Measuring Snow Depth in the Arctic

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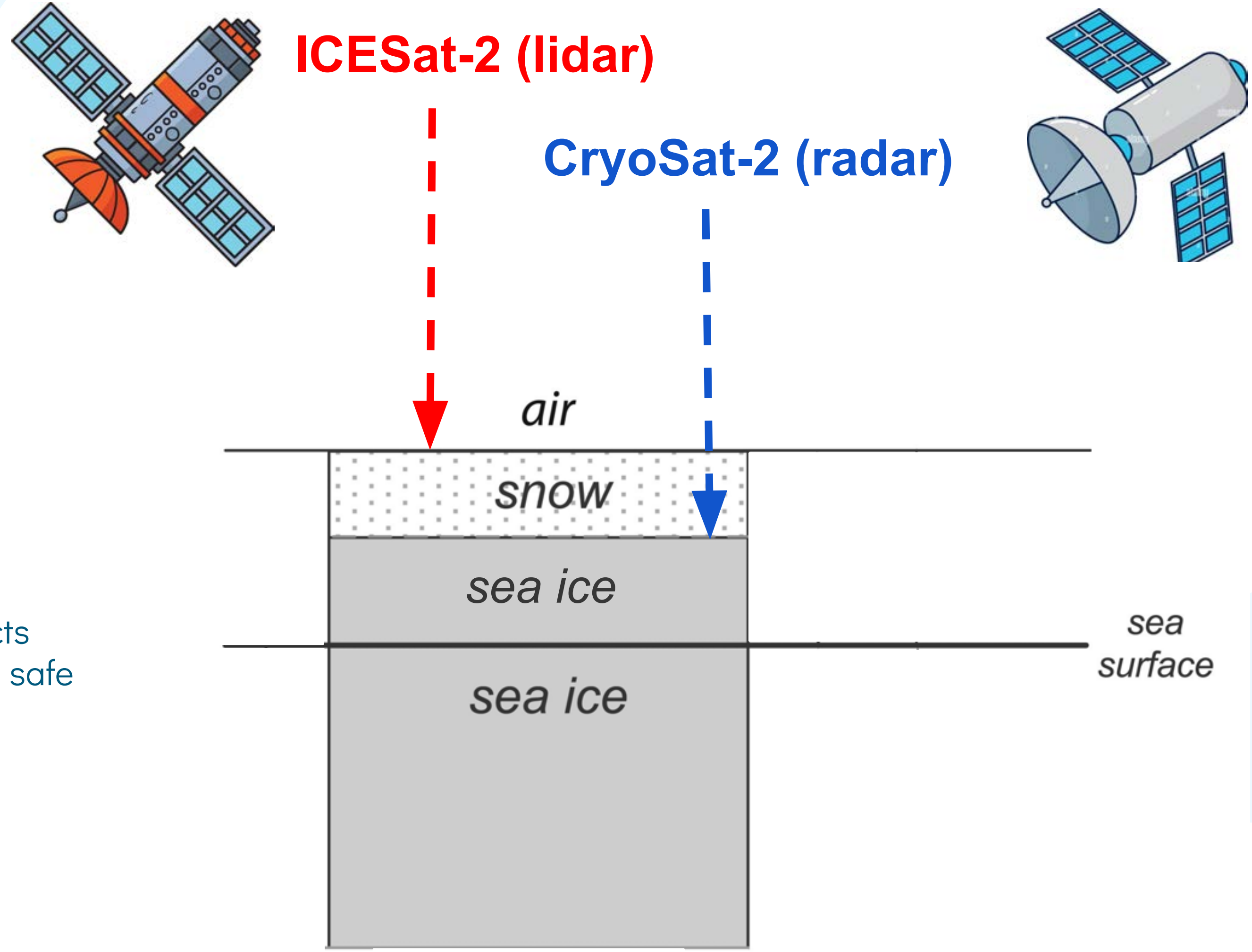
Outline

- Background
  - Arctic snow and its importance for climate system
  - Techniques used to derive snow depth
- Validation of remote sensing measurements using in-situ measurements
- Results
  - Snow depth from remote sensing and in-situ measurements
  - Comparison with other studies
- Summary

Arctic Snow 101

- Snow is crucial for local climate and global climate
  - Insulating and reflective
  - Prevent rising sea levels
- Difficult to study
  - In-situ missions outdated or challenging
  - Models lack data

