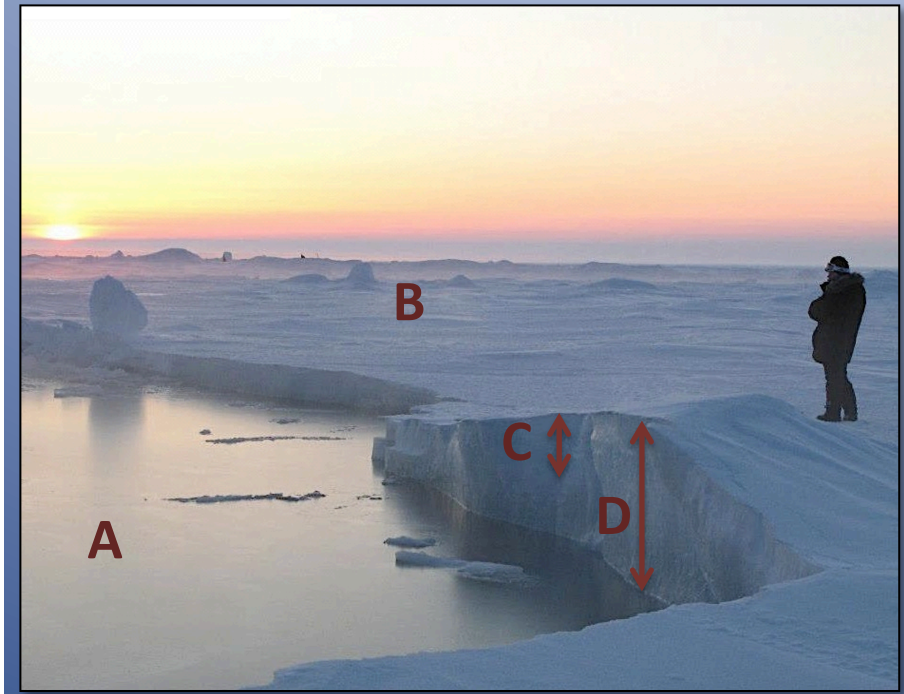


Photo Credit: Andrew Roberts, SEDNA 2007

Altimetric Measurements

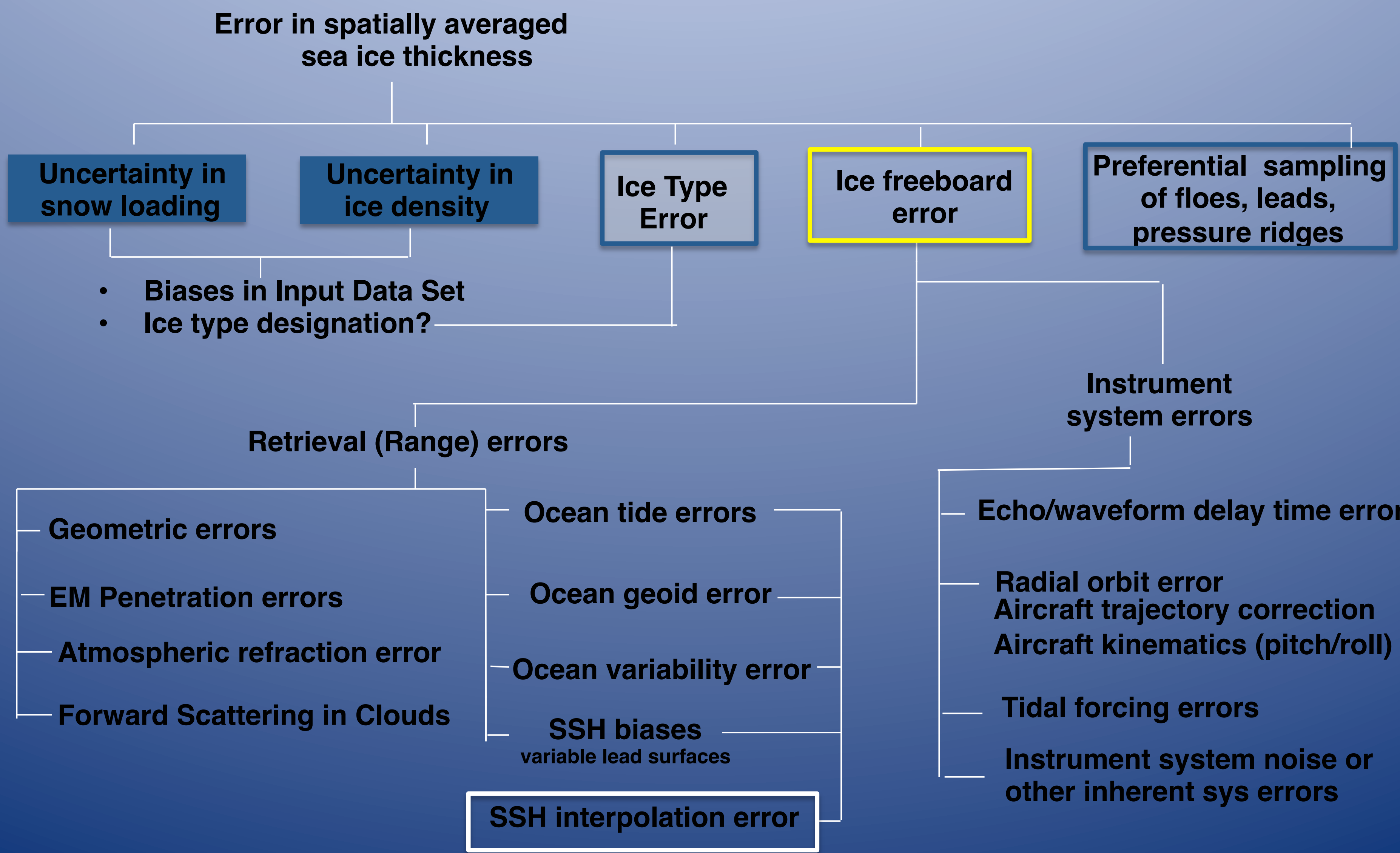
(Based on waveform discrimination and fitting)

