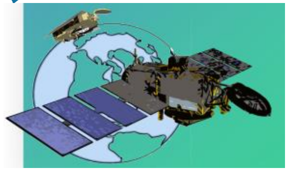

Improving the estimation of Lake Ice Thickness with high resolution radar altimetry data

Anna Mangilli[1], Claude Duguay[2,3], Justin Murfitt[3], Thomas Moreau[1] , Samira Amraoui[1], Jaya Sree Mugunthan[3], Pierre Thibaut[1], Craig Donlon[4]

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S6JTEX Final Review meeting
ESA-ESTEC 24th April 2024

Lake Ice Thickness

- Lake Ice Thickness (LIT): sensitive indicator of climate change, recognized as an Essential Climate Variable (ECV) by the Global Climate Observing System (GCOS)

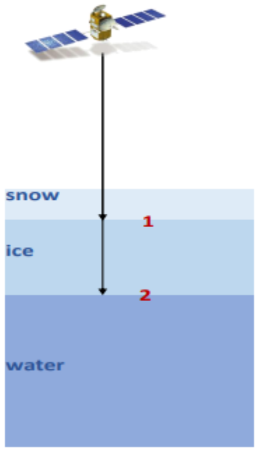
GCOS req.	Spatial resolution	Temporal resolution	Uncertainity (2σ)
Minimum	10Km	annual	15cm
Breaktrhrough	1Km	monthly	10cm

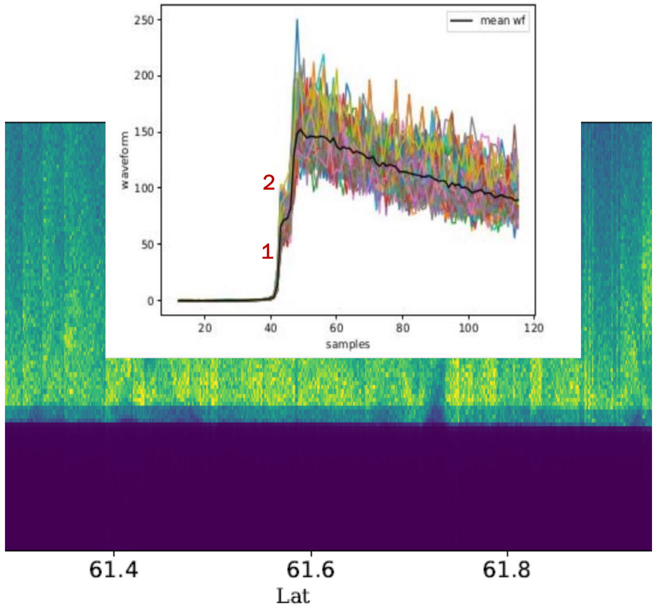
- The monitoring of seasonal variations and trends in lake ice thickness is important from a climate change perspective, and also for the operation of winter ice roads. Yet, field measurements tend to be sparse in both space and time: need to develop accurate retrieval algorithms from satellite remote sensing
- To date, few studies have investigated the potential of radar altimetry data for the estimation of LIT e.g. Beckers et al 2017 & Ye et al 2024 (CryoSat2 data), Shu et al 2020, Yang et al 2021 & Li et al 2023 (Lake Water Level studies). Empirical methods based on thresholds, that rely on in situ validation (not always possible, difficult to compare) and hard to generalize to different targets
- Development of analytical based retrackers that allow a robust and continuous monitoring of LIT:
    - **LRM_LIT retracker** [Mangilli et al 2022]. ESA CCI-Lakes project
    - **SAR_LIT & FFSAR_LIT retracker** [Mangilli et al 2024]. ESA S6JTEX project

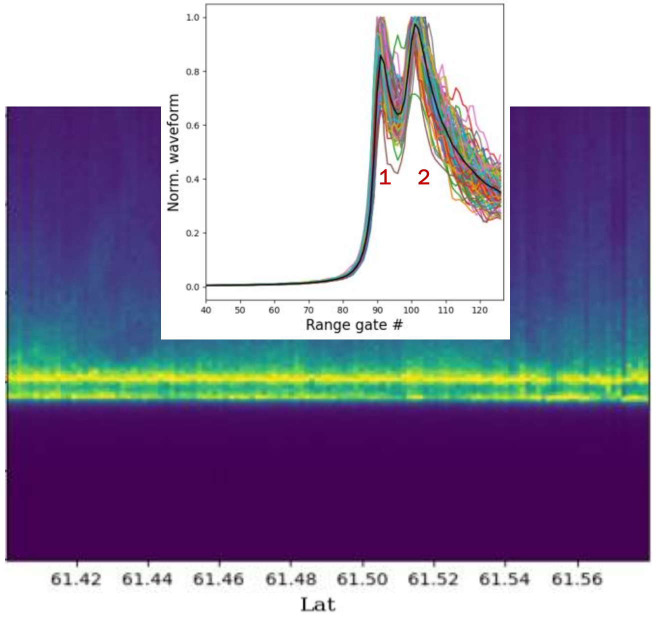
The LIT signature on Ku band radar waveforms

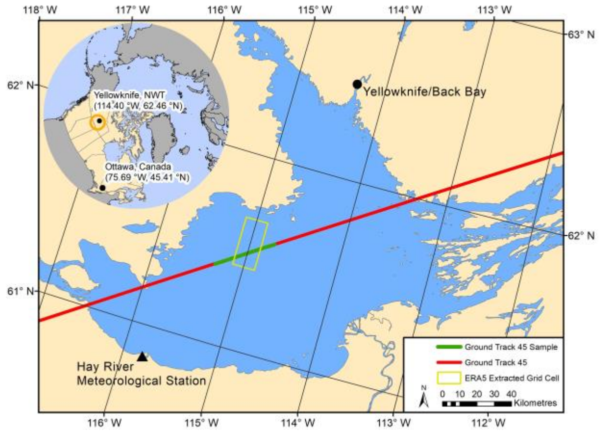
- Specific LIT signature on Ku radar waveforms related to the backscattering of the radar wave at two interfaces snow/ice (1) and ice/water (2): : “step” (LRM) and double peak (SAR)

The Great Slave Lake in February 2021 as seen by Jason3 (LRM) and S6 (SAR) during the tandem phase







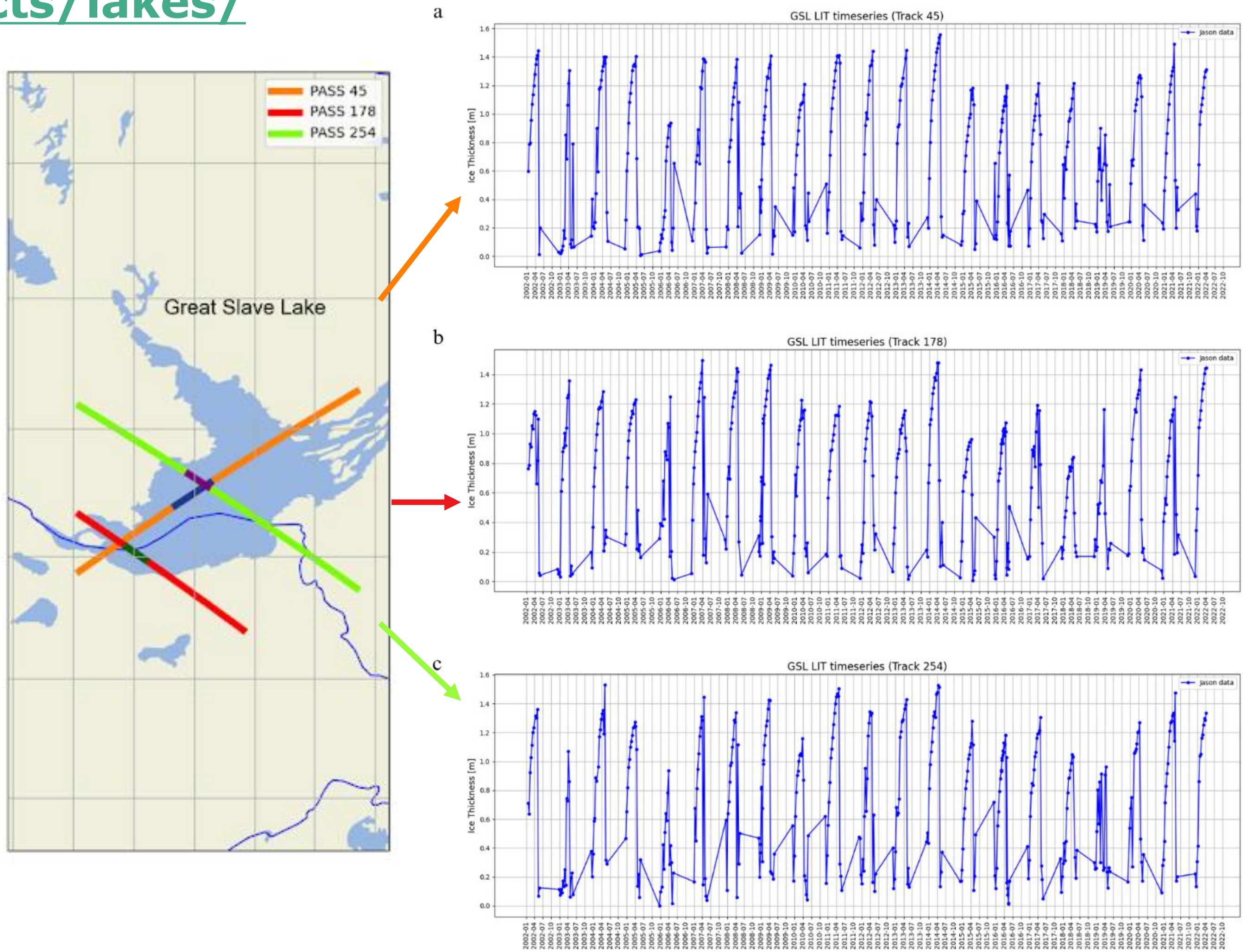


- The width of the step (LRM) and the peak separation (SAR) is linked to the ice thickness