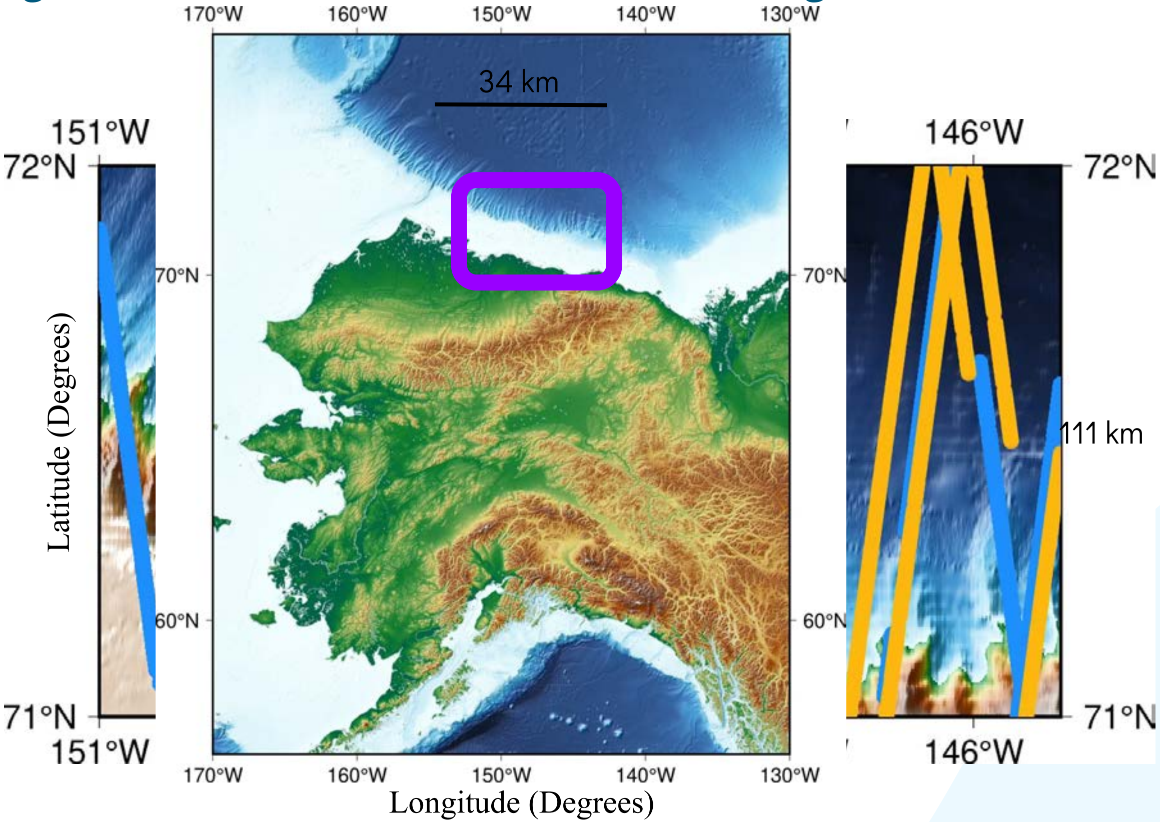


Satellites!

- Numerous products
- Remote sensing = safe

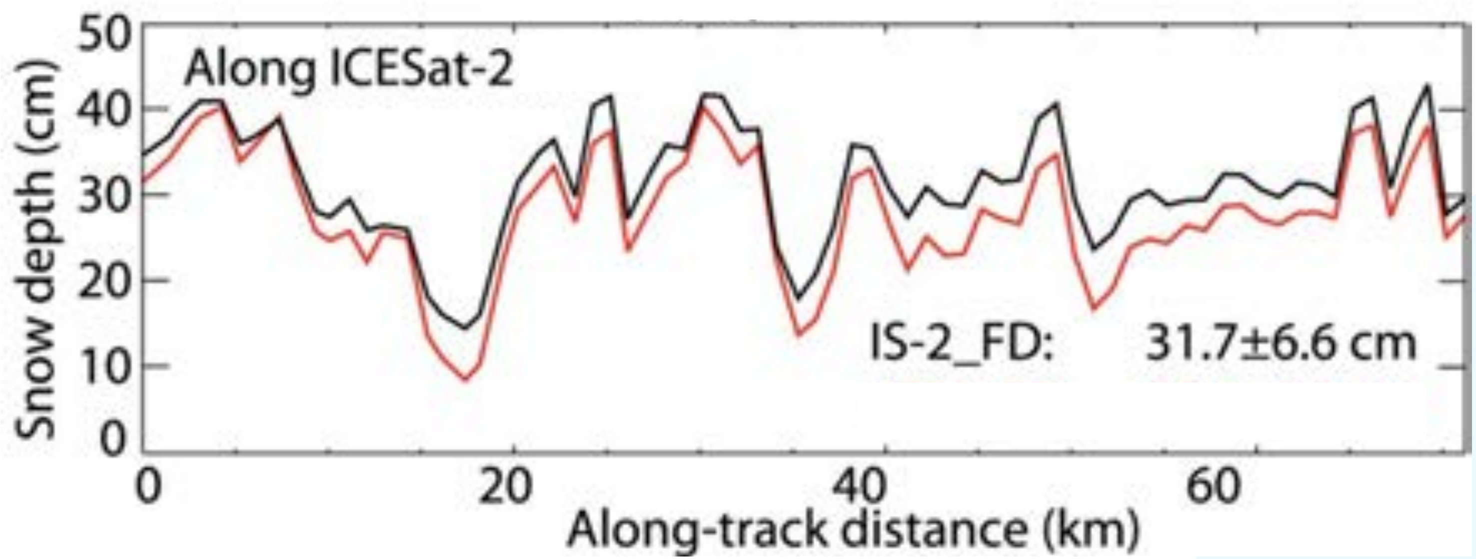
ICESat-2, CryoSat-2 ocean tracks during March 2021

- Blue: ICESat-2 (IS2)
- Orange: CryoSat-2 (CS2)
- Ideal: measurement at same place and time



