# Comparing Coincident Elevation and Freeboard of IceBridge ATM, Cryosat-2, and Sentinel-3 over Arctic Sea Ice

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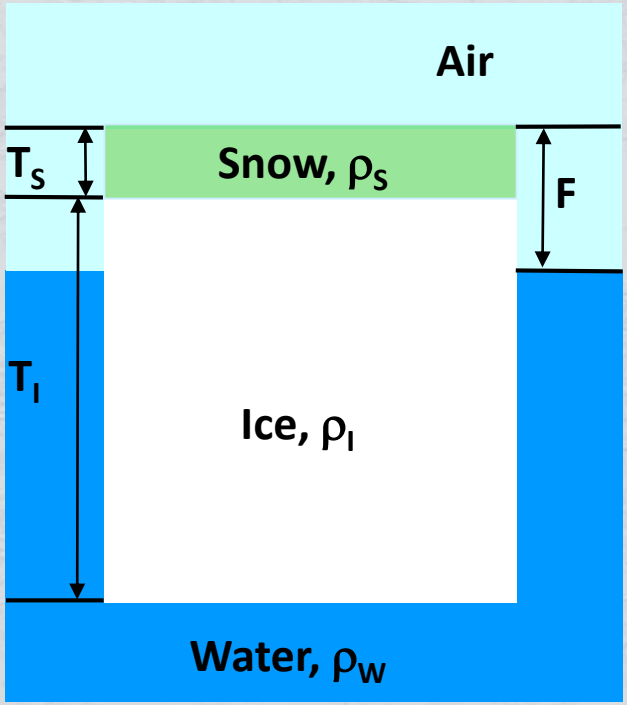
# Sea Ice Elevation, Freeboard, and Thickness




**How good are the assumptions?**

**ATM/ICESat-2:** Air/Snow boundary and Air/Water boundary

**Cryosat-2/Sentinel-3:** Snow/Ice boundary and Air/Water boundary

**Snow Thickness:** $H_{laser} - H_{radar}$
OIB Snow radar, AMSR-E, Climatology, Models

**Archimedes' principle**

Sea Ice Thickness $T_I$ is a function of Freeboard F and Snow Thickness $T_S$ :

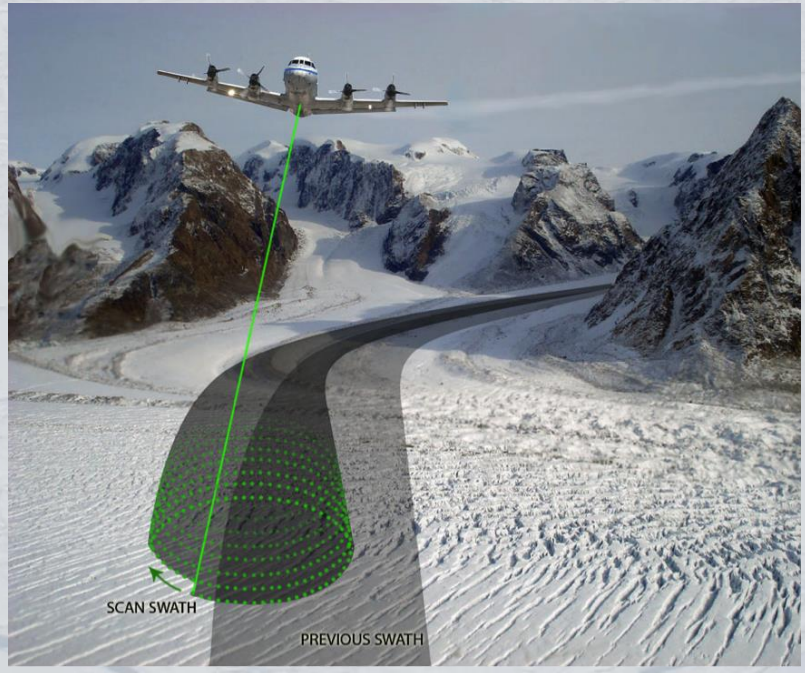
$$T_I = \rho_W/(\rho_W - \rho_I) \times F - (\rho_W - \rho_S)/(\rho_W - \rho_I) \times T_S$$