- **(A)** Lead Elevation: sea surface height
- **(B)** Floe Elevation: sea-ice surface topography and roughness
- **(C)** Snow Depth (& uncertainty): direct measurement by Kansas OIB snow radar

Derived Products:

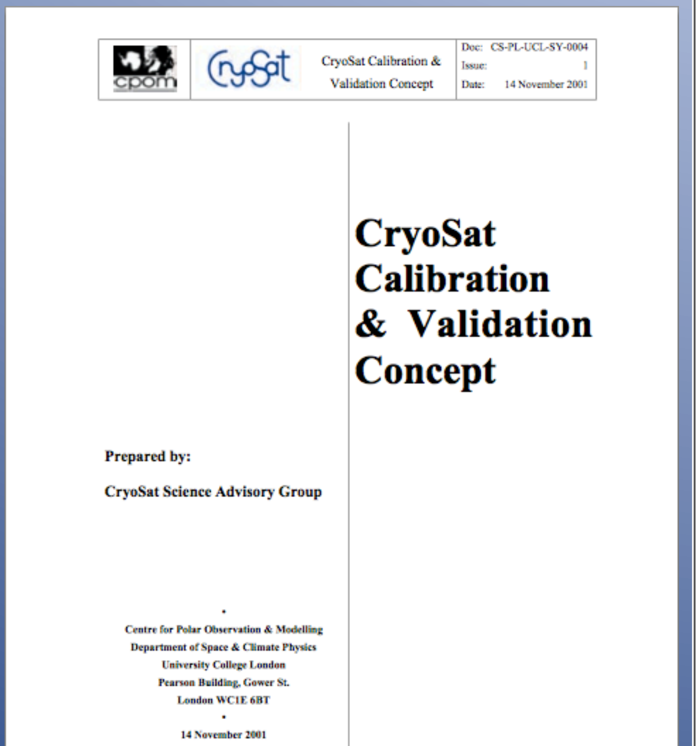
- **(D)** Mean Freeboard (& uncertainty) **(B-A)**
- Ice Thickness (& uncertainty) **(C, D)**
- Ice Volume (ice conc.)
- Gridded, monthly or seasonal mappings of sea ice thickness, interannual change

Contributions to Uncertainty in Altimetric Sea Ice Thickness



Adapted From: *CryoSat Sci. Advisory Group* (2001), CryoSat Calibration and Validation Concept

Breakdown of Sea Ice Thickness Uncertainty



		CryoSat Calibration & Validation Concept	Doc: CS-PL-UCL-SY-0004 Issue: 1 Date: 14 November 2001