Previous Work

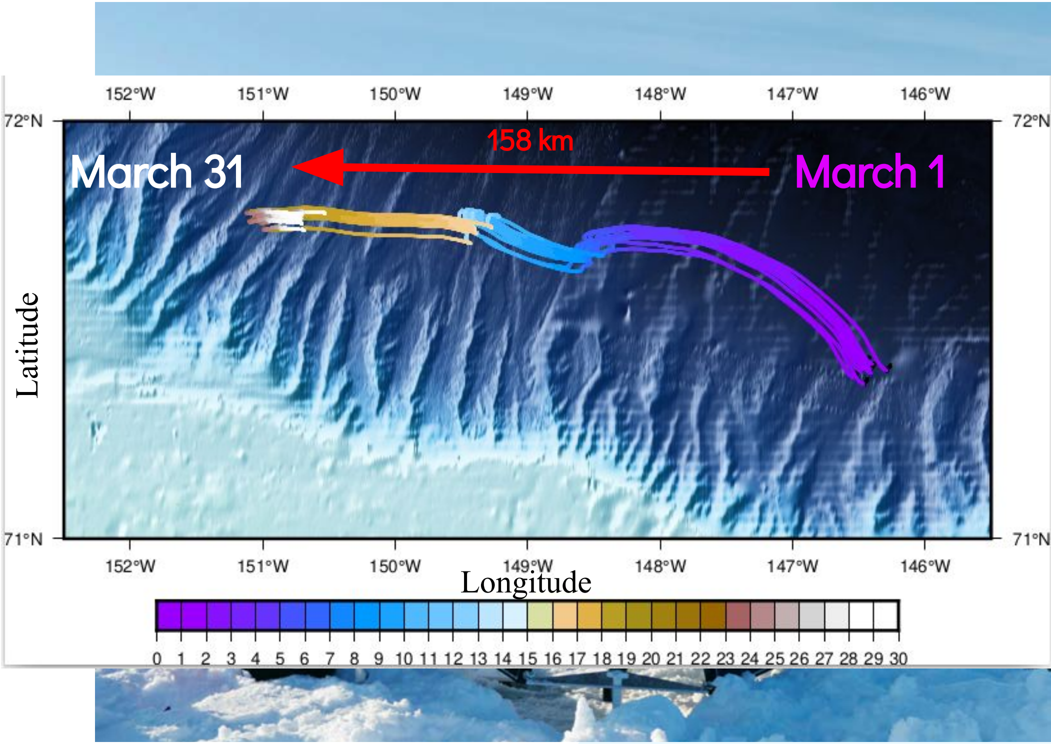
- In the past few years, many have tried using ICESat-2 and CryoSat-2 together
- Difficulties in comparing remote sensing with remote sensing
- Compared a single day -> I compare data for a month



Kwok et al. (2020)

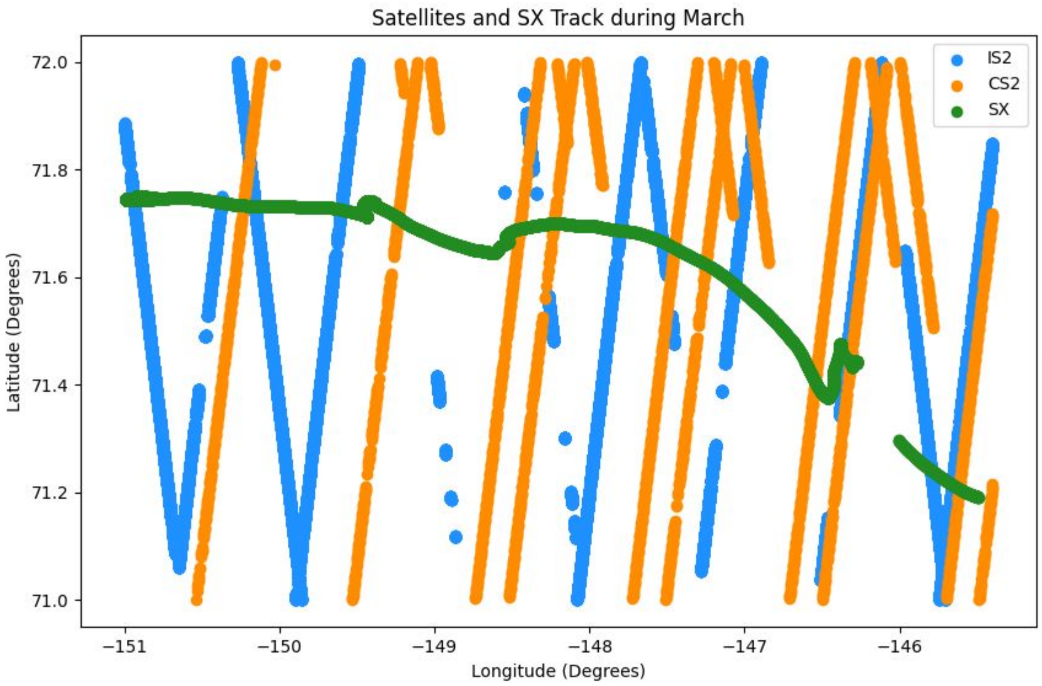
The S in SIDEx stands for superhero

- **S**ea **I**ce **D**ynamic **Ex**periment
- Height and GPS information
- Ice Drift