LIT @ CCI LAKES

https://climate.esa.int/en/projects/lakes/

- **Project timeline: 2022-2025.**
- **cci LIT ECV lead:** A.Mangilli & C.Duguay
- **Long LIT timeseries (20+ years)** from Jason1/2/3 & S6 LRM generated with the LRM_LIT retracker [Mangilli et al 2022]
- Current data release (fall 2023) **of LIT validated products** over **3 regions** of the **Great Slaves Lake (Canada)**
- LIT trends and climatology study underway. LIT validated timeseries products on new targets lakes will be provided for the next release (2025)



Improving the LIT estimation with high resolution radar altimetry data

- Formalism: analytical LIT retrackers for UFSAR and FFSAR data
- LIT analysis of Sentinel-6MF UFSAR data at 20 Hz, UFSAR & FFSAR at 140 Hz
- Two representative targets: the Great Salve and the Baker lakes (Canada)
- Validation. Comparison with:
  - LRM LIT estimates from Jason-3 and S6 during the tandem phase
  - Thermodynamical LIT simulations [Duguay et al. 2003]
  - Optical/radar images
- Conclusions and perspectives

Article

Improving the Estimation of Lake Ice Thickness with High Resolution Radar Altimetry Data

Anna Mangilli [1*], Claude R. Duguay [2,3], Justin Murfitt [3], Thomas Moreau [1], Samira Amraoui [1,4], Jaya Sree Mugunthan [3], Pierre Thibaut [1] and Craig Donlon [5]

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Abstract: Lake ice thickness (LIT) is a sensitive indicator of climate change identified as a thematic variable of Lakes as an Essential Climate Variable (ECV) by the Global Climate Observing System (GCOS). Here, we present a novel and efficient analytically based retracking approach for estimating LIT from high-resolution Ku-band (13.6 GHz) synthetic aperture radar (SAR) altimetry data. The retracker method is based on the analytical modeling of the SAR radar echoes over ice-covered lakes that show a characteristic double-peak feature attributed to the reflection of the Ku-band radar waves at the snow-ice and ice-water interfaces. The method is applied to Sentinel-6 Unfocused SAR (UFSAR) and Fully Focused SAR (FFSAR) data, with their corresponding tailored waveform model, referred to as the SAR_LIT and FFSAR_LIT retracker, respectively. LIT retrievals from Sentinel-6 SAR data at different posting rates are evaluated against those obtained from thermodynamic lake ice model simulations and Low Resolution Mode (LRM) Sentinel-6 and Jason-3 data over two ice seasons during the tandem phase of the two satellites, allowing precise assessment of the continuity between LRM and SAR LIT retrievals. Consistency checks of the Sentinel-6 SAR LIT estimates are also performed using optical/radar images that provide information on the snow/ice conditions on the same dates. The analysis is performed on Great Slave Lake and Baker Lake (Canada) that differ in terms of lake size, bathymetry, snow/ice properties, and seasonal evolution of LIT. The accuracy of the LIT estimates with the SAR LIT retrackers is on the order of 5 cm once the ice is well established on the lakes, meeting the GCOS requirements of LIT measurement uncertainty, which is a factor of 2 to 3 times better than that of LIT obtained with LRM data, bringing a further improvement compared to previous analyses and methods. The SAR LIT retrackers presented are promising tools for monitoring the inter-annual variability and trends in LIT from current and future SAR altimetry missions.

Keywords: Radar altimetry, ice thickness, Unfocused SAR, Fully-Focused SAR, Sentinel-6 Michael Freilich, Jason-3, lake ice, cryosphere, hydrology

Citation: Mangilli A.; Duguay C.R.; Murfitt J.; Moreau T.; Amraoui S.; Mugunthan J.S.; Thibaut P.; Donlon C. Title. *Journal Not Specified* **2024**, *1*, 0. https://doi.org/

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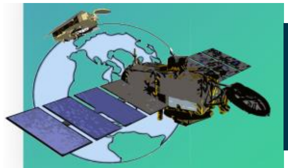
1. Introduction

Lake ice thickness (LIT) is a sensitive indicator of climate change recognized as a thematic variable of Lakes as an Essential Climate Variable (ECV) by the Global Climate Observing System (GCOS) of the World Meteorological Organization (WMO) [1]. LIT also plays a significant role on the economy of northern regions through its influence on transportation, travel, fishing, and recreation activities [2]. The thickness of lake ice has been decreasing with climate warming and is expected to further decrease in the foreseeable future [3]. Yet, continuous monitoring of LIT is limited as field measurements are sparse in both geographical coverage and time, and has been decreasing over the last few decades [4]. Remote sensing can help to fill this gap, ensuring global monitoring, but,

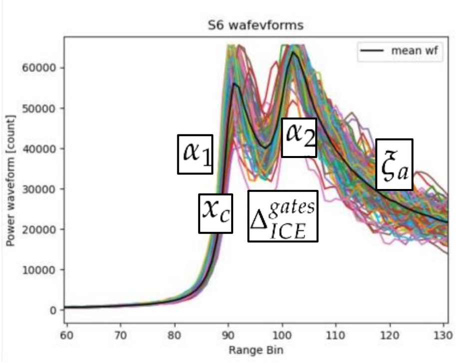


The SAR-LIT & FFSAR-LIT retrackers

- **Analytical waveform model:**
  - Based on SAMOSA waveform model (Ray et al 2015)
  - The double-peaked SAR waveforms can be modelled as the sum of two SAR waveforms. The separation between the two peaks is related to the ice thickness
  - SAR-LIT retracker: multi-look SAR waveform model with 5 parameters

$$P^{SAR-LIT}(x, \mathbf{p}) = \frac{1}{L} \sum_{\ell=-L/2}^{\ell=+L/2} P_{SL}^{LIT}(\theta_\ell, x, \mathbf{p}) \qquad \mathbf{p} = \{\Delta_{ICE}^{gates}, \alpha_1, \alpha_2, \xi_a, x_c\}$$

1. the ice thickness (range gate unit),
2. the amplitude of the first backscatter
3. the amplitude of the second backscatter,
4. the attenuation of the trailing edge
5. the central gate (epoch)



  - FFSAR-LIT retracker (S6): single-looked echo of the central beam

$$P^{FFSAR-LIT}(x, \mathbf{p}) = P_{SL}^{LIT}(\theta_\ell, x, \mathbf{p})|_{\ell=L/2}$$

- **Optimization:** Weighted Levenberg-Marquardt least square fit of individual waveforms
- **Parameters estimation:** Mean and standard deviation of the best-fit values of the 5 parameters in the Region of Interest over a target lake