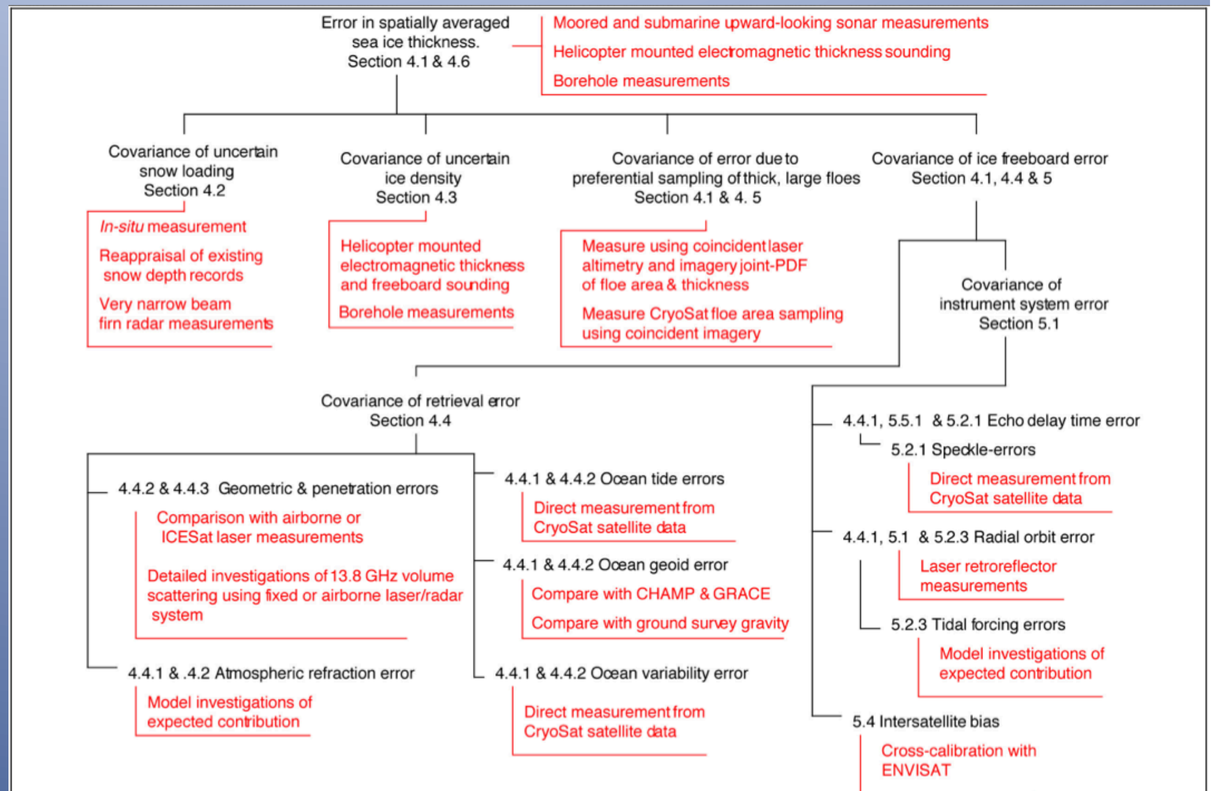
CryoSat Calibration & Validation Concept

Prepared by:

CryoSat Science Advisory Group

Centre for Polar Observation & Modelling
Department of Space & Climate Physics
University College London
Pearson Building, Gower St.
London WC1E 6BT

14 November 2001



From: Wingham, D. J. and CryoSat Science Advisory Group (***2001***)
“CryoSat Calibration and Validation Concept”

Estimating Sea Ice Thickness Uncertainty

- Giles et. al. 2007

("Combined airborne laser and radar altimeter measurements over the Fram Strait in May 2002", RSE)