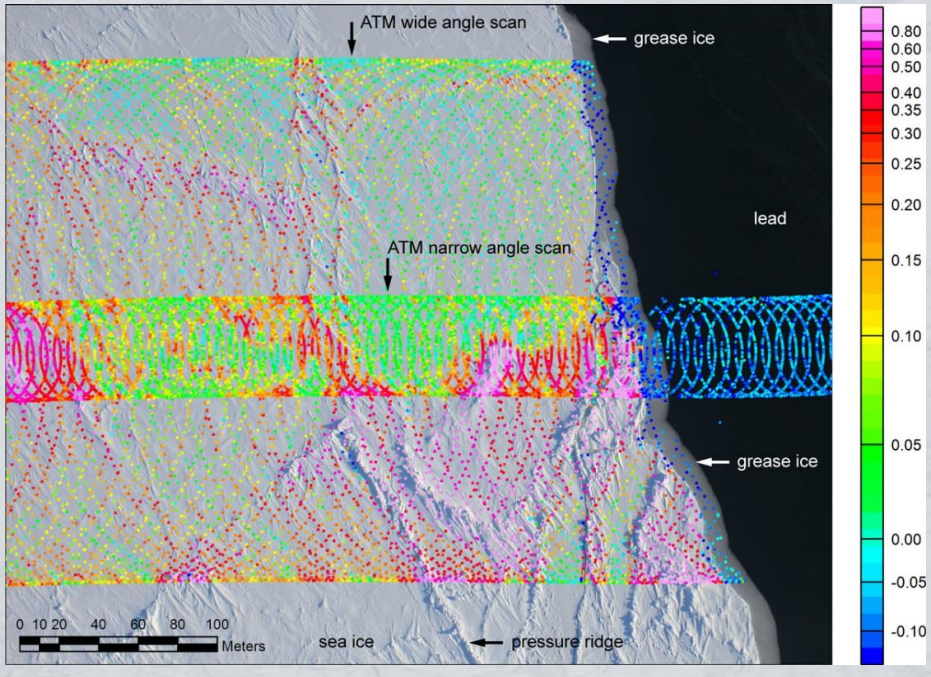
$$T_I = 9.411 \times F - 6.653 \times T_S$$

# Airborne Topographic Mapper (ATM)

## Two conical scanning laser altimeters:

| Off-nadir Scan Angle | Swath Width at 1500 ft AGL | Wavelength | Footprint at 1500 ft AGL | Elevation Accuracy/ Precision |
|---|---|---|---|---|
| 15° - wide | 250 m | 532 nm | 1 m | < 7 cm / 8 cm Brunt et al., 2017 |
| 2.5° - narrow | 40 m | 532 nm | 1 m | < 7 cm / 3 cm |



