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TAKING THE PULSE OF OUR PLANET FROM SPACE

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# A New Approach for the Retrieval of Lake Ice Thickness From Satellite Altimetry Missions

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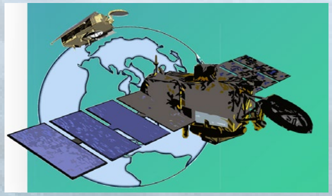
# OUTLINE

- Overview: Lake Ice Thickness (LIT) and altimetry
- A new approach for the estimation of LIT from conventional radar altimetry data (ESA Climate Change Initiative project CCI-LAKES)
  [A. Mangilli, P. Thibaut, C. Duguay, J. Murfitt, IEEE TGRS 2022]
- Preliminary results of LIT estimation from SAR data (ESA S6JTEX project)



- Conclusions and perspectives

# OVERVIEW

**Lake Ice Thickness (LIT):**

- Recognized by GCOS as a thematic variable under Lakes as **Essential Climate Variable (ECV)**
- **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 lake ice thickness is important from a climate change perspective**, and it is also relevant for the operation of winter ice roads used by northern communities

- **Field measurements tend to be sparse** in both space and time; **satellite radar altimetry can play an important role in providing broad-scale and regular monitoring of LIT**

- **Few studies have investigated the potential of radar altimetry data for the estimation of LIT**, e.g. Beckers et al. 2017 (CryoSat-2 data) and Yang et al. 2020 (Jason data, improve Lake Water Level estimates)**. Empirical methods** based on thresholds are difficult to generalize to different targets

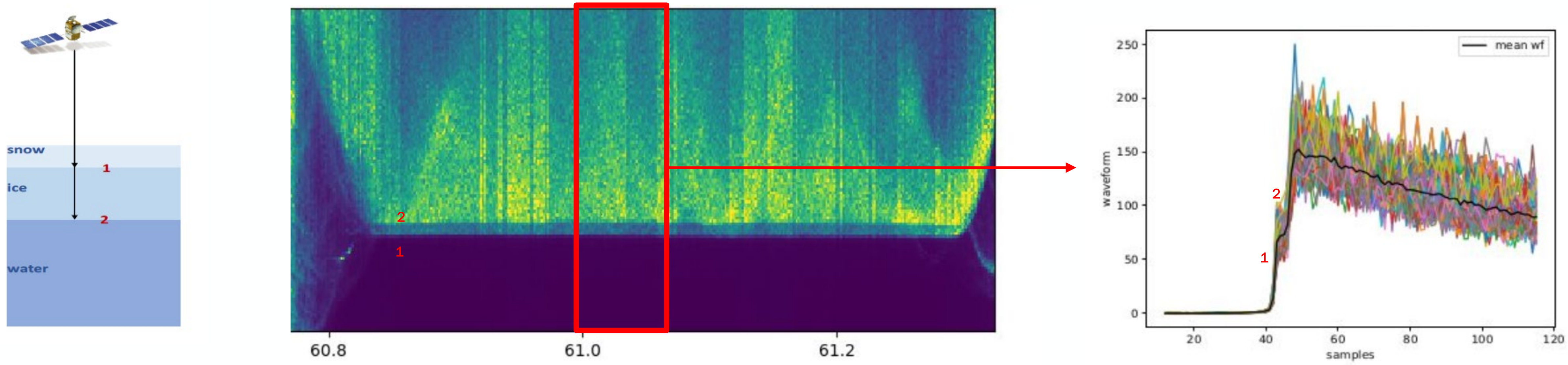
- **Goal : To develop a method based on the physical/analytical modelling of radar waveforms for the estimation of LIT.**

# OVERVIEW

## Lake Ice Thickness signature in Ku-band Low Resolution Mode (LRM) echoes

**Step-like feature in the radar echoes** on iced lake surface due to the double backscattering of the radar wave at the snow/ice interface (1) and at the ice/water interface (2).