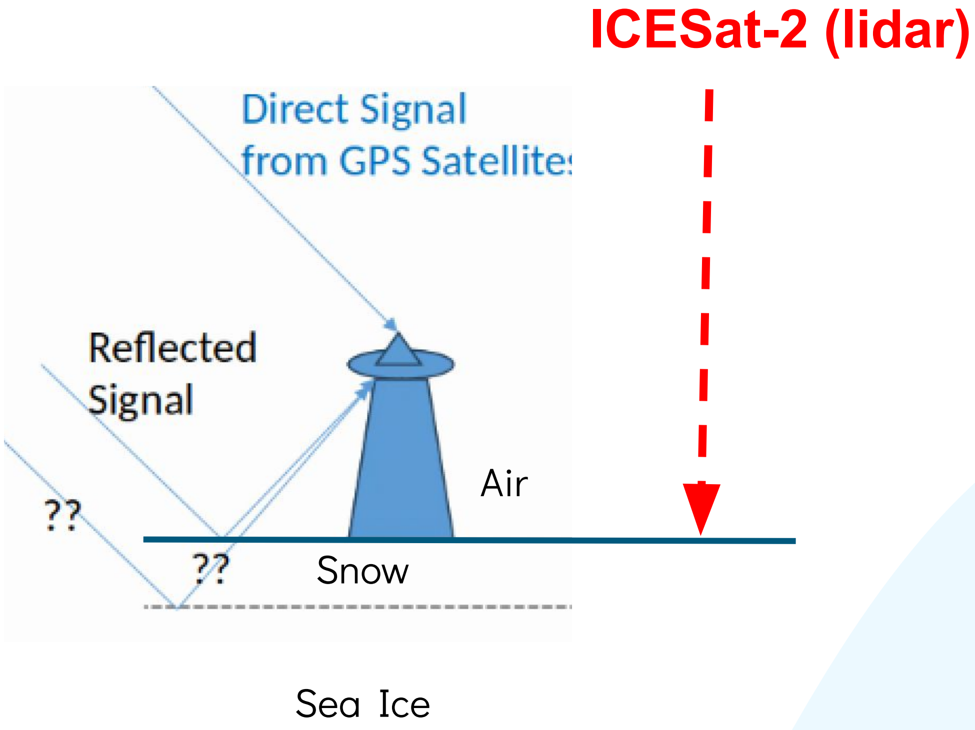
SIDEx (SX) Track with Satellite Tracks

- More intersections
- 3 height differences
  - IS2 - SX
  - CS2 - SX
  - Snow depth: IS2 - CS2
- Still have issues of distance and time
- Tried minimizing distance first by looking at intersections