# ATM, Cryosat-2, Sentinel-3, and ICESat-2

Operation IceBridge ATM, 2009 - 2019

CryoSat-2, 2010 - present

Sentinel-3, 2016 - present

ICESat-2, 2018 - present

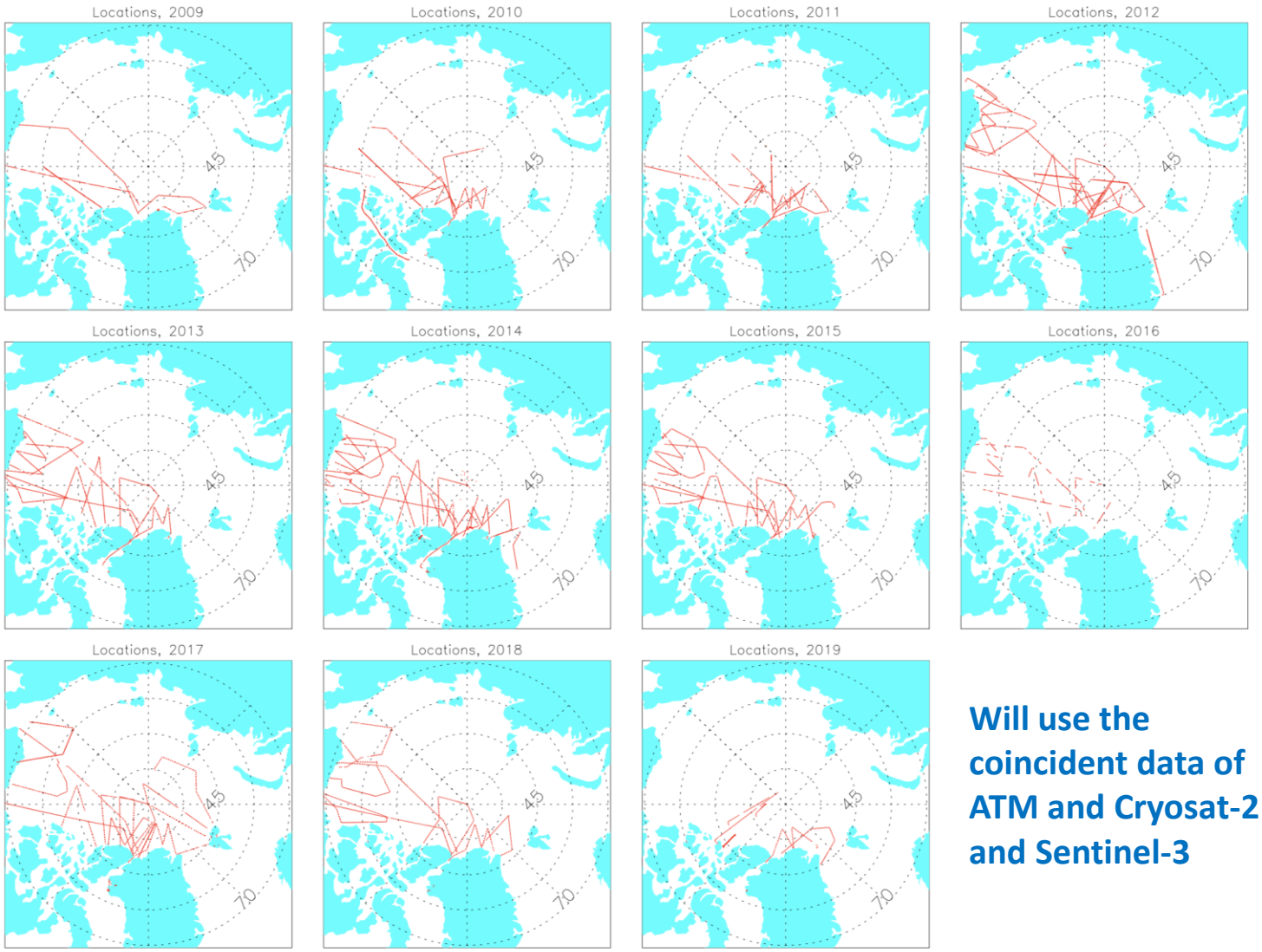
**Data to be compared:**

- Coincident ATM elevations, freeboard, IceBridge Snow depth
VS
Cryosat-2/Sentinel-3 elevations and freeboards
(Standard Cryosa-2/Sentinel-3 data products and **Fully Focused SAR results**)

- Coincident Cryosat-2 and ICESat-2 elevations and freeboards

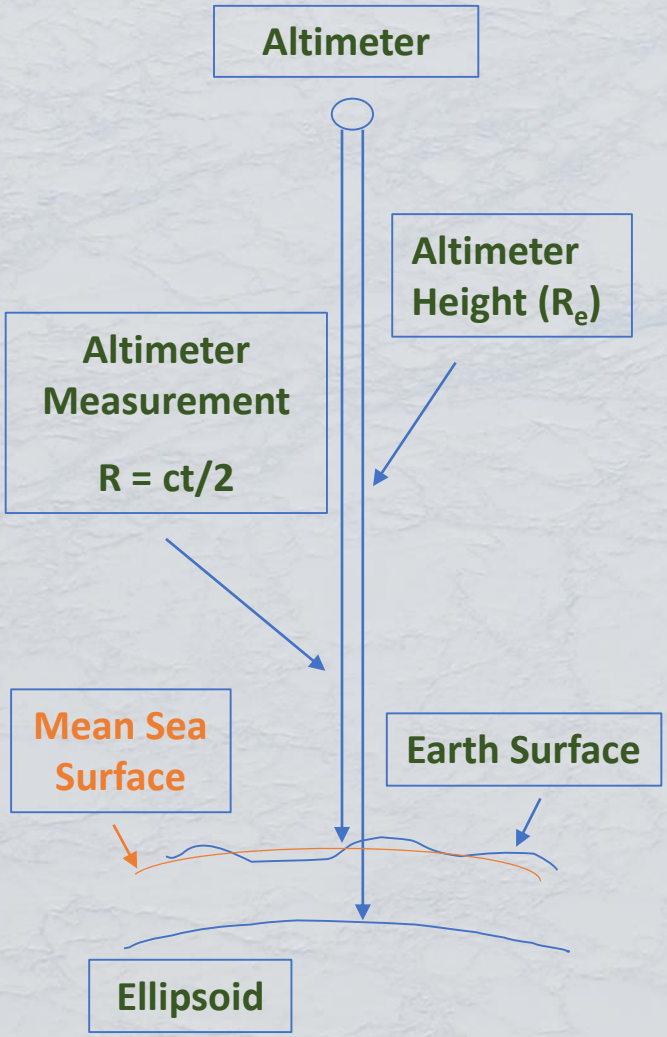
- CRISTAL data in the future

# ATM data coverage (2009-2019)




**Will use the coincident data of ATM and Cryosat-2 and Sentinel-3**

# Surface Elevation




## Sea Surface Elevation

$$H = h_e - h_{mss} - h_{st} - h_{ot} - h_{lt} - h_{pt} - h_{dac}$$

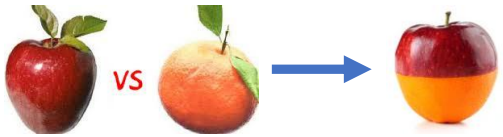
$h_e$: elevation reference to ellipsoid (WGS84)

$h_{mss}$: mean sea surface reference to $h_e$ (DTU18MSS: including $h_{geoid}$ and $h_{dynamic\_topography}$)

$h_{st}$, $h_{ot,}$ and $h_{lt}$ are solid earth tide, ocean tide, and load tide

$h_{pt}$: permanent tide

$h_{dac}$: dynamic atmospheric correction




Identical ellipsoid, geoid model, tide model, and dynamic atmospheric corrections for CryoSat-2, Sentinel-3, ICESat-2, and IceBridge data to eliminate elevation biases due to their differences.