The LIT analysis of S6 UFSAR 20Hz data

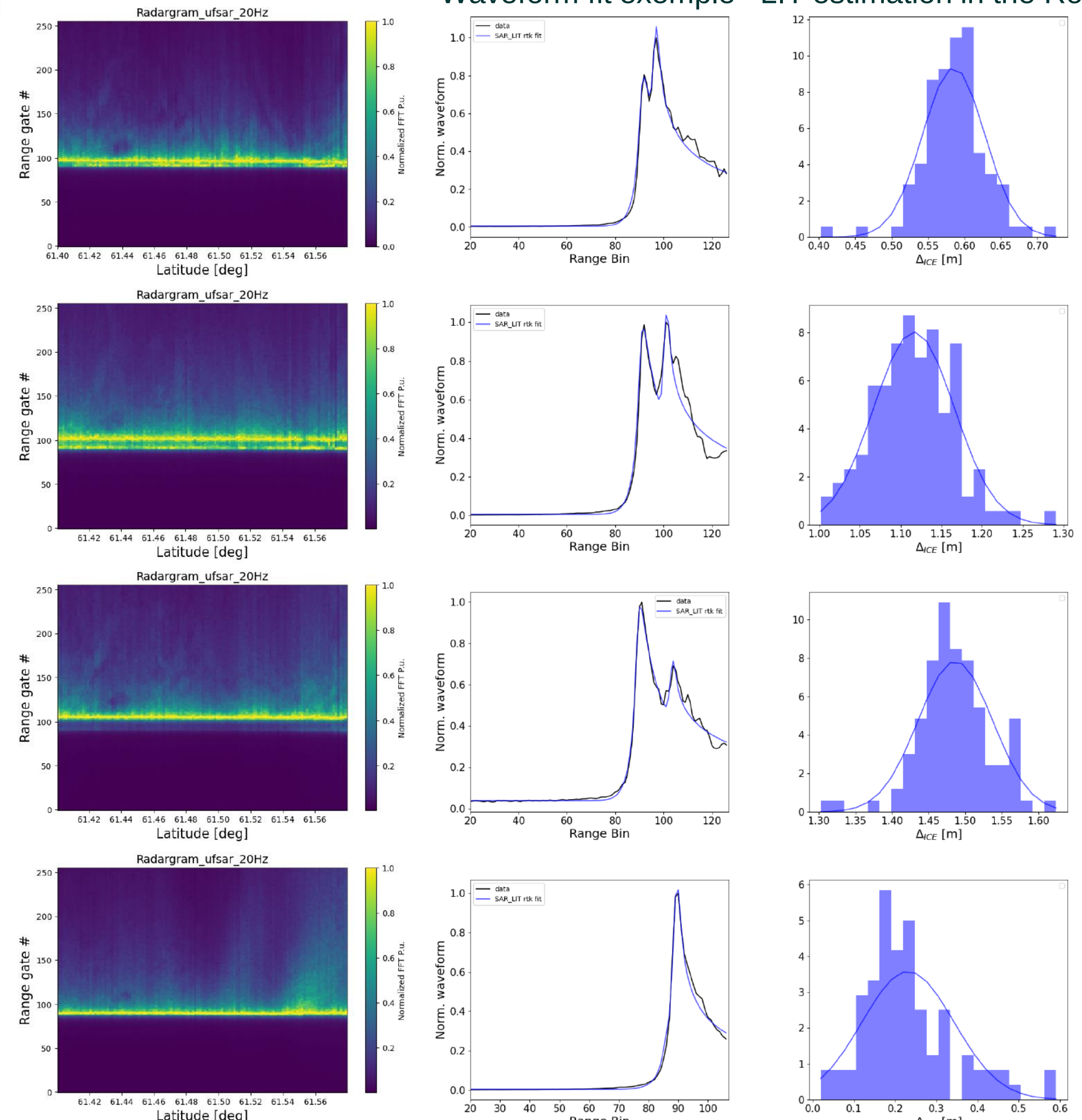
Waveform fit exemple   LIT estimation in the RoI (~100 WFS)

Dec2021

Feb2021

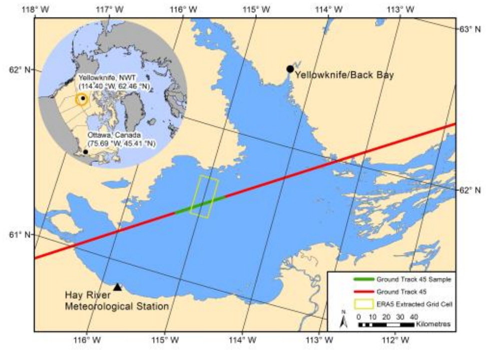
Apr2021

May2021



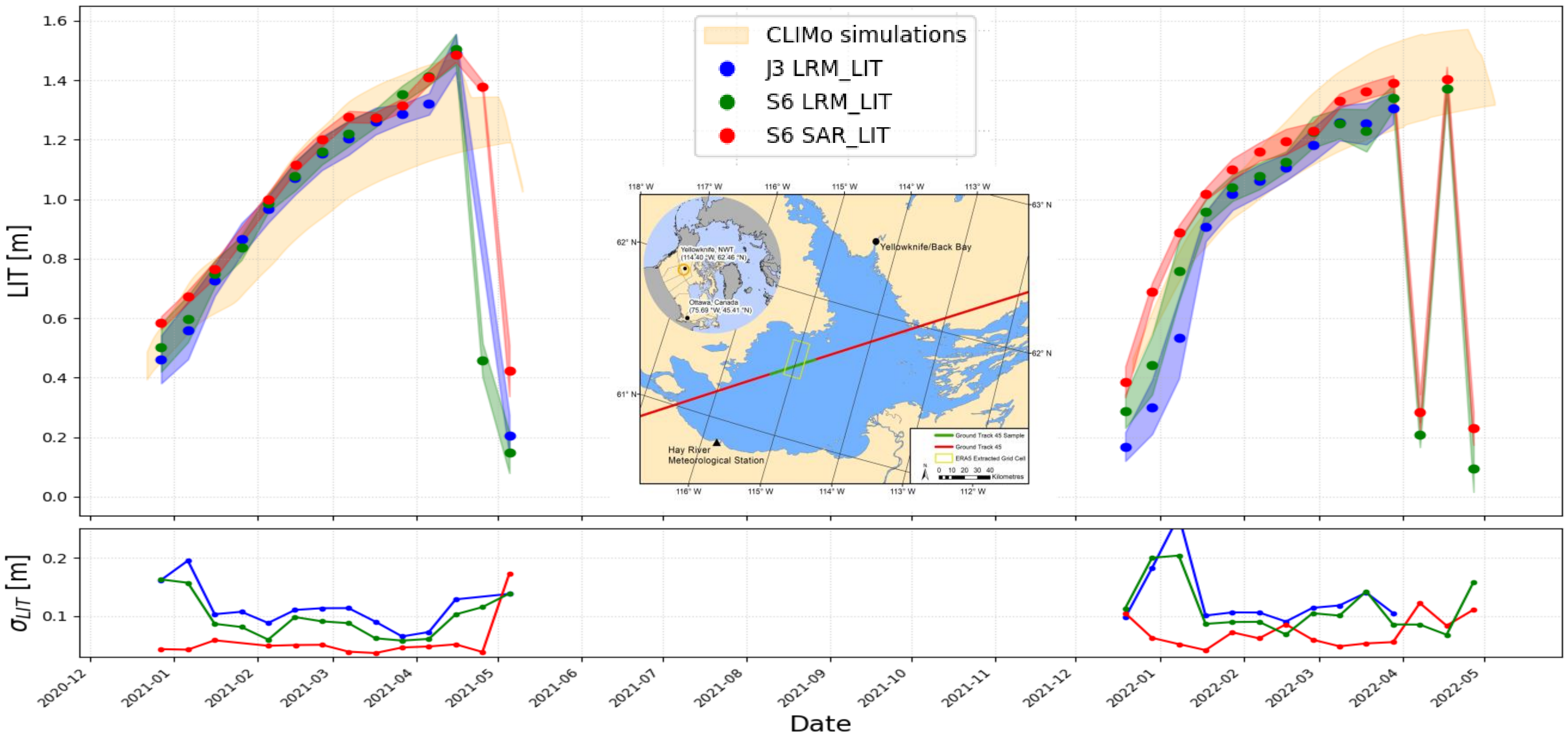
SAR-LIT retracker:

- Good fit performance
- Can accurately capture the LIT evolution and the ice forming and melting transitions