**The width of the step is linked to the ice thickness**.




Great Slave Lake in winter as seen by Jason-3. Pass 45 cycle 148 (February 2020)

# A NEW APPROACH FOR THE ESTIMATION OF LIT

## LRM_LIT retracker [Mangilli et al. 2022]

- Based on the physical (Brown's) modelling of the radar waveforms: analytical description of the waveform as the sum of two backscattered echoes:

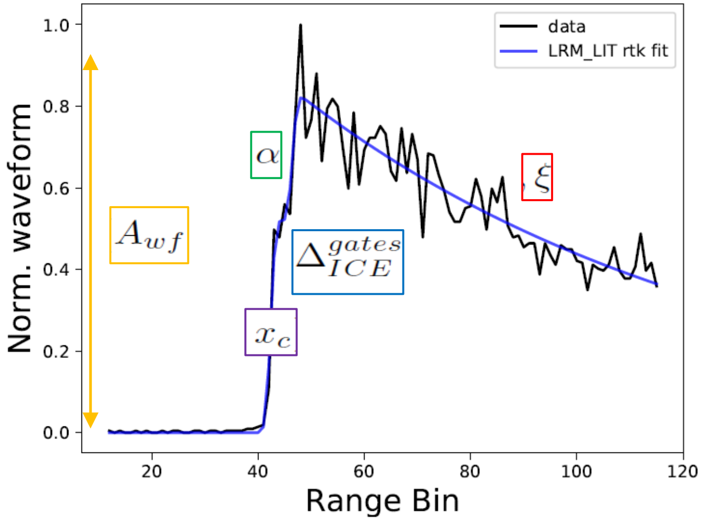
$$S(\mathbf{x}) = [S_1(\mathbf{x}) + \alpha S_2(\mathbf{x})]\, e^{-\xi \hat{\mathbf{x}}} + N_t$$

$$S_1(\mathbf{x}) = \mathrm{erf}(\mathbf{x} - x_c) + 1$$
$$S_2(\mathbf{x}) = \mathrm{erf}(\mathbf{x} - x_c - \Delta_{ICE}^{gates}) + 1$$

- 5-parameter model: $S_{LRM\_LIT}(\mathbf{x}, \theta_\mathbf{p}) = A_{wf}\hat{S}(\mathbf{x})$

$$\theta_\mathbf{p} = \{A_{wf}, \Delta_{ICE}^{gates}, \alpha, \xi, x_c\}$$

the overall amplitude, the ice thickness (range gate unit), the amplitude of the second scatter, the attenuation of the trailing edge, and the central (epoch) gate.




- Ice thickness in units of metres:

$$\Delta_{ICE} = \Delta_{ICE}^{gates}\frac{c_{ice}}{2B} = \Delta_{ICE}^{gates}\frac{c}{n_{ice}2B}$$

# A NEW APPROACH FOR THE ESTIMATION OF LIT

## LRM  LIT retracker [Mangilli et al. 2022]

For each data cycle in a chosen analysis window over a target lake, 2 steps:

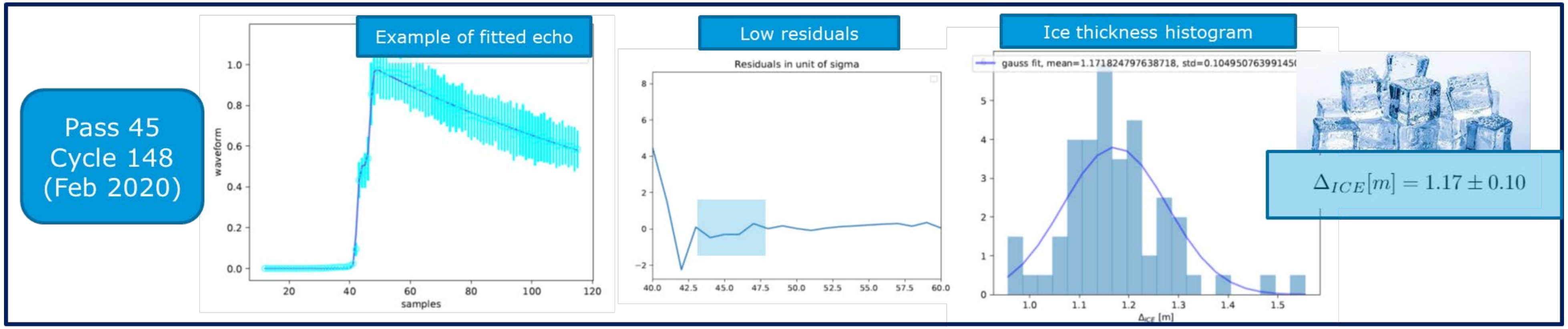
- **Optimization:** Weighted Least Square Levenberg-Marquardt fit of LRM individual waveforms (typically ~100 echoes)