# Methods

## To derive Cryosat-2/Sentinel-3 elevation and freeboard:



### Fully Focused SAR Altimetry: Theory and Applications

Alejandro Egido, *Member, IEEE*, and Walter H. F. Smith

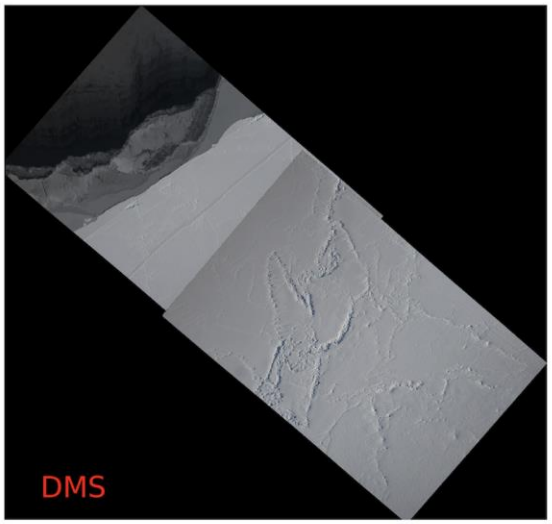
## To compare elevation and freeboard:

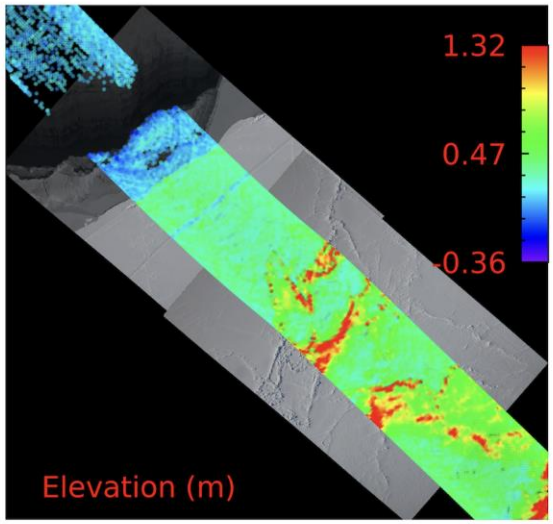


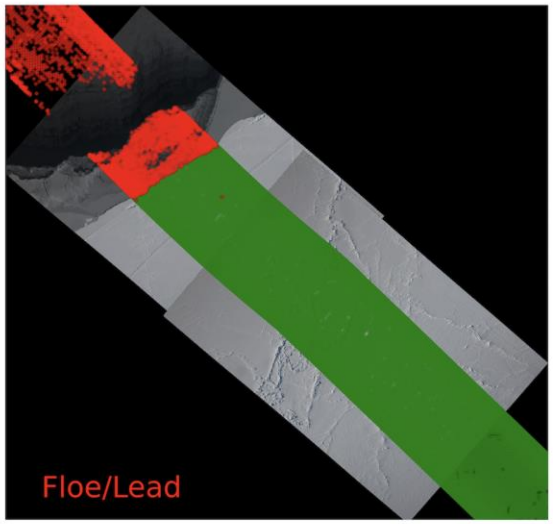
### Comparing Coincident Elevation and Freeboard From IceBridge and Five Different CryoSat-2 Retrackers

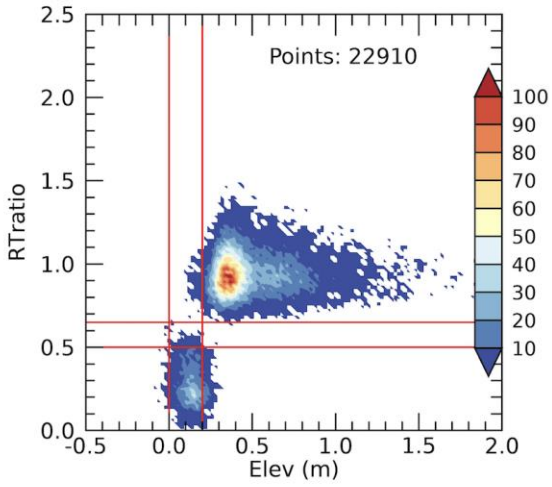
Donghui Yi, Nathan Kurtz, Jeremy Harbeck, Ron Kwok, Stefan Hendricks, and Robert Ricker

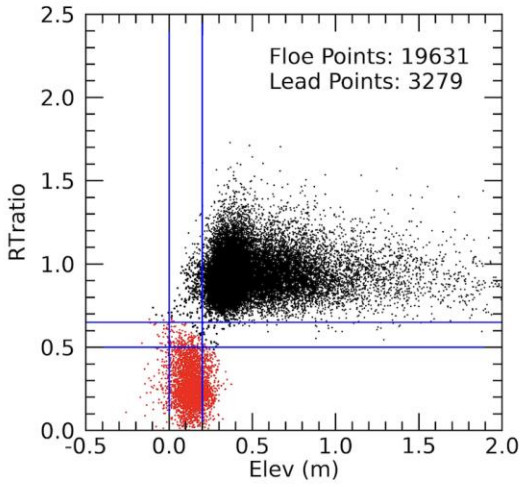
# ATM Cluster Analysis – Separate floe and lead