Lake Ice Thickness: LRM vs UFSAR at 20 Hz

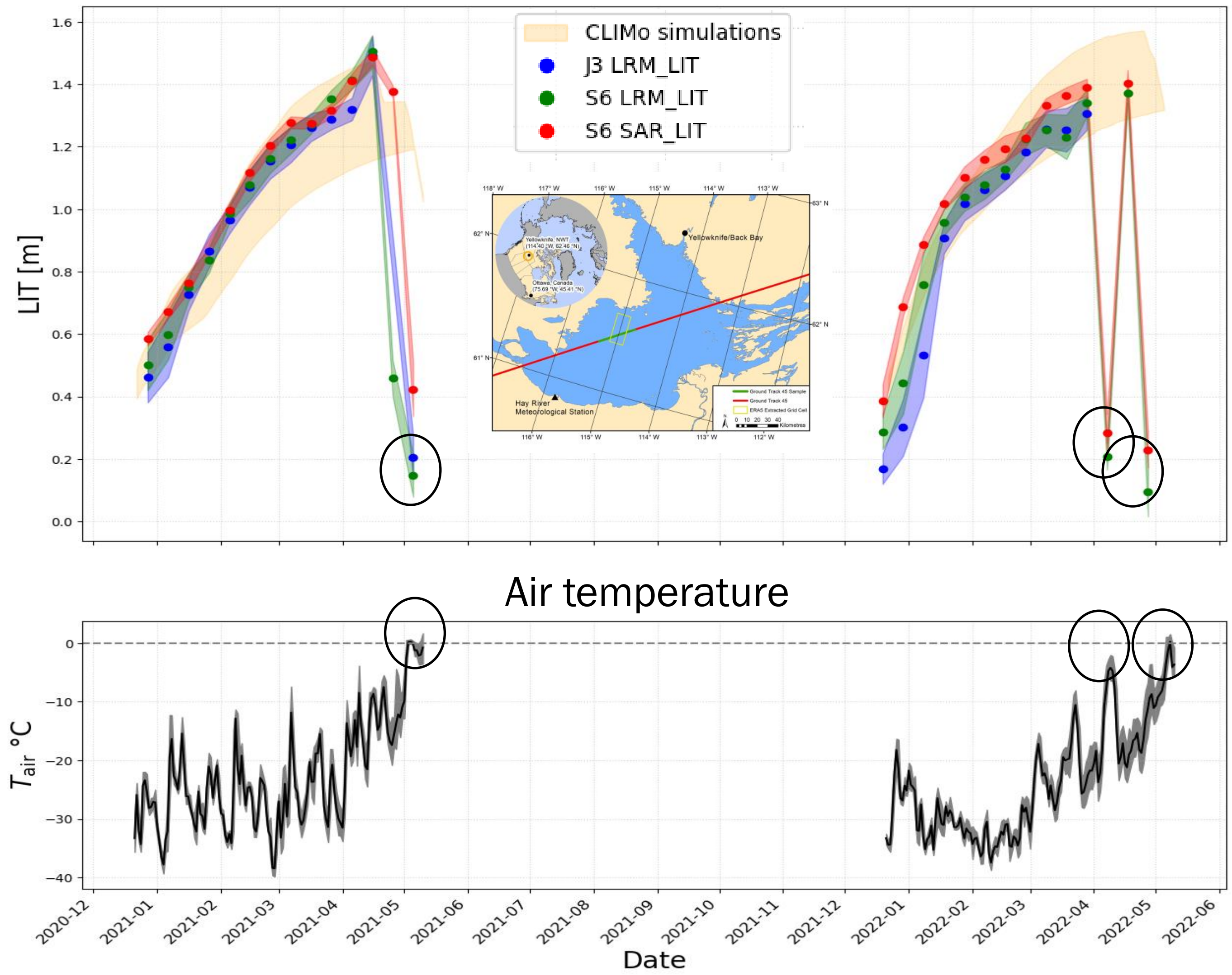
LIT evolution over the Great Slave Lake (2020-2022 ice seasons)



- Good consistency among LRM and SAR LIT results. Seasonal transitions and inter-annual LIT variations are captured
- S6 LRM better accuracy than J3 (~20-30% improvement, likely due to the sampling improvement)
- Improved accuracy with UFSAR 20Hz wrt LRM (factor of ~2 – 3 improvement between S6 UFSAR and S6LRM): σLIT~5cm
- Evolution of the LIT estimates fully compatible with CLIMo simulations

Lake Ice Thickness: LIT drops and correlation with air temperature

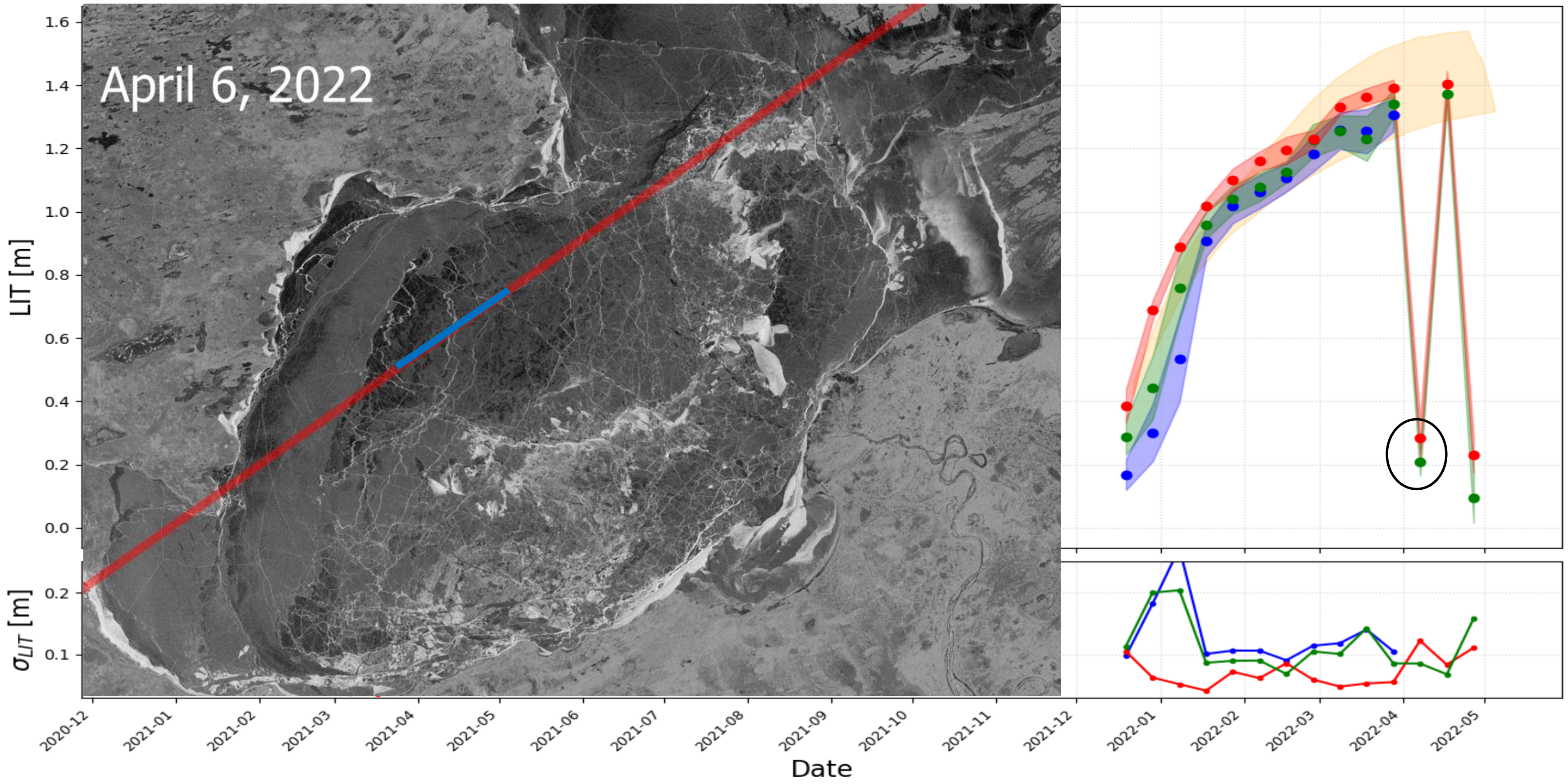
LIT evolution over the Great Slave Lake (2020-2022 ice seasons)



- clear correlation between the detected LIT drops and the rise of the air temperature near or above 0°C
- snow/ice on the lake surface starts to melt: the LIT signature is no longer present in the radar waveforms (no or a very small LIT is retrieved).
- Then, with refreezing, the LIT signature is again detectable

