A NEW APPROACH FOR THE RETRIEVAL OF LAKE ICE THICKNESS FROM ALTIMETRY MISSIONS

Results from the ESA CCI+ LAKES and S6JTEX projects

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ABSTRACT: Lake ice thickness (LIT) is recognized as an Essential Climate Variable (ECV) by the Global Climate Observing System (GCOS). LIT is a sensitive indicator of weather and climate conditions through its dependency on changes in air temperature and on-ice snow depth. The monitoring of seasonal variations and trends in ice thickness is not only important from a climate change perspective, but it is also relevant for the operation of winter ice roads that northern communities rely on. Yet, field measurements tend to be sparse in both space and time, and many northern countries have seen an erosion of in situ observational networks over the last three decades. Therefore, there is a pressing need to develop retrieval algorithms from satellite remote sensing to provide consistent, broad-scale and regular monitoring of LIT at northern high latitudes in the face of climate change. Here we present a novel, physically-based retracking approach for the estimation of LIT by using conventional low-resolution mode (LRM) and synthetic aperture radar (SAR) Ku-band radar altimetry data. The advantage of a physically-based and analytical retracker is that it does not rely on empirical or by-hand settings, allowing to derive robust and continuous LIT estimates over different target lakes and radar altimetry missions. Results will focus on LIT estimation obtained using Jason-2, Jason-3, and Sentinel-6 data over the Great Slave Lake (GSL) in Canada for different winter seasons. These methods significantly improve the accuracy of the LIT estimations, paving the way towards regular and robust LIT monitoring with current and future LRM and SAR altimetry missions.

The LIT signature on Ku-band radar waveforms. The Ku band radar waveforms on ice covered lakes show, in the case of LRM, a step-like break in the leading edge, and, in the case of SAR, a double peak. This specific signature is related to the double backscattering of the radar wave due to ice. For freshwater lake ice, recent studies based on Ku-band ground-based scatterometry (e.g. [Gunn et al 2015]) and CS2 radar altimetry [Beckers et al 2017] show that, in the case of dry snow, the radar waves scatter at 1) the snow–ice interface and 2) at the ice-water interface. These two interfaces and the radar wave scattering in the case of a Jason-3 LRM waveform and of a S6 SAR waveforms on the GSL are illustrated in Fig. 1. It is worth to notice that the double backscatter signature is generally not observed over sea ice due to the salinity of the ice pack that modifies the reflection properties of the medium.