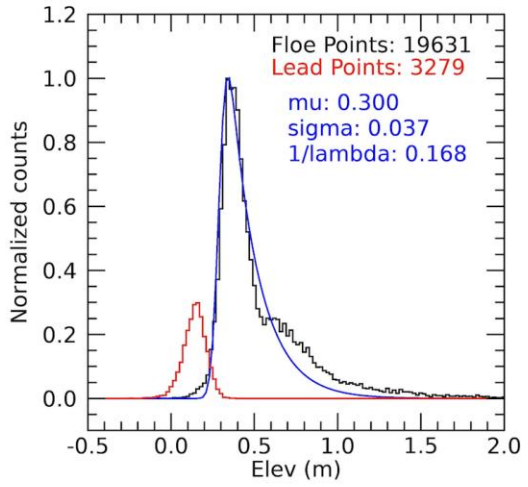


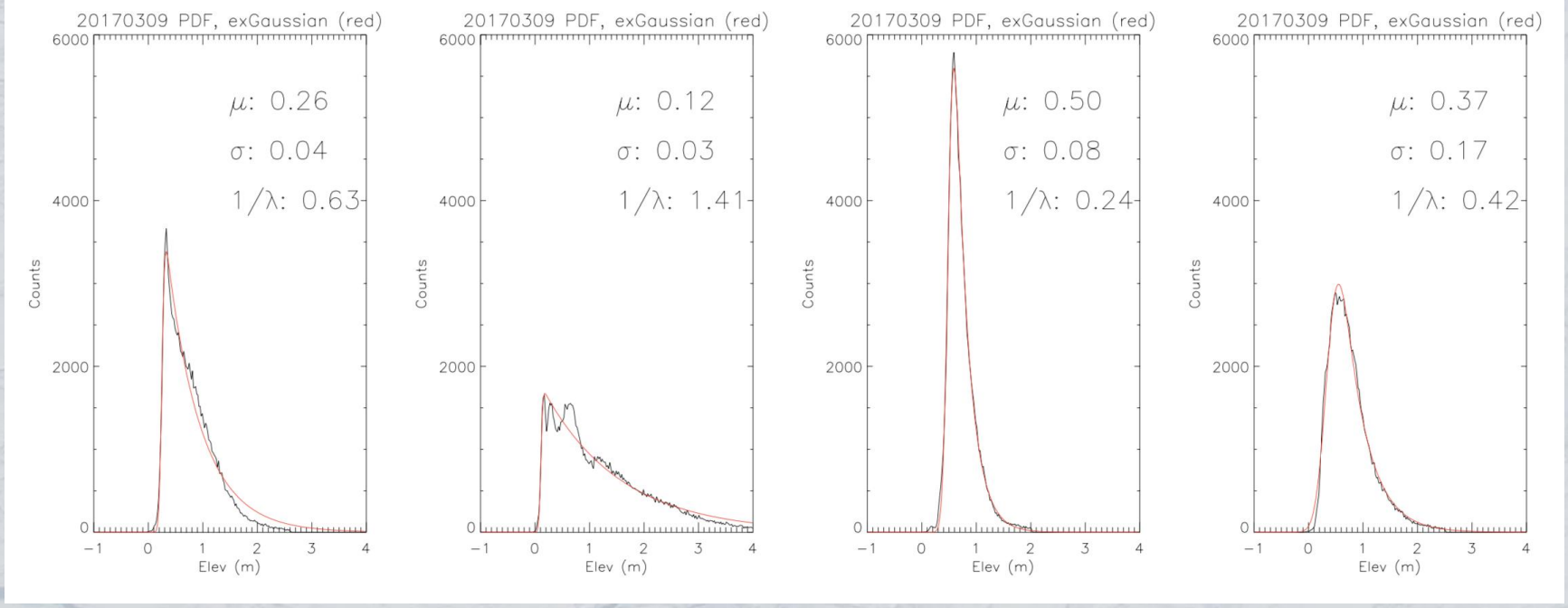



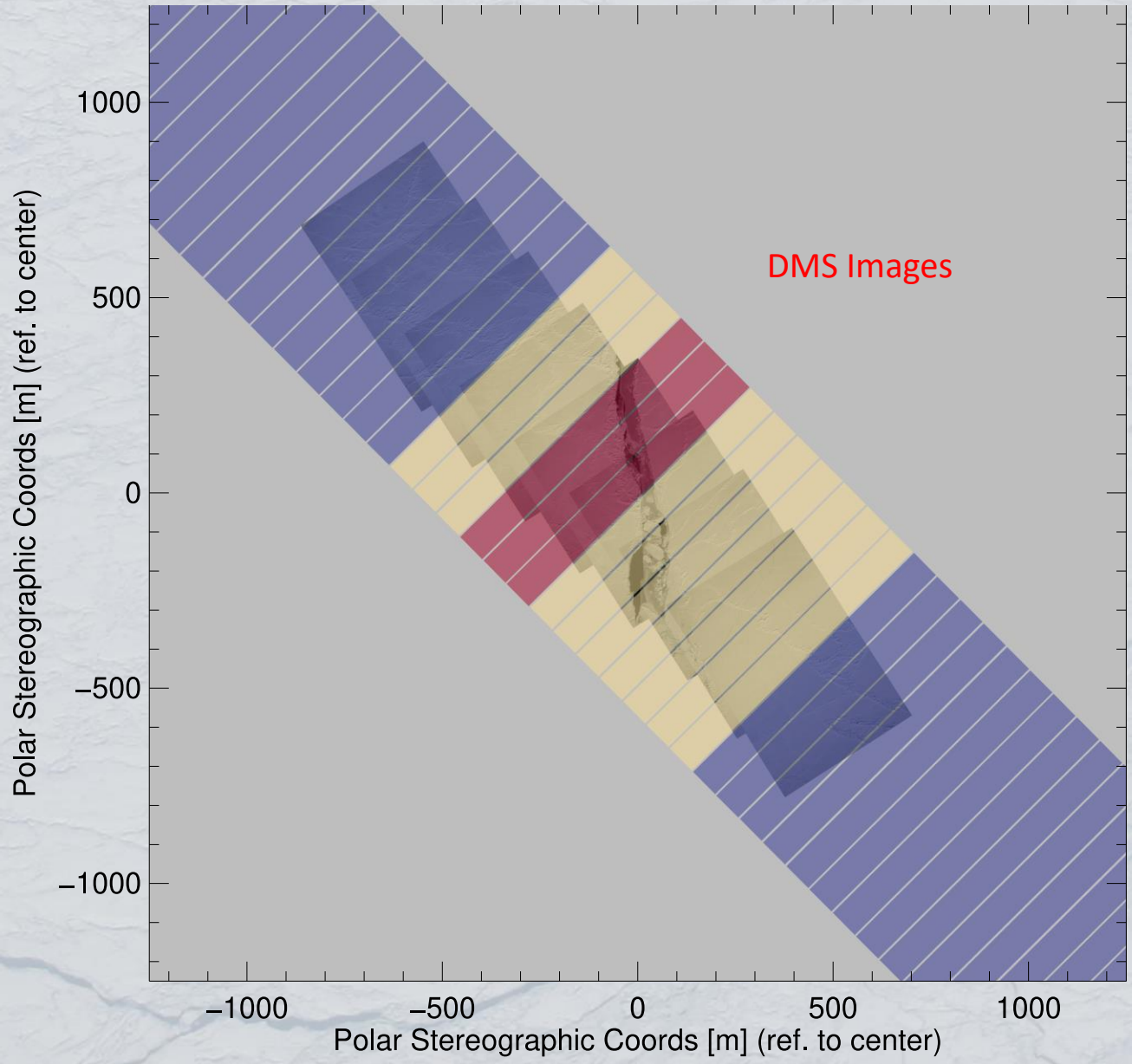
# ATM elevation PDF and exGaussian fitting

**The probability density function (PDF) of the surface height is calculated from ATM elevation and modeled using the probability density function of the exponentially modified normal distribution (exGaussian),**