Lake Ice Thickness: LRM vs SAR

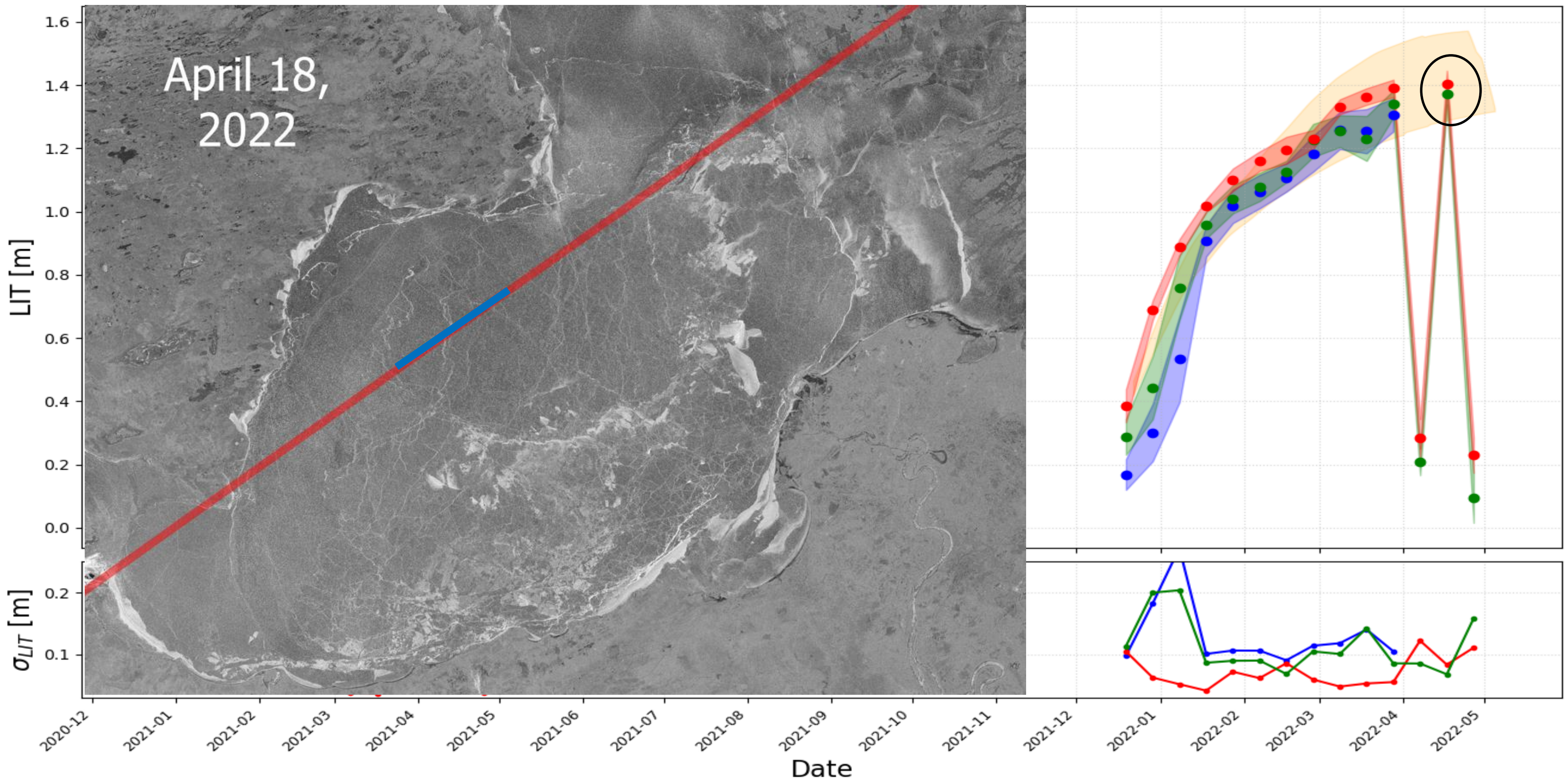
LIT evolution over the Great Slave Lake (2021-2022 ice season)



Drop in the LIT estimation: real feature due to snow/ice melting

Lake Ice Thickness: LRM vs SAR

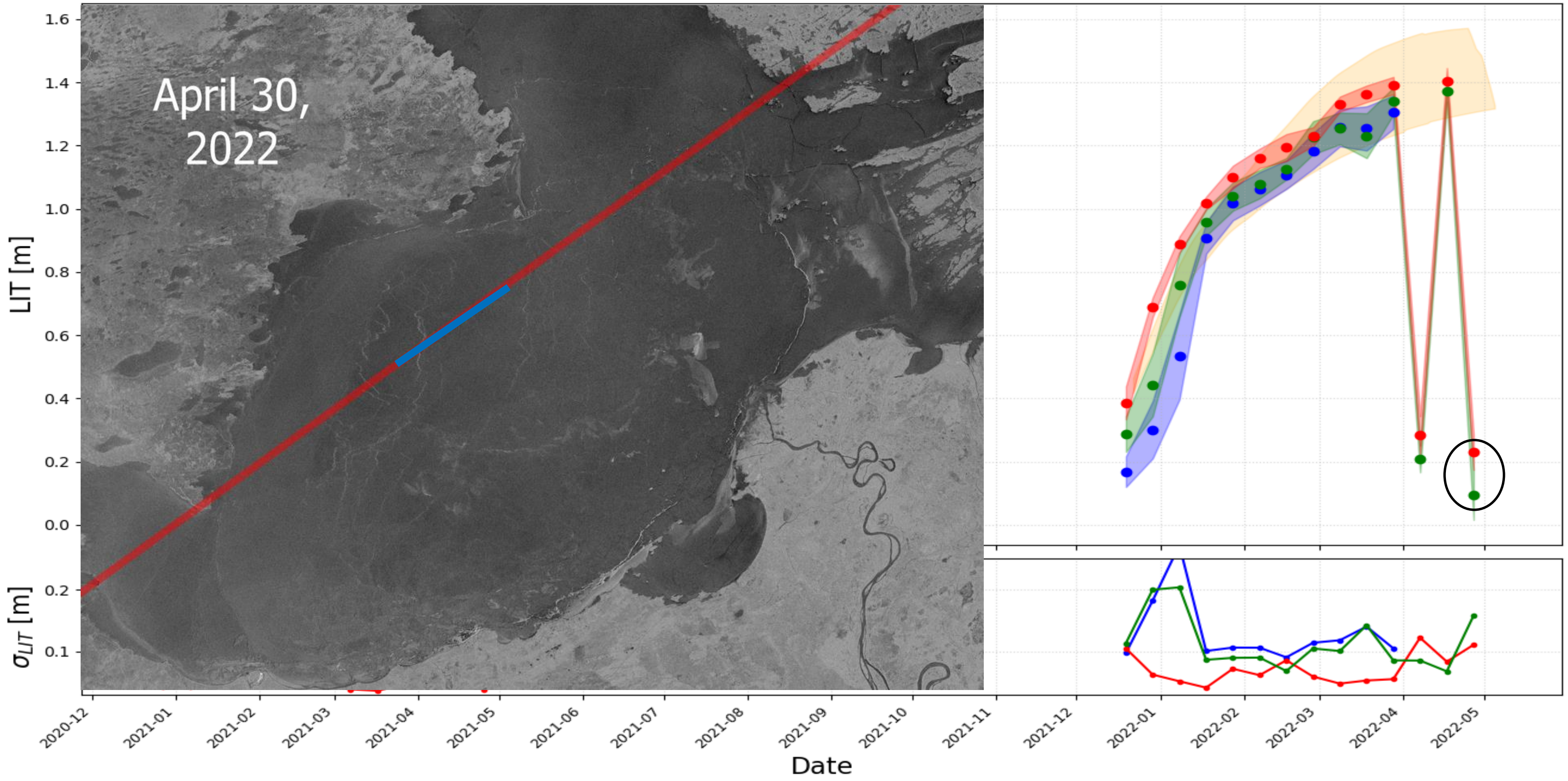
LIT evolution over the Great Slave Lake (2021-2022 ice season)



The lake surface froze again

Lake Ice Thickness: LRM vs SAR

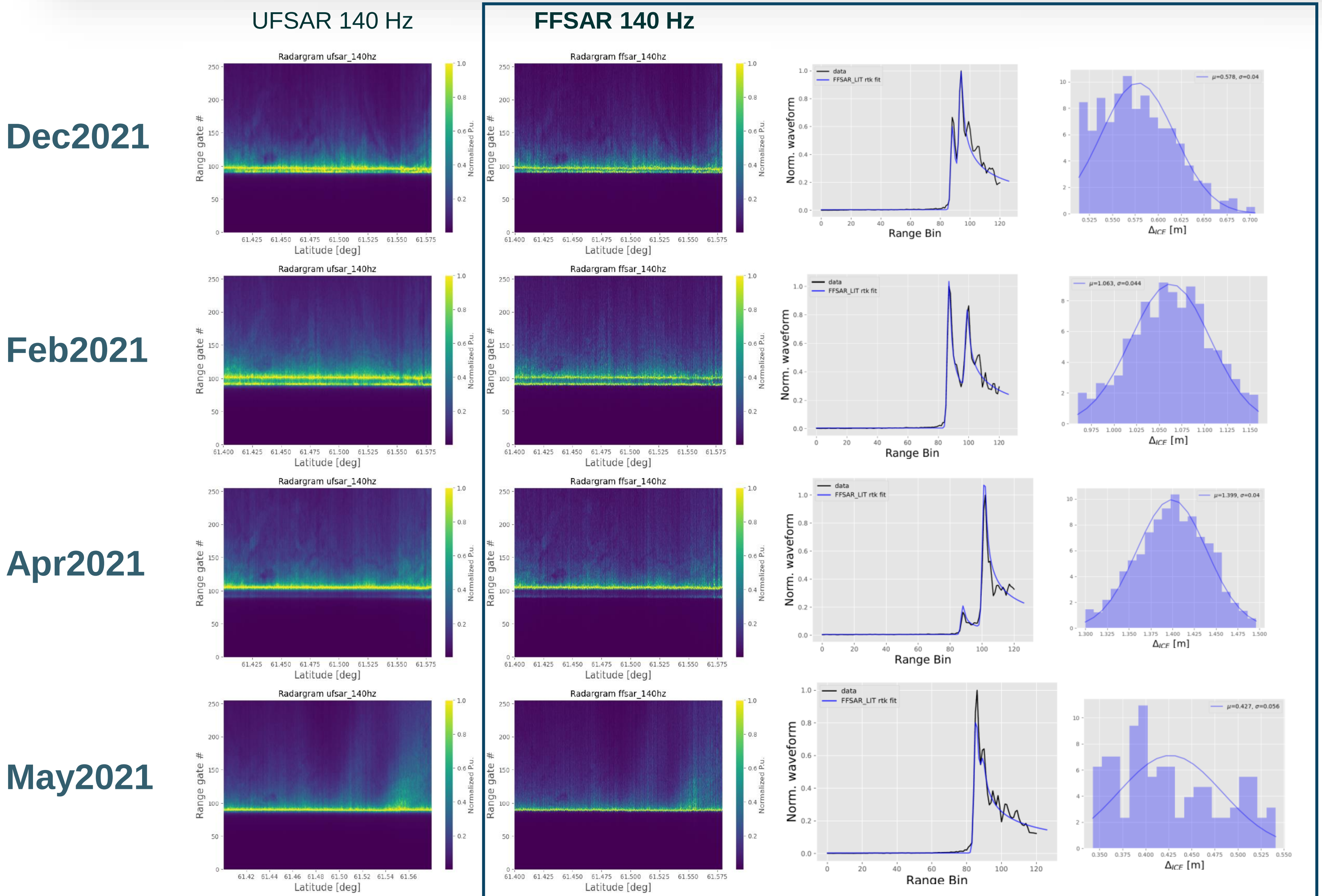
LIT evolution over the Great Slave Lake (2021-2022 ice season)