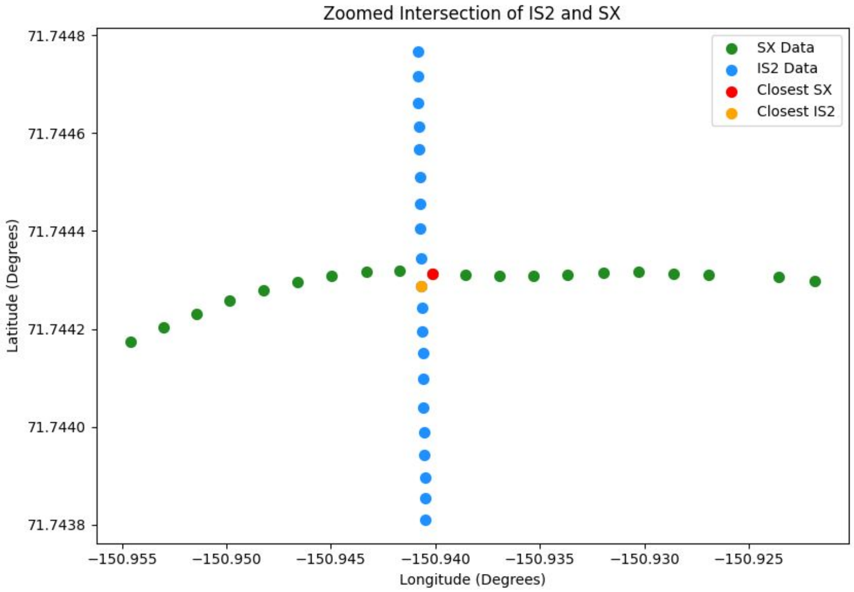


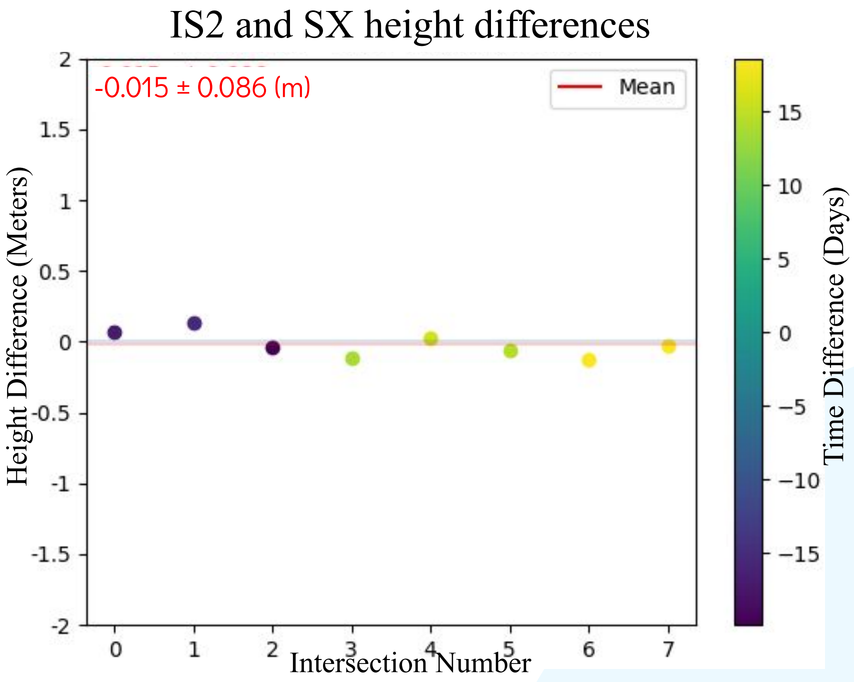
GPS Reflectometry

- IS2 - SX
- Hoping to confirm SX signal reflection if we saw a height difference centered at 0



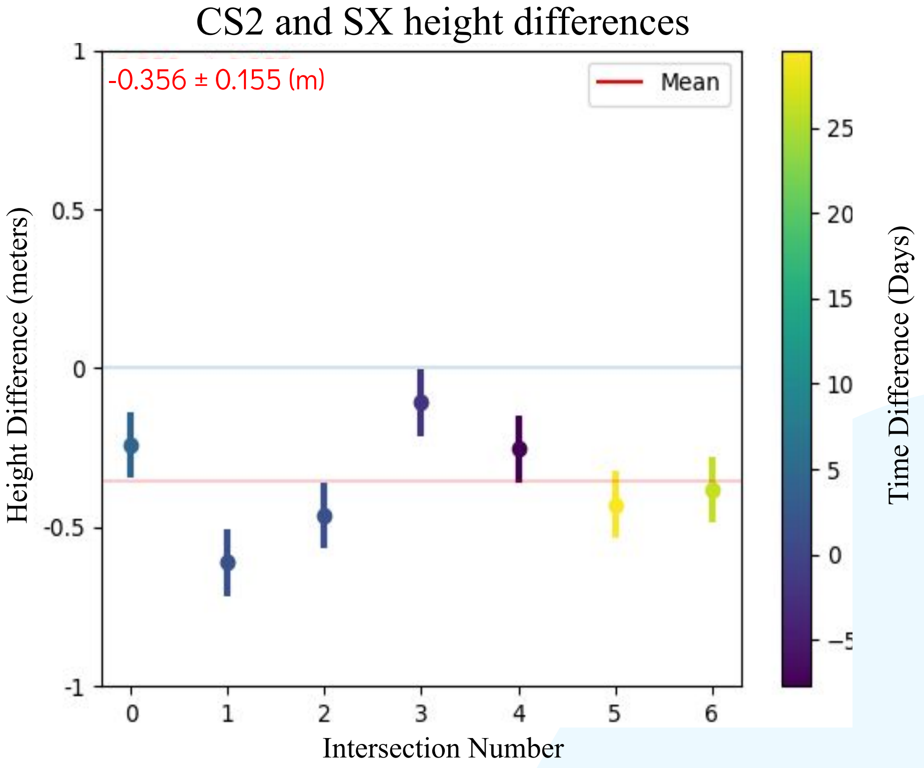
IS2 and SX Difference





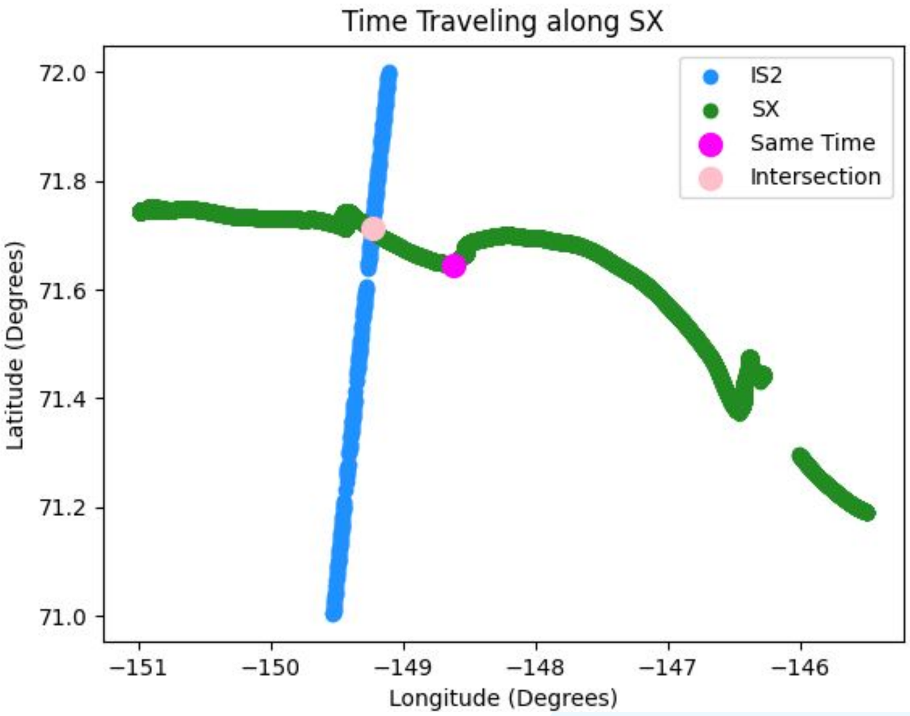
Snow Depth? (CS2 - SX)