$$\chi^2 = \mathbf{r}^T \mathbb{C}^{-1} \mathbf{r} \simeq \sum_i \left(\frac{r_i}{\sigma_i}\right)^2$$

residuals $\mathbf{r} = y(\mathbf{x}) - S_{LRM\_LIT}(\mathbf{x}, \theta_{\mathrm{p}})$

weights ($\sigma_i$): std of the echoes in the analysis window

- **Parameters estimation:** Mean and standard deviation of the best-fit values of the 5 parameters in the analysis window (Gaussian fit of the parameter histograms)



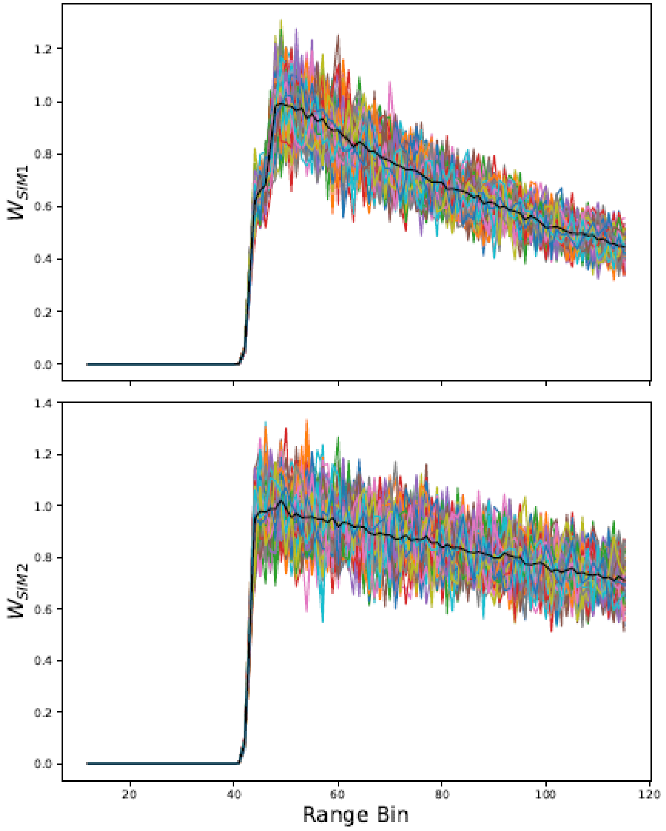

The LRM LIT retracker allows for **LIT estimations with uncertainties**