Melting transition

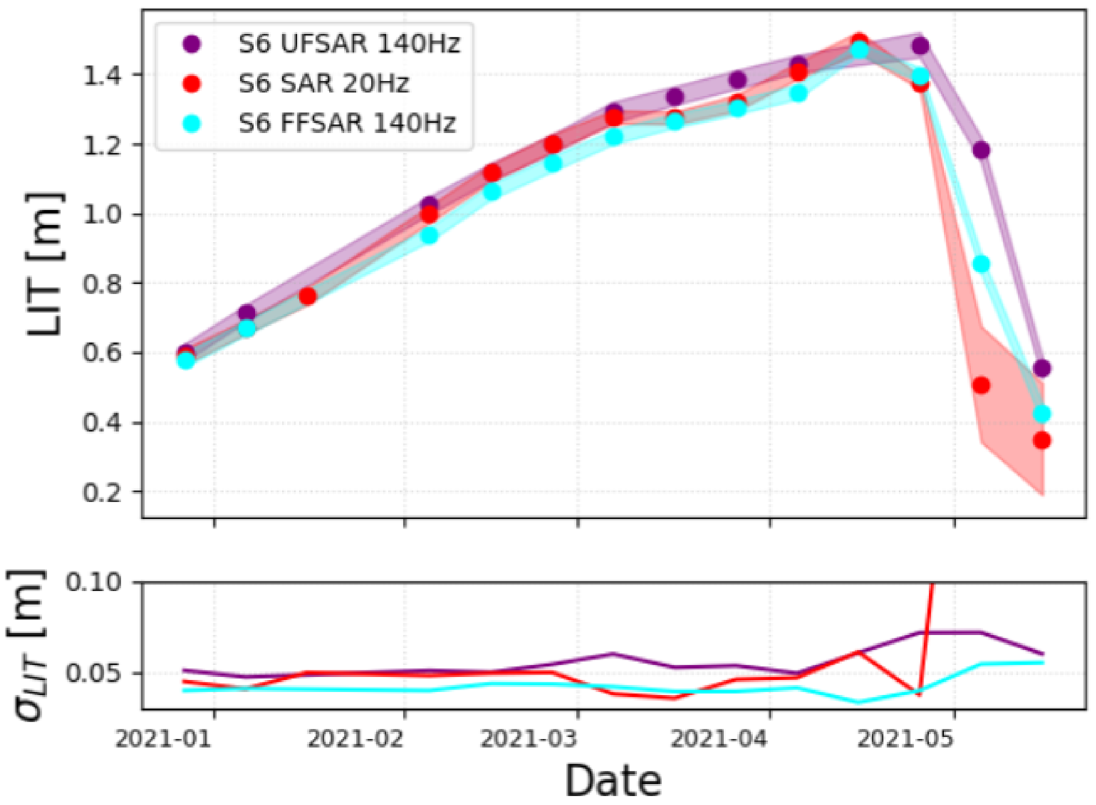
- The **LIT signature depends on the properties and thickness of the snowpack and the ice layer** and could be erased if some conditions are not met, as for instance in the case of snow-free lake ice or melting snow on the ice surface
- **LIT retrackers can capture the melt transition but they cannot precisely follow the evolution of LIT during melting** since the radar waves are reflected by the surface (i.e., they do not penetrate through wet snow and ice).

Lake Ice Thickness estimation with high(er) resolution S6 data: FF&UFSAR at 140Hz



- 140Hz data: increased statistics with respect to 20Hz data
- FF-SAR: double peak LIT signature seen at higher resolution
- Good fit performances of the FFSAR_LIT retracker

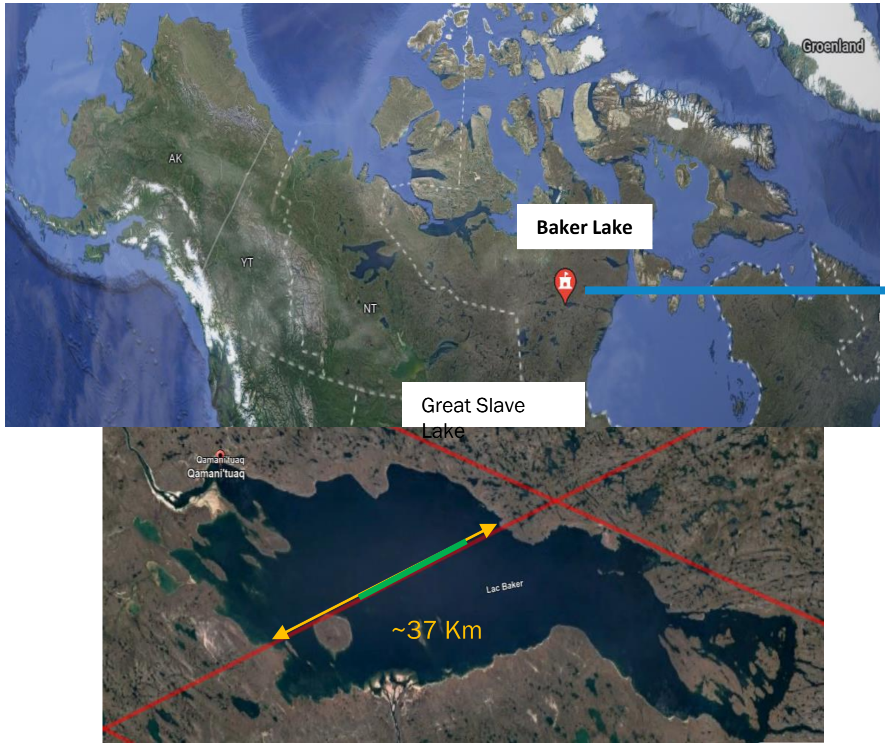
Lake Ice Thickness estimation with high(er) resolution S6 data: FF&UFSAR at 140Hz