$$f(x;\mu,\sigma,\lambda) = \frac{\lambda}{2} e^{\frac{\lambda}{2}(2\mu+\lambda\sigma^2-2x)} \, erfc\left(\frac{\mu+\lambda\sigma^2-x}{\sqrt{2}\sigma}\right)$$



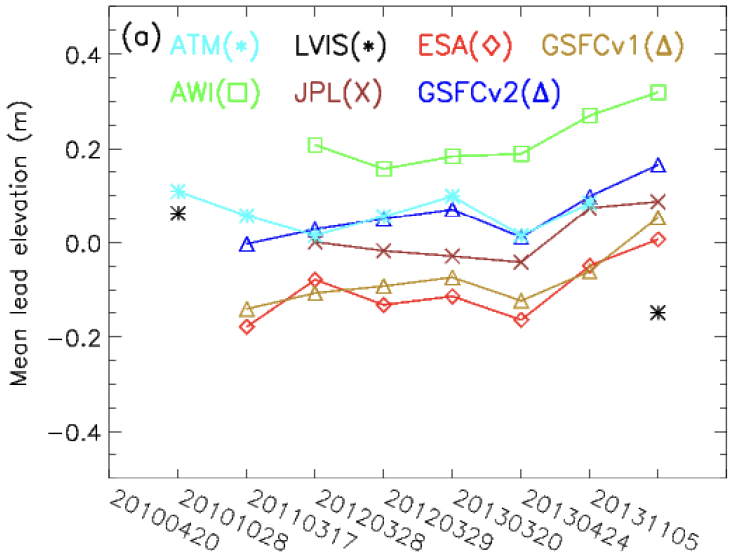
# SAR Waveform Classification

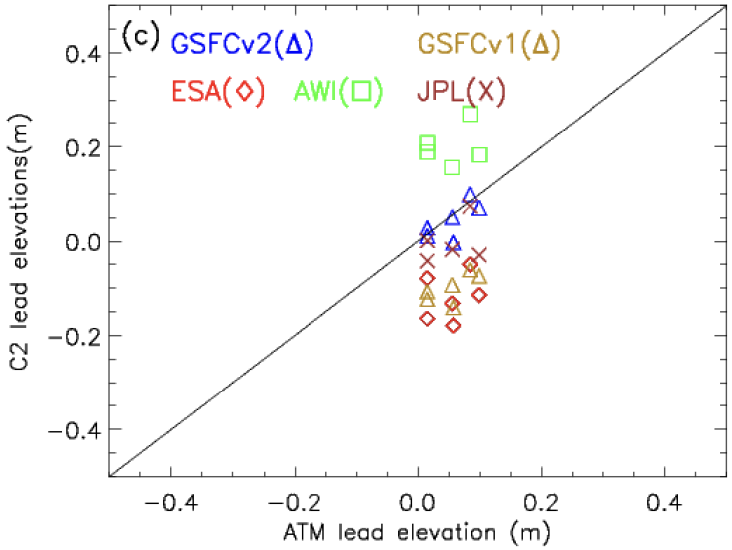



Sea Ice Lead
Ambiguous
Sea Ice Floe

SAR Waveform classification results based on ZD-ON Ratio, represented over DMS imagery. S3A underflight, April 21, 2016