# VALIDATION OF THE LRM_LIT RETRACKER ON SIMULATIONS

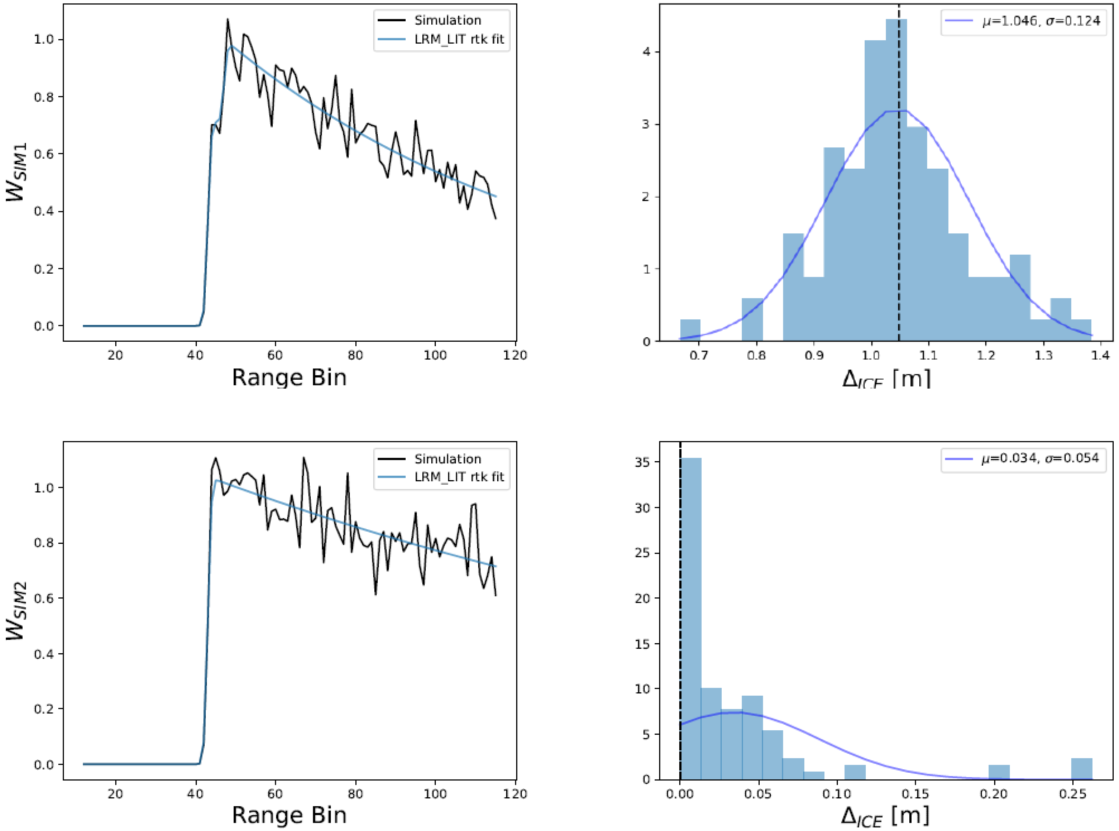
Jason-like waveform simulations: $W_{SIM} = W_{model}^{SIM} N_{speckel} + N_t$

Winter-like SIMS (LIT~1m)

Summer-like SIMS (LIT=0)




LRM_LIT retracker




- Very good fit performances, unbiased LIT results for both simulation sets
- LIT uncertainty of ~ 10 cm

# LIT ANALYSIS OF JASON DATA OVER GREAT SLAVE LAKE

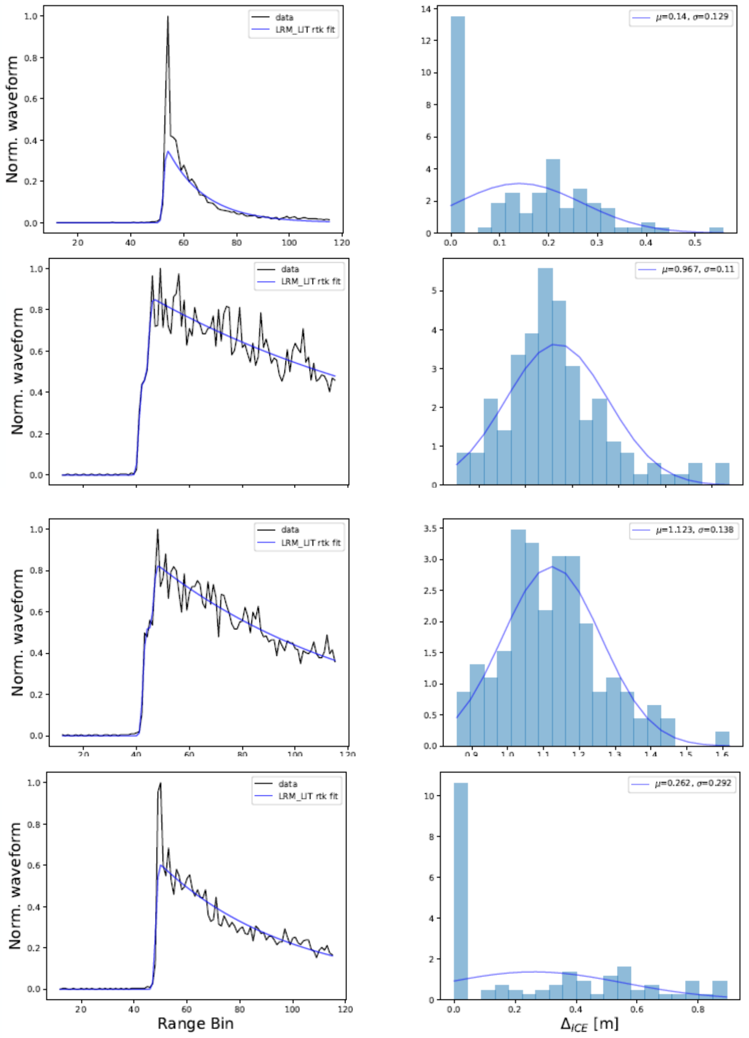
**LRM-LIT fit example** | **LIT histogram**