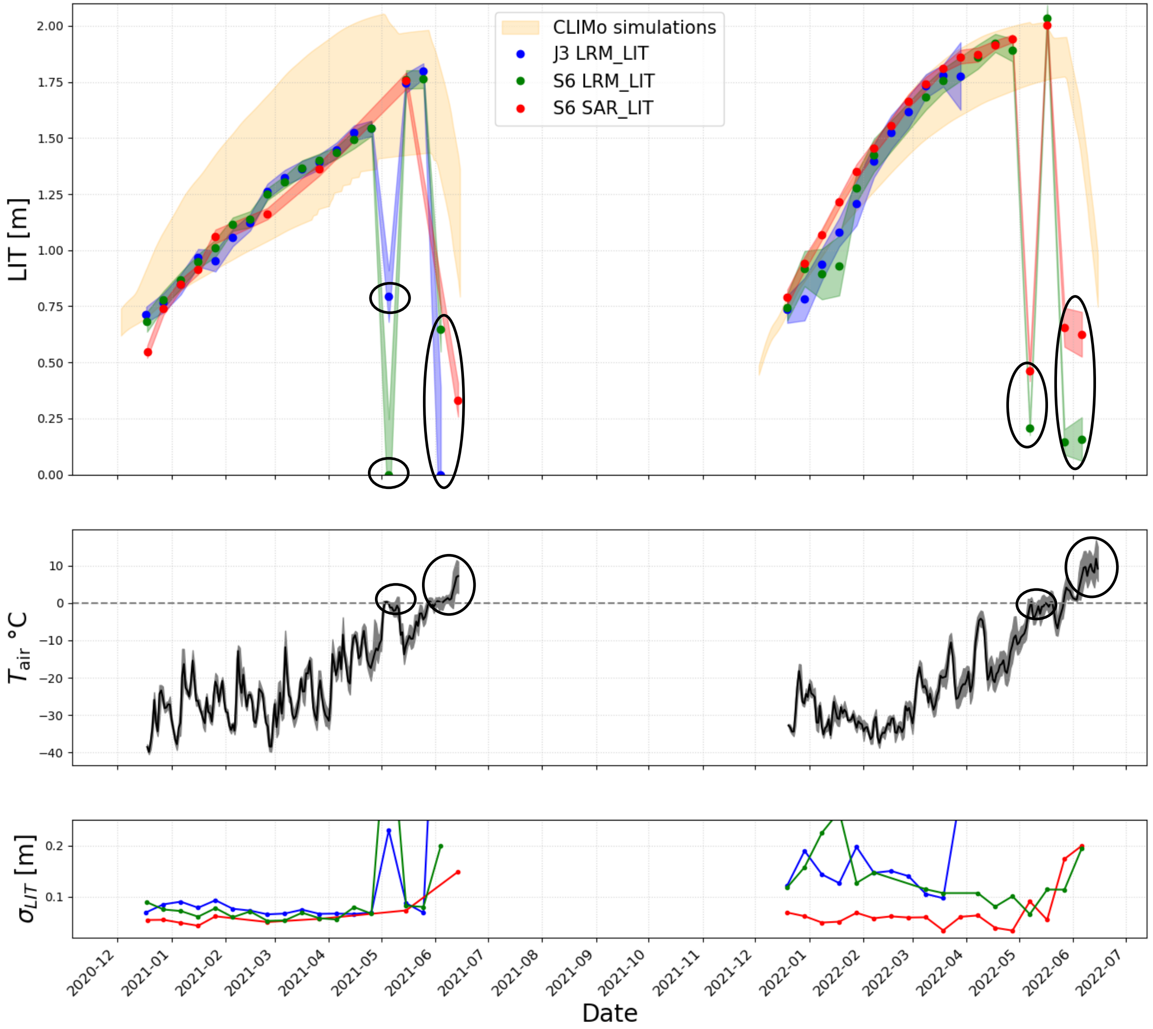


- Overall consistent results among the 3 datasets
- Increased performance with data at higher posting rate (140 Hz), in particular at the melting transition
- At equivalent posting rate, the FF SAR seems to allow for a better accuracy (~20 % smaller errorbars)

Lake Ice Thickness estimation on a smaller target: the Baker Lake

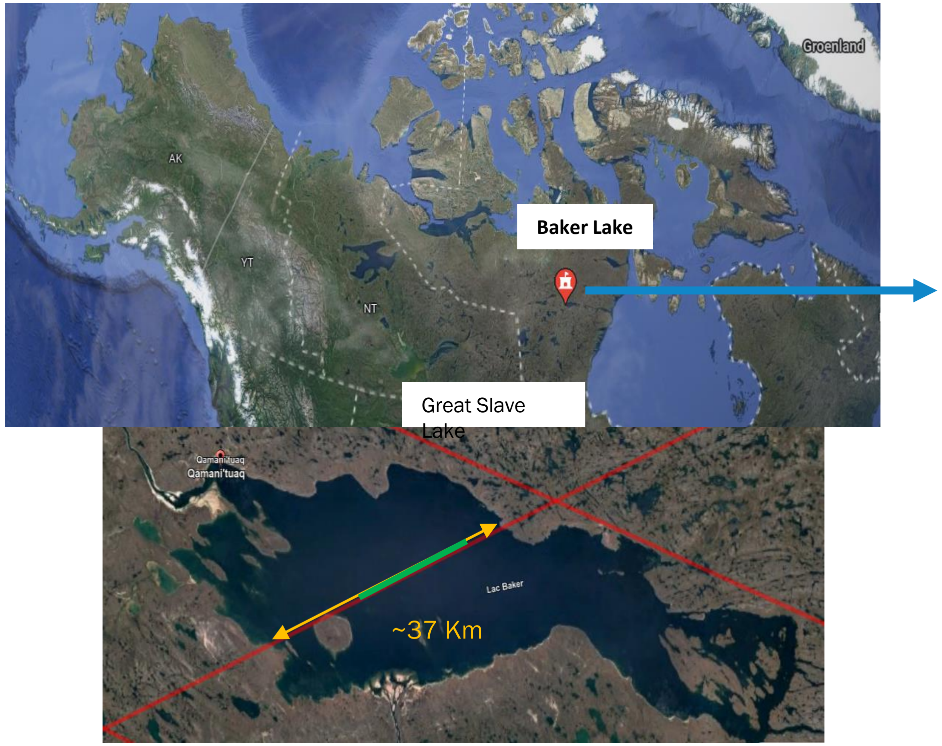
- Smaller target at higher latitude wrt GSL: different environnement, snow and ice properties and evolution
- More challenging: reduced number of waveforms (less statistics) & land contamination

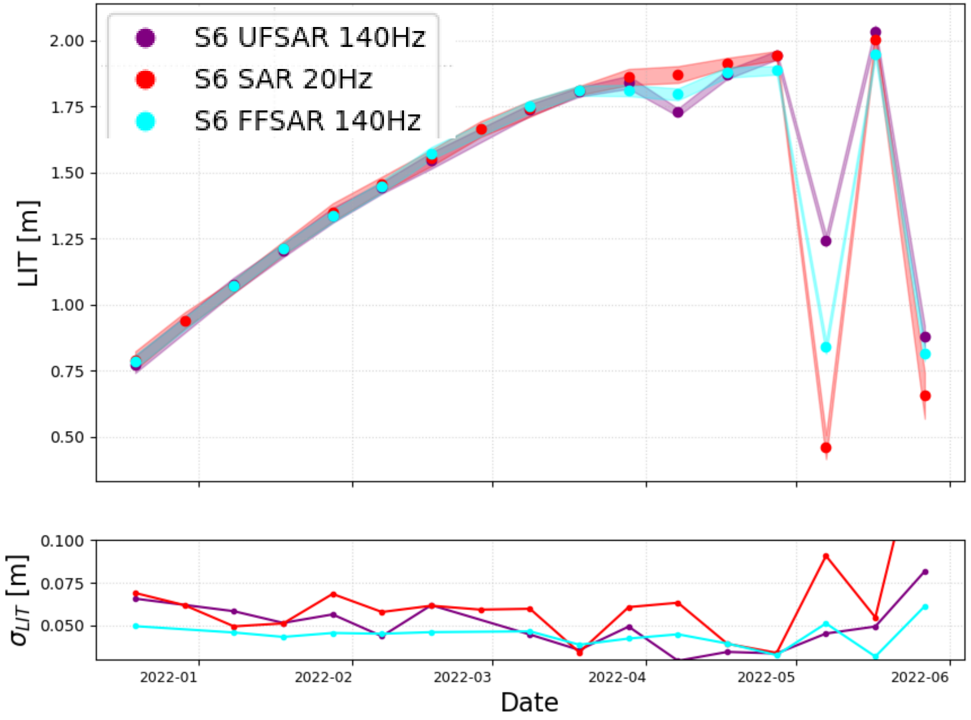




- Good performances of the LRM and SAR LIT retrackers
- Consistent results between LRM and SAR data
- Longer ice season detected wrt to Great Slave lake

Lake Ice Thickness estimation on a smaller target: the Baker Lake





- Good performances of the SAR & FFSAR LIT retrackers
- Increased performance with data at higher posting rate (140 Hz), in particular at the melting transition