- Radar

$$\varepsilon_{\mathrm{r}}^2 = \varepsilon_{\mathrm{fi}}^2 88.56 + \varepsilon_{\mathrm{hs}}^2 8.62 + \varepsilon_{\rho \mathrm{s}}^2 8 \times 10^{-6} + \varepsilon_{\rho \mathrm{w}}^2 9.79 \times 10^{-4} + \varepsilon_{\rho \mathrm{i}}^2 1.16 \times 10^{-3}$$

$$\varepsilon_{\mathrm{r}}^2 = 0.08 + 0.10 + 6.8 \times 10^{-5} + 2.5 \times 10^{-4} + 2.9 \times 10^{-2}$$

$$\varepsilon_{\mathrm{r}} = 0.46m$$

- Laser

$$\varepsilon_{\mathrm{l}}^2 = \varepsilon_{\mathrm{fs}}^2 88.56 + \varepsilon_{\mathrm{hs}}^2 41.92 + \varepsilon_{\rho \mathrm{s}}^2 8 \times 10^{-6} + \varepsilon_{\rho \mathrm{w}}^2 9.8 \times 10^{-4} + \varepsilon_{\rho \mathrm{i}}^2 1.6 \times 10^{-3}$$

$$\varepsilon_{\mathrm{l}}^2 = 0.04 + 0.51 + 6.8 \times 10^{-5} + 2.5 \times 10^{-4} + 2.9 \times 10^{-2}$$

$$\varepsilon_{\mathrm{l}} = 0.76m.$$

Example: IceBridge sea ice thickness uncertainty

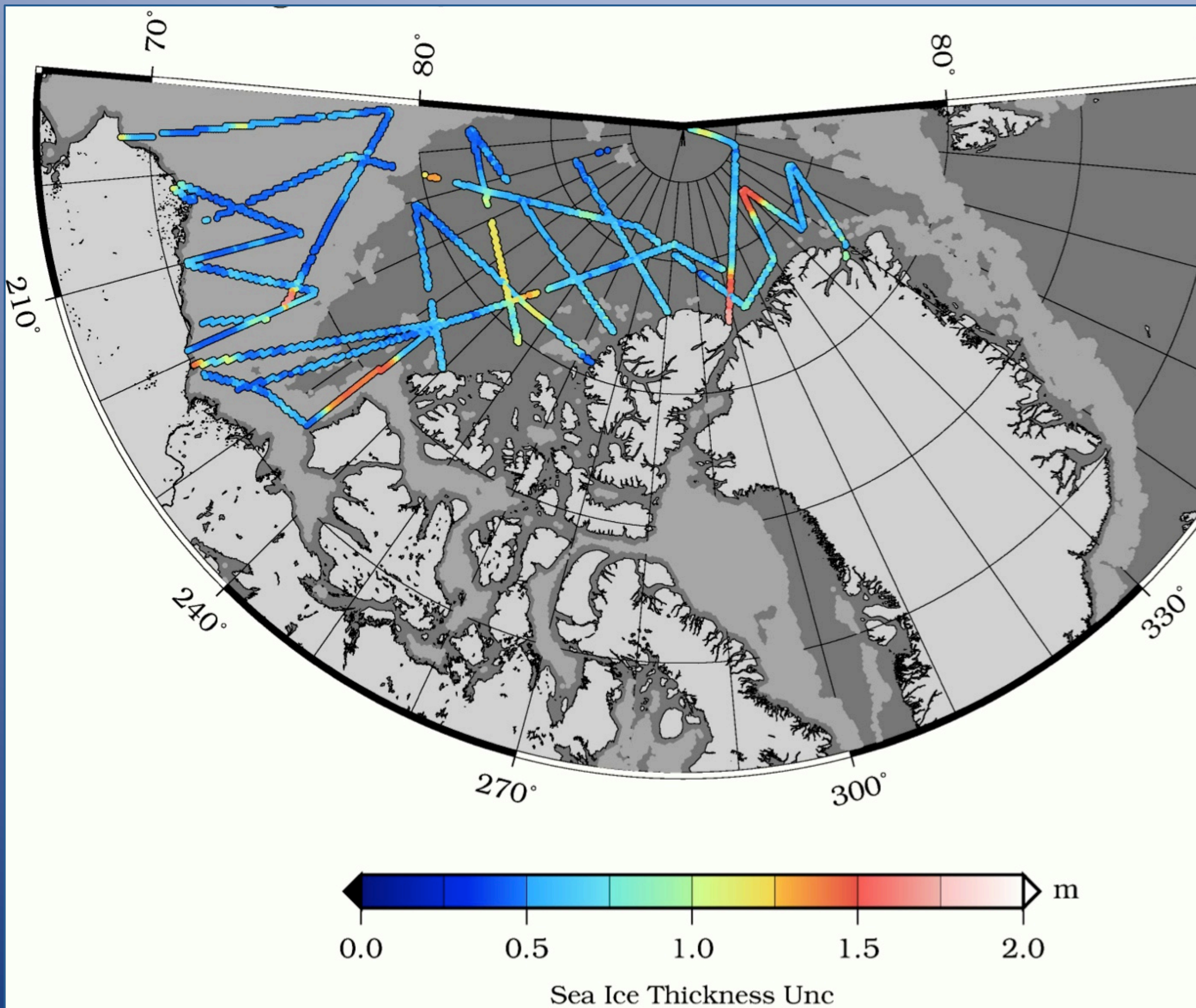
- Average ice thickness uncertainty in the IceBridge data **~ 0.65 m**
- Formally calculated includes freeboard & snow depth uncertainty (constant)
  - Prevalence of leads therefore major contributing factor
  - See Kurtz et al (2013) for detailed description of uncertainty estimation