- Literature suggests a value closer to 25 centimeters
- Large spread
- Still ignoring time



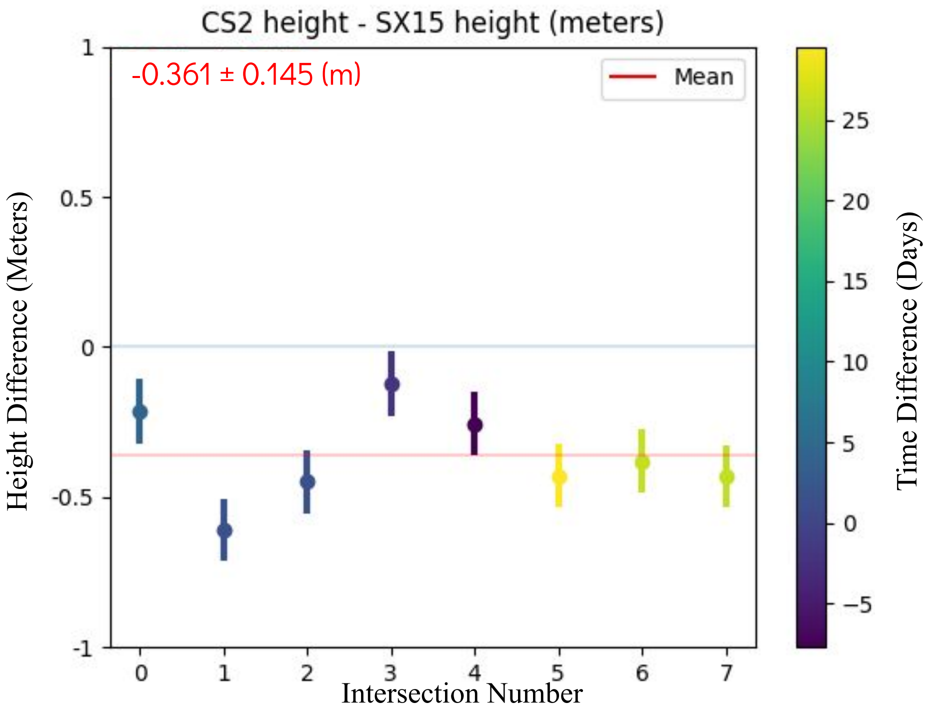
Better Method: Time Travel!

- We don't need to minimize distance between tracks rather the distance between measured pieces of ice
- Ice also moves
- Go to the point along SIDEx track at the same time as the satellite measurement!!



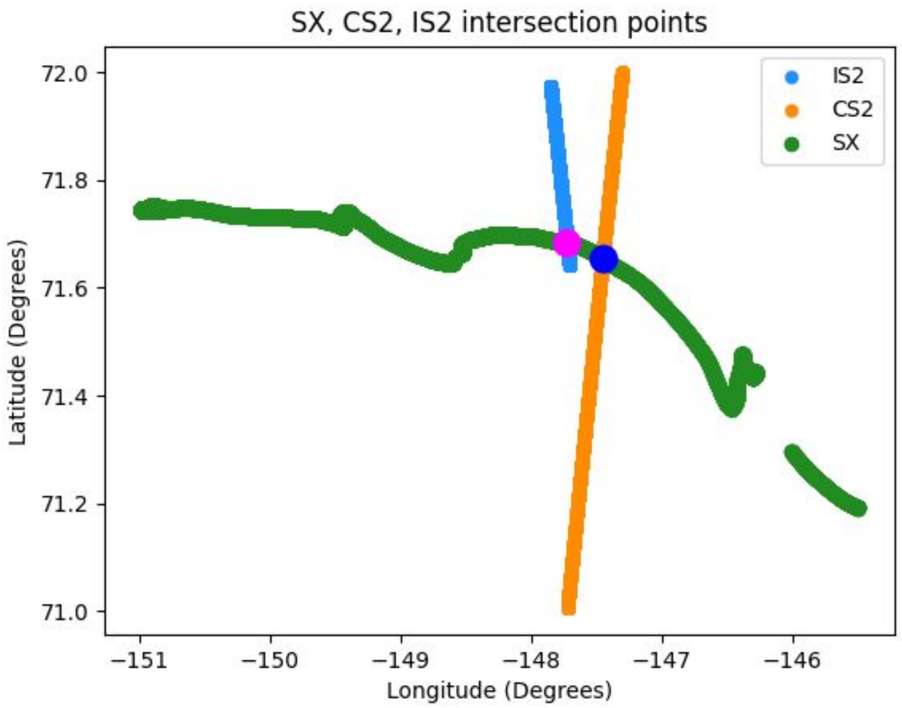
Snow Depth Improved (CS2 - SX)