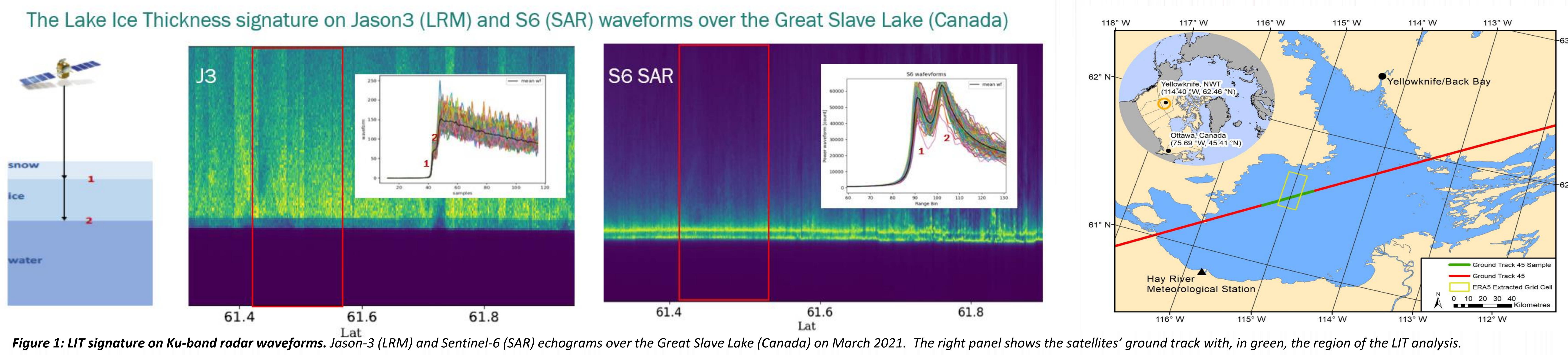
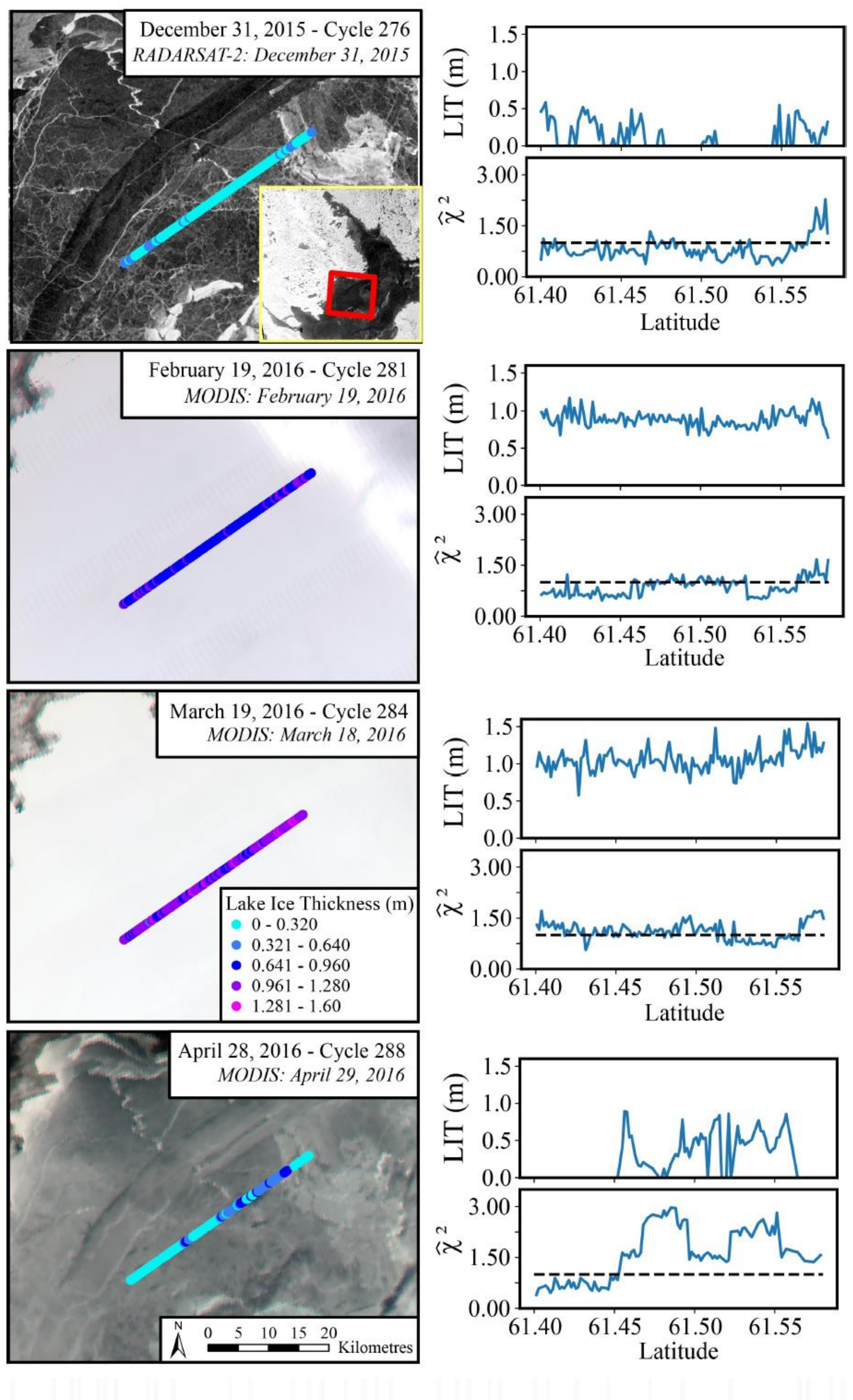


Figure 1: LIT signature on Ku-band radar waveforms. Jason-3 (LRM) and Sentinel-6 (SAR) echograms over the Great Slave Lake (Canada) on March 2021. The right panel shows the satellites' ground track with, in green, the region of the LIT analysis.

Method. We developed a new retracker approach to measure the LIT from the LRM and SAR waveforms over ice covered lakes (see [Mangilli et al.2022] for LRM and [Mangilli et al in prep.] for SAR). Both LRM and SAR retrackers rely on the physical modelling of the waveforms as the sum of two backscattered echoes. The LRM_LIT retracker is based on a Brown-like modelling with an additional LIT parameter related to the width of the step in the leading edge. The SAR_LIT retracker is based on the Samosa formalism [Ray et al. 2015] with an additional LIT parameter linked to the peak separation. For each data cycle, and a given Region of Interest (RoI) defined over a target lake, the LIT analysis consists of two steps: 1) the optimization step, that is the waveform fit, and 2) the estimation of the parameters mean and standard deviation. The optimization step consists of performing a Least Square Levenberg-Marquardt weighted fit of each echo in the LIT analysis window. The weights are computed as the standard deviation of the echoes within the LIT analysis window, thus accounting for the waveform noise and providing with an optimal parameter estimation. The parameter estimation is done by computing the mean and standard deviation of the fitted parameters in the RoI.



Results: We analyzed Jason-2, Jason-3 and S6-LRM with the LRM_LIT retracker and S6-SAR data with the SAR_LIT retracker over a representative section of GSL for different ice seasons, and we obtained consistent and robust LIT estimates. The comparison with RADARSAT-2 and MODIS images over an ice season, showed in the left panel of Fig. 2, further confirms the consistency of the results, showing the capability of the retracker to capture the seasonal transitions of ice formation and melt. However, due to the difficulty in retracking heterogeneous and highly reflective surfaces, the retracker cannot follow precisely the ice formation and melt within the transition periods, namely the evolution and thinning of the melting ice.