December

February

March

End of April




Early winter season: no clear ice signature. Peaky waveforms. Heterogeneous and reflecting surface.

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

Beginning of the melt season: the snow cover has largely melted from the ice surface (lower reflectance). Peaky waveforms. Heterogeneous and reflecting surface

# LIT ANALYSIS OF JASON DATA OVER GREAT SLAVE LAKE

esa

lakes cci

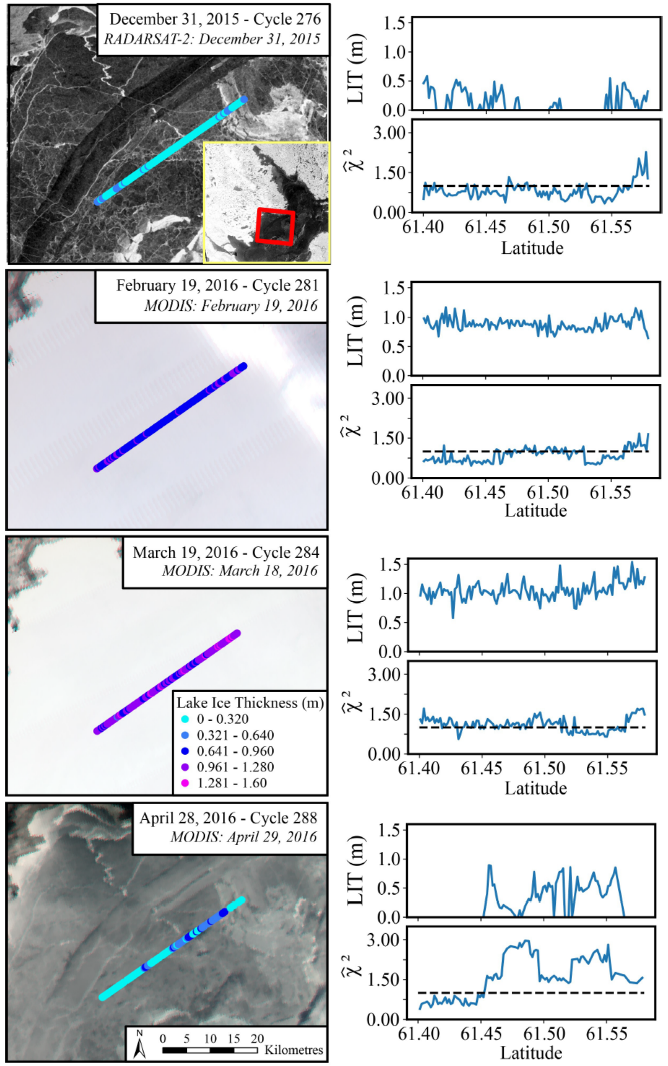
## LRM_LIT estimates and MODIS/RADARSAT images

December

February

March

End of April




Early winter season: no clear ice signature. Peaky waveforms. Heterogeneous and reflecting surface.

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