- Minor improvement to spread but suggests we are moving in the right direction



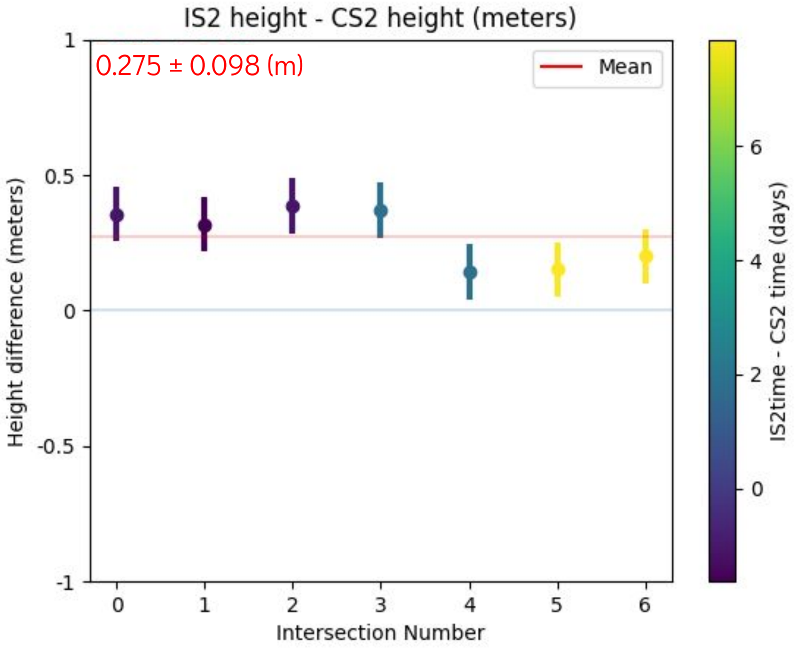
Good Things Come in Threes

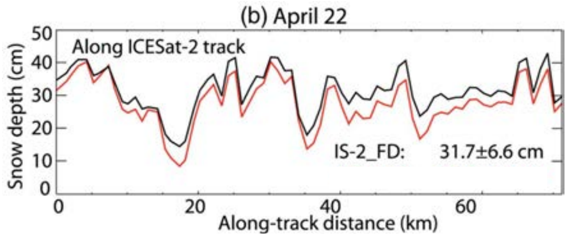
- Use both satellites together with in-situ SIDEx
- Ensure two satellites measure similar piece of ice



Final Snow Depth in March (IS2 - CS2)

- ICESat-2 - CryoSat-2 = snow depth
- Close agreement in mean with other results





Kwok et al. (2020)

Summary

- Used SIDEx’s in-situ data with ICESat-2 and CryoSat-2 satellites
  - Validate satellite heights
  - Provides accurate snow depth measurements
- Future steps:
  - Experiment more with data from other months
  - Incorporate all stations

Acknowledgements

Thank you for listening! Thank you to my mentors Dhiman Mondal, Pedro Elosegui, John Barrett, Chet Ruszczyk, John Swoboda for providing feedback, direction, and support.

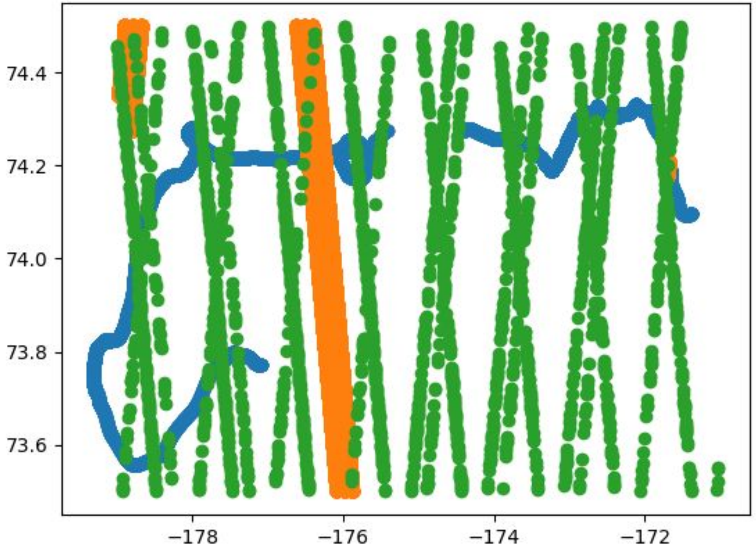
Thank you to IT and the entire Haystack community; to NSF for funding and MIT for hosting the REU

Thank you to the rest of the REU students for being the best cohort


Questions?