$$\sigma_{h_i} = \left[\left(\frac{\rho_w}{\rho_w - \rho_i} \right)^2 \sigma_{h_f}^2 + \left(\frac{\rho_s - \rho_w}{\rho_w - \rho_i} \right)^2 \sigma_{h_s}^2 + \left(\frac{h_s(\rho_s - \rho_w) + h_f \rho_w}{(\rho_w - \rho_i)^2} \right)^2 \sigma_{\rho_i}^2 + \left(\frac{h_s}{\rho_w - \rho_i} \right)^2 \sigma_{\rho_s}^2 \right]^{\frac{1}{2}}$$

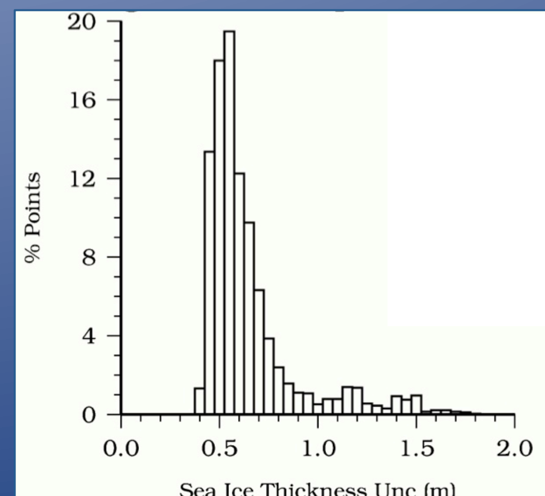
- **Uncertainty has decreased with time**
  - improvements in instrumentation and processing techniques ?
  - discarding data with a freeboard uncertainty of > 0.1 m.

IceBridge Campaign	Mean Thickness Uncertainty (m)	Mode (m)	Uncertainty Range (m)	Discarded %
2009	**0.71 ± 0.19**	0.66	0.38 - 3.54	**48**
2010	**0.66 ± 0.18**	0.55	0.37 - 2.00	**37**
2011	**0.66 ± 0.17**	0.56	0.38 - 2.39	**20**
2012	**0.70 ± 0.17**	0.63	0.38 - 2.60	**16**
2013	**0.59 ± 0.15**	0.50	0.38 - 2.58	**9**