We compared the altimetry based LIT results obtained with different missions with LIT estimations from the CLIMo simulations [*Duguay et al. 2003*] and in-situ data. A summary example of the comparison is given in the middle panel of Fig.2. We find a very good agreement between the Jason2-3 LIT estimations and the CLIMo simulations. We note that in situ data are collected near the shore, while altimetry data are taken from a track in the middle of the lake. These are indeed two different environments in terms of bathymetry, wind exposure, snow type and quantity. All these parameters play a key role on ice formation and thickness and they can lead to LIT differences in the order of tens of centimeters. Therefore, the comparison between LIT estimates from altimetry missions and in situ data must be treated with caution and should be considered only as qualitative.

The bottom right panel of Fig. 2 shows the comparison between LIT estimates obtained with LRM data (Jason-3 and S6) and SAR data (S6) over the same GSL region for one ice season during the S6-J3 tandem phase (2020-21), highlighting the consistency of the LIT measurements between different missions and data type. The accuracy of retrievals, once the ice is well established on the lake surface, is in the order of 10 cm for LRM data and only 3 cm for SAR data, providing a significant improvement when compared to previous studies.

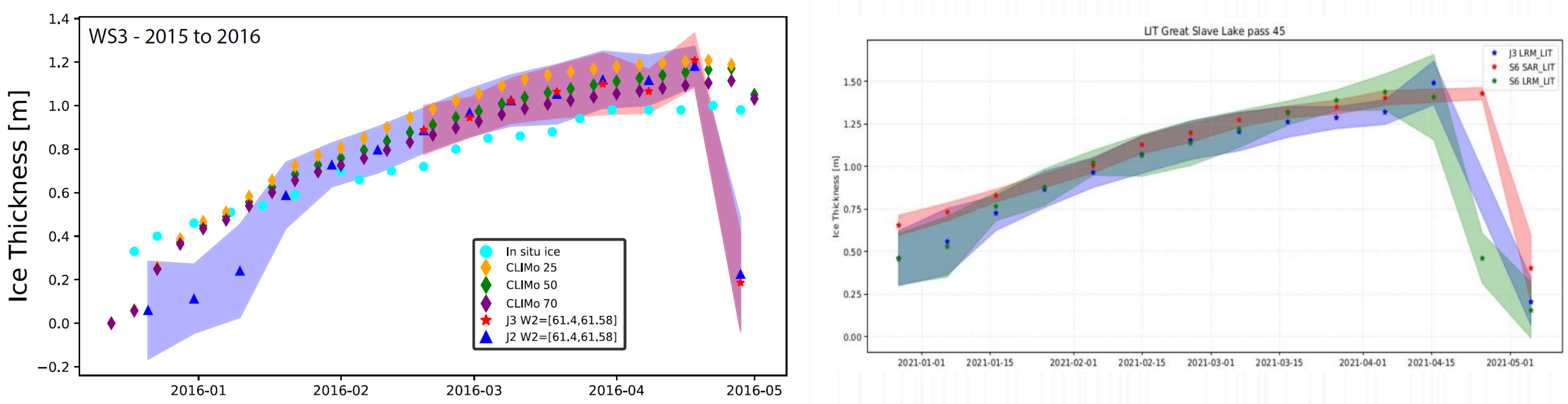


Figure 2: LIT retrievals on the Great Slave Lake from Jason-2/3 (LRM) and Sentinel-6 (LRM and SAR) data for different ice seasons [Mangilli et al. 2022]. The left panel shows the evolution of the along-track Jason-2 LIT estimates superimposed on MODIS images for the 2015-16 ice season. The middle panel shows the comparison between LIT estimates from Jason-2 and Jason-3 data, CLIMo simulations and in situ data for the same season. The right panel shows the comparison between LIT estimates obtained with LRM data (Jason-3 and S6) and SAR data (S6) over the same GSL region for one ice season during the S6-J3 tandem phase (2020-21). The shaded areas correspond to the LIT estimation uncertainties.

Conclusions: We developed a new and efficient retracking approach for the estimation of LIT by using LRM and SAR Ku-band radar altimetry data. The method is based on the physical modelling of the radar backscatter over ice covered lakes and provides an analytical description of the radar waveforms that show a specific LIT signature. The LIT retracker allows to capture the LIT seasonal evolution and the inter-seasonal ice variability with improved accuracy with respect to previous methods, making it a powerful tool for the understanding and monitoring capabilities of this important ECV in the context of climate change.

Acknowledgements: The LRM_LIT algorithm has been developed in the framework of the ***European Space Agency's Climate Change Initiative (CCI+) Lakes*** project and is currently being implemented for the production of LIT time series from LRM data for Phase 2 of the project started in July 2022. These data will be publicly available to the scientific community through a dedicated data platform, following the project schedule (2022-2025). The SAR_LIT algorithm is being developed within the ***ESA S6JTEX project*** that aims at enhancing the scientific return of the tandem phase between the Jason-3 and Sentinel-6 reference missions, allowing for continuity of observations across 30 years of conventional altimetry (from Topex or ERS in 1992) and SAR altimetry data.

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