Future Improvements

- Experiment more with data from other months
- Incorporate all SIDEx tracks



Unique Properties of snow

- High albedo - the ground absorbs about four to six times more of the sun's energy!
- Low thermal conductivity
- Smooth hard snow can reflect sound well - conversations can be heard up to 2 miles away!
  - Fresh, fluffier snow can absorb and dampen sound waves

Different Types of Snow

- Usually classified into dry/wet depending on how much water the snow contains
- Dry
  - Less dense and leads to blowing snow
  - Contains less water
- Wet
  - Sticks to surfaces
  - Contains 2 to 3 times more water than dry snow making it much heavier

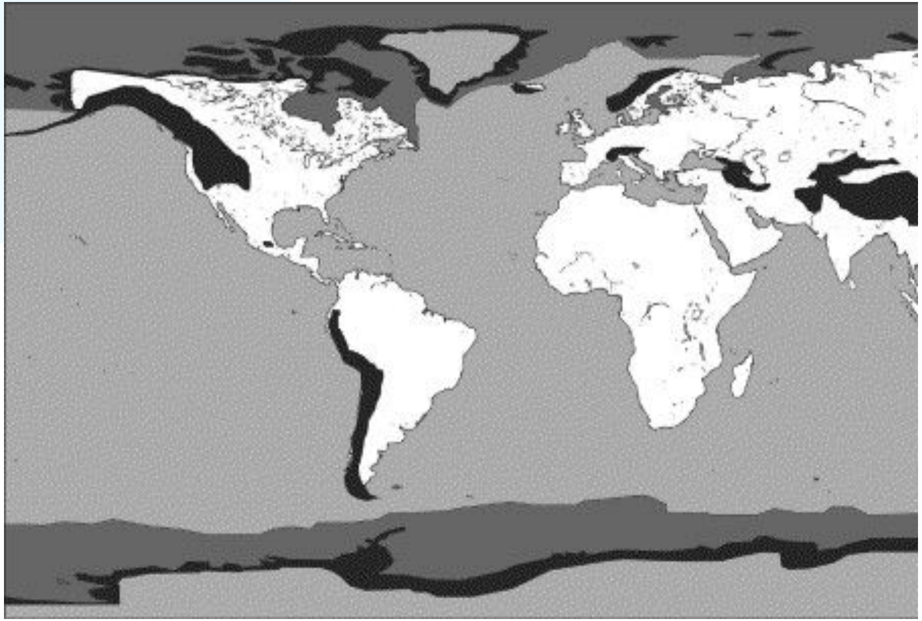
Satellite Specifications

TABLE I
DATA SPECIFICATIONS

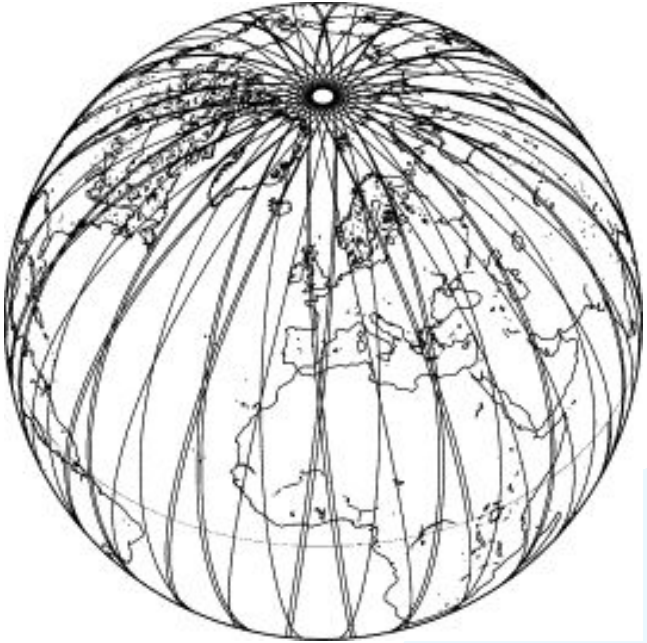
Data set	Spatial Along-track Resolution	Inclination and Altitude	Period
ICESat-2 ATL07	$\sim$20 m	92 ° at $\sim$ 500 km	369 days
CryoSat 2 SAR Level 2	$\sim$ 305 m	92 ° at $\sim$ 717 km	91 days

SAR vs SARIn mode

- SARIn has proved to be better at measuring freeboard and yield lower uncertainties
  - Uses across-track interferometry through a second antenna to better determine location
  - Various retracking algorithms to determine surface
  - Not available over our GPS region or much of the Arctic



SAR vs SARIn mode use



92 degree inclination orbit

Source: [https://www.sciencedirect.com/science/article/pii/S0273117705009348#fig6]

Table 2. Nature and source of geophysical corrections

Correction	Source	Typical winter magnitude at 80°N, averaged over 1 month and $10^4 km^2$.	Reference
Ocean tide	FES 02	0.03 m	Le Provost et al. (1998)
Ocean loading tide	FES 02	0.002 m	Francis and Mazzega (1990)
Long-period tide	FES 02	0.0075 m	Le Provost et al. (1998)
Solid Earth	Cartwright Edden	0.015 m	Cartwright and Edden (1973)
Polar tide	Wahr	0.0025 m	Wahr, 1985
Dry troposphere	Meteo France/ECMWF	2.3 m ±0.02 m	Saastamoinen, 1972
Inverse barometric correction	Meteo France/ECMWF	0.03 m	Ponte (1991)
Wet troposphere	Meteo France/ECMWF	0.01 m	Saastamoinen (1972)
Ionosphere	Bent model	0.015 m	Llewwllyn and Bent (1973)

Corrections common to all radar altimeter mission and not specific to CryoSat

Freeboard Differences

$$h_{fs} = \frac{\left(h_f^{IS2} - h_{fi}^{CS2}\right)}{\eta_s},$$

η = the refractive index at K_u band (dependent on bulk snow density)