# ATM VS Cryosat-2 retrackers (Yi et al, 2019 )




## Mean lead elevation

The five Cryosat-2 retrackers used are:

- ESA (Laxon et al, 2013)
- GSFCv1 (Kurtz et al, 2014)
- AWI (Ricker et al, 2014)
  - (there is an new version)
- JPL (Kwok and Cunningham, 2016)
- GSFCv2 (an improved version of GSFCv1)

These retrackers show distinct differences in mean elevation up to 0.45 meters over leads.

**Elevation is retracker dependent!**

# Mean floe elevation (Yi et al, 2019 )

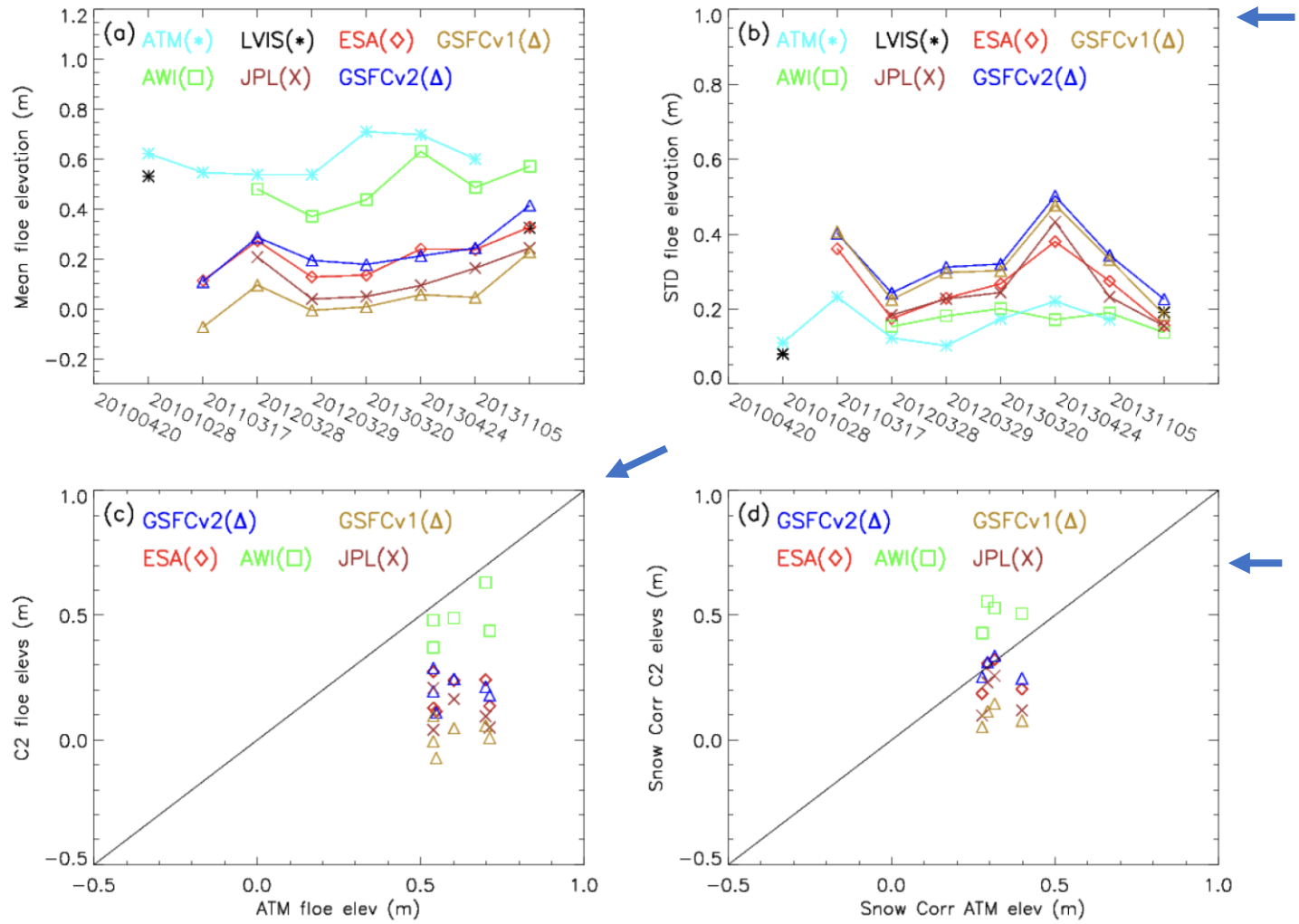



Fig. 6. (a) Mean floe elevation, (b) STD of floe elevation, (c) CryoSat-2 floe elevation versus ATM floe elevation, and CryoSat-2 versus ATM elevation at the snow/ice interface (d).