Sea Ice Thickness Uncertainty (σh_i) – March/April 2013



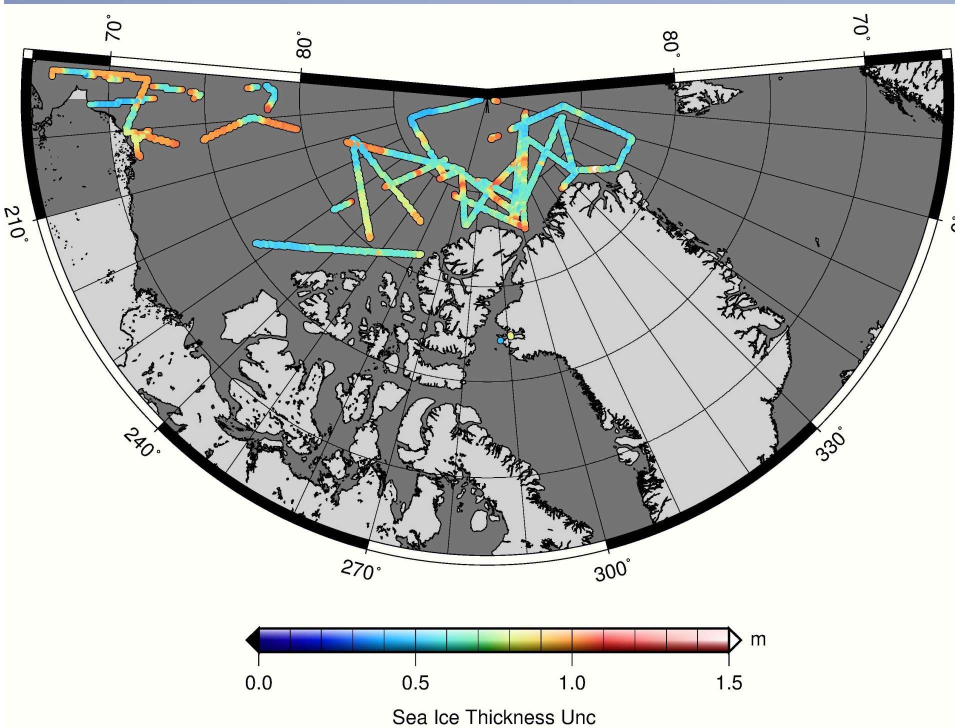
- ✧ **Varies Spatially**
- ✧ **Driven by SSH interpolation error/ leads**
- ✧ **Since snow depth error is held constant at 6 cm**
- ✧ **Mean Ice Thickness Uncertainty: <u>0.65 ± 0.24 m</u>**



nsidc.org/data/docs/daac/icebridge/evaluation_products/sea-ice-freeboard-snowdepth-thickness-quicklook-index.html

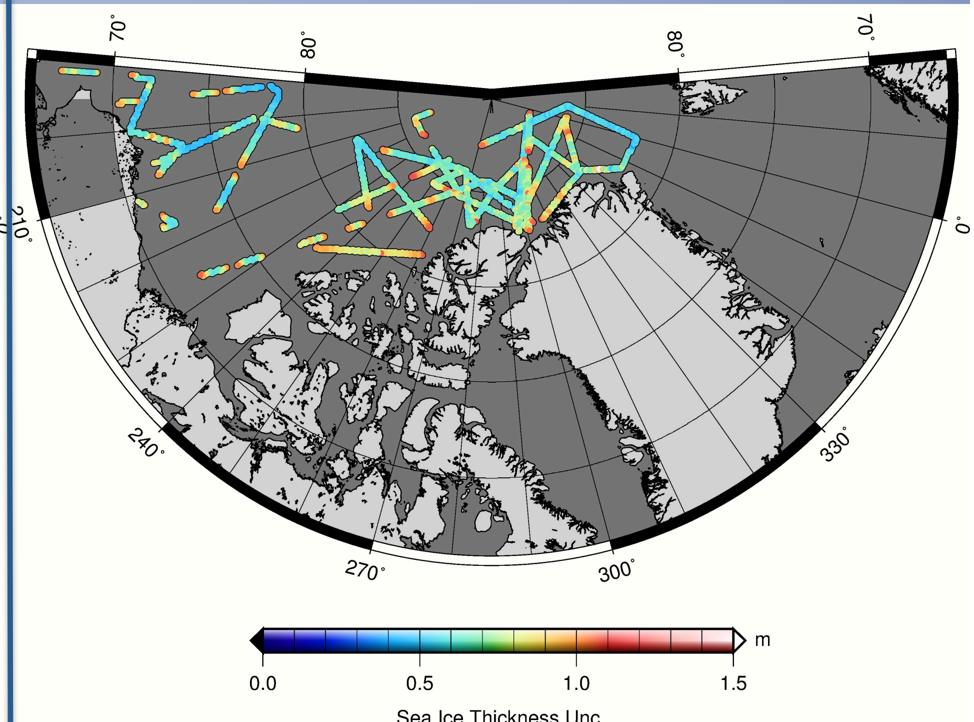
Sea Ice Thickness Uncertainty (σh_i) – March/April 2012

✧ 2012 Standard/Final Product at NSIDC



Mean SIT_Unc: **0.86 m ± 0.37 m** (# 323538)
After filtering:
Mean SIT_Unc: **0.72 m ± 0.19 m** (# 259045)

✧ 2012 Quick Look Product at NSIDC



Mean SIT_Unc: 0.81 m ± 0.32 m (# 344386)
After filtering
Mean SIT_Unc: 0.70 m ± 0.17 m (# 288115)

Filtering = discard data with freeboard uncertainty of > 0.1 m