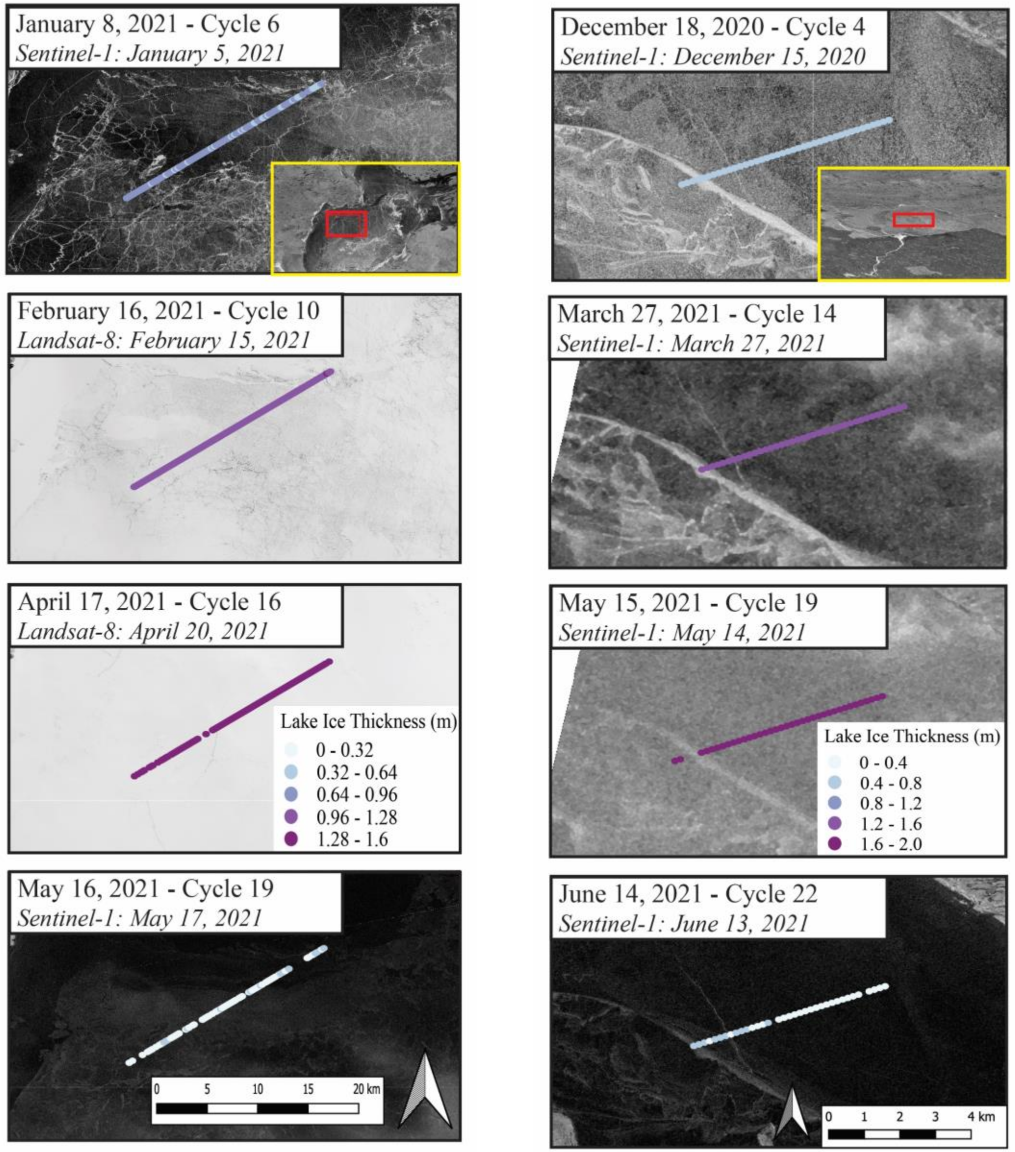
Comparison with optical/radar images

Early winter season:

Middle of the ice season: clear LIT detection with evolving thickness

Beginning of the melting season: the snow cover has largely melted from the ice surface

Great Slave Lake | Baker Lake



Take away message:

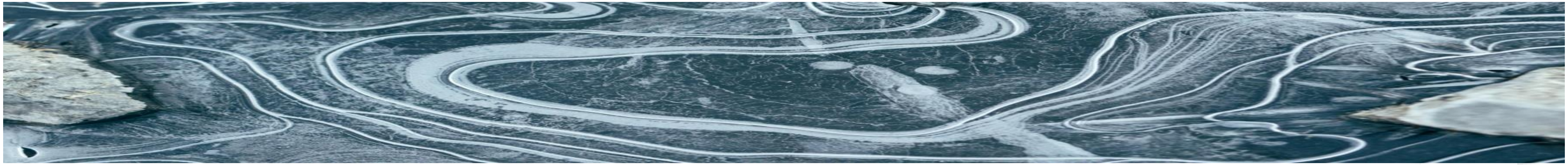
- ✓ Sentinel-6MF LIT estimates (UFSAR@20Hz) are fully consistent with Landsat/Sentinel1 images
- ✓ The SAR_LIT retracker provides reliable estimates of the spatial evolution of LIT and can capture the seasonal transitions for targets with different size, environment and LIT properties

Conclusions and Perspectives

- The Lake Ice Thickness (LIT) is an important variable in the context of climate change that needs precise and continuous monitoring.
- We developed and validated novel analytical retrackers for LIT retrivals from LRM, UFSAR &FFSAR Ku-band radar altimetry data [Mangilli et al 2022, Mangilli et al 2024] that allow to to generate reliable and consistent LIT estimates, precisely capturing the LIT evolution, the seasonal transitions and the inter-annual LIT variability,
- Good consistency between LRM and SAR LIT estimations
- Significant improvement of the LIT estimation with high resolution data UFSAR & FFSAR (LIT uncertainty reduced by a factor of 2 up to 3 wrt to LRM) towards the fulfillment of GCOS requirements

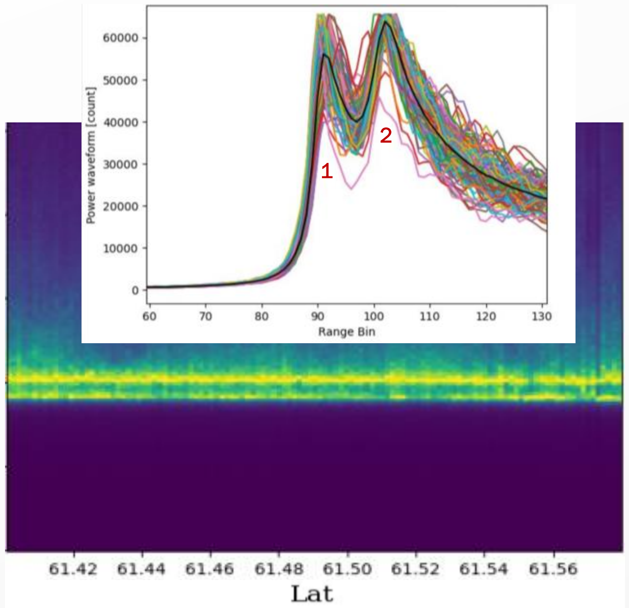
Perspectives

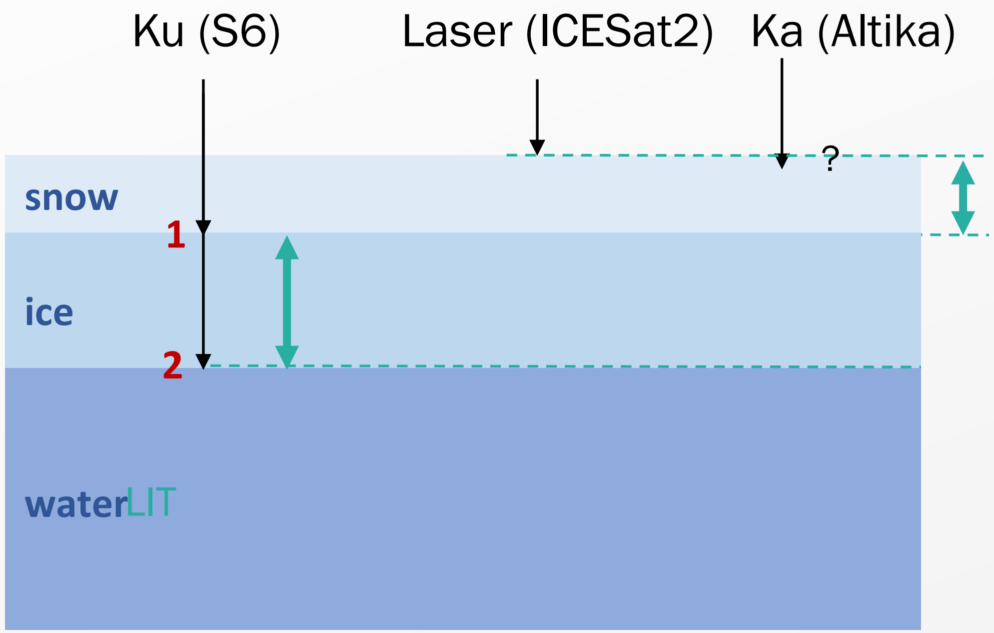
- Climatological studies of long LIT timeseries
- LIT timeseries with SAR data, as Sentinel-6 and Sentinel-3 (higher latitude), to enrich the cci_Lakes datasets
- CLE2VER: development of retracker algorithm for LIT retrivals to be implemented in the CRISTAL prototype processor
- Multi-sensor approach to assess the possibility of measure snow-on-ice depth



Follow-up: CCN proposal

Main goal: assess the possibility of measuring snow-on-ice depth with altimetry data over iced covered lakes. To this purpose, a comparison between data from different sensors will be exploited, namely Ku-band (Sentinel-6), Ka-band (Altika) and laser (IceSat2) data.





Possible additional topic: further investigation of surface roughness of interfaces within the ice and snow column could provide better insights into the impact of these properties on radar waves and could be further supported by radiative transfer models such as SMRT [Picard et al 2018]

Timescale: 2025(-26?). Team: CLS & University of Waterloo/H2OGeomatics

Thank you!

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