**(a), (c) Original elevation;**

**These retrackers show distinct differences in mean elevation up to 0.75 meters over floes.**

**(d) Snow/ice interface**

**ATM - Snow depth**

**Cryosat-2 + 0.2191 × snow depth (speed of light Correction)**

# Mean freeboard (Yi et al, 2019 )

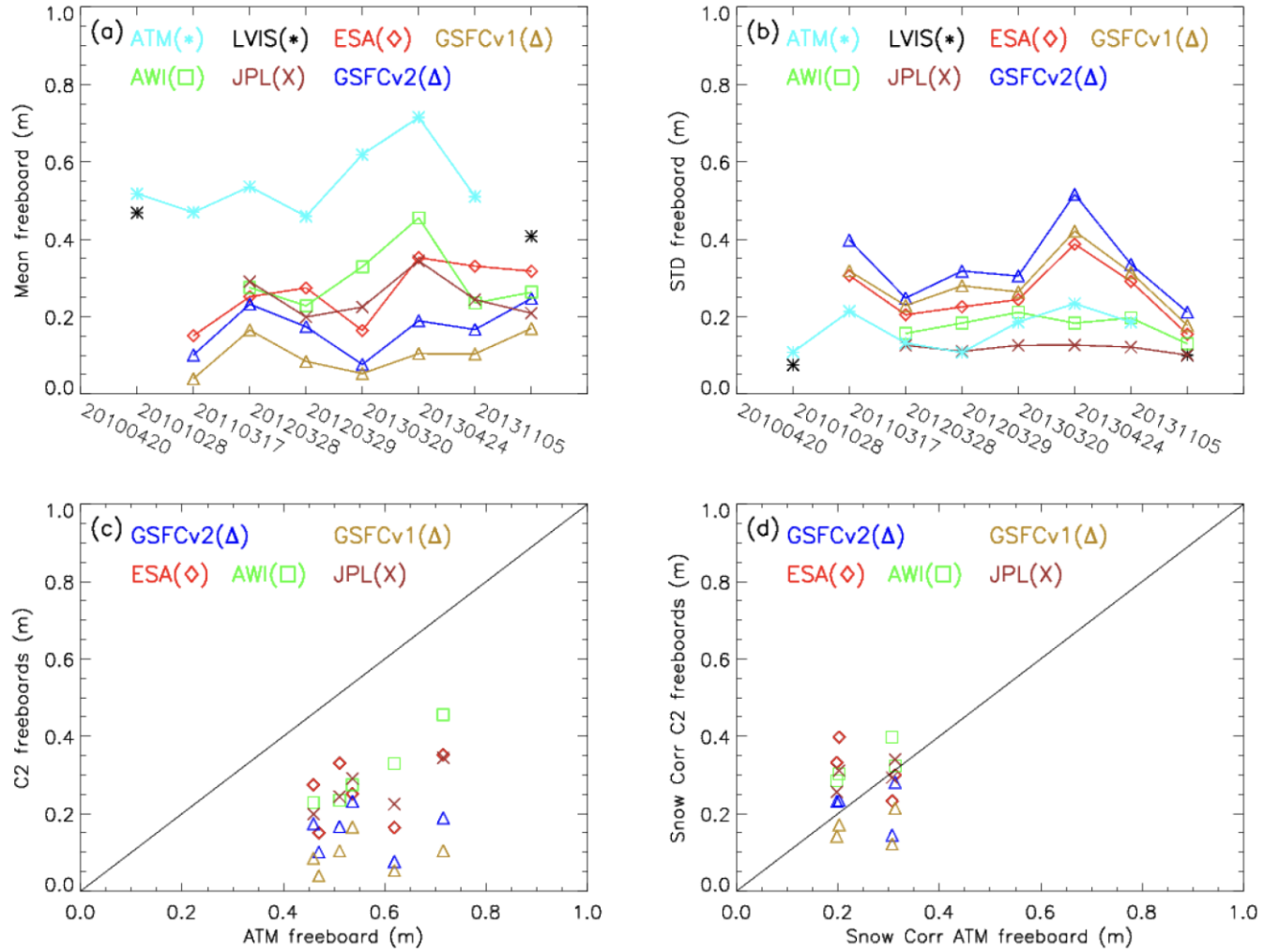



Fig. 7. (a) Mean freeboard, (b) STD of freeboard, (c) CryoSat-2 freeboard versus ATM freeboard (c), and (c0CryoSat-2 versus ATM freeboard at the snow/ice interface (d).

**Snow/ice interface**

**ATM – Snow depth**

**Cryosat-2 + 0.2191 × snow depth (speed of light Correction)**

**Mean Cryosat-2 - ATM: -0.03, 0.04, 0.06, 0.07, and -0.09 meters.**

# Summary

Radar altimeter sea ice elevation and freeboard are retracker dependent. Since sea ice freeboard retrieval methods use relative elevations, the freeboard biases are less than floe elevation biases between the retrackers.

Snow depth can be estimated by Laser – Radar freeboard and it is also retracker dependent.

We believe Fully Focused SAR technique will improve Cryosat-2/Sentinel-3 waveform retracking and will compare ATM elevation and freeboard with FFSAR results for calibration/validation.

Similar technique can be used for Cryosat-2/ICESat-2 data comparison and maybe for future CRISTAL data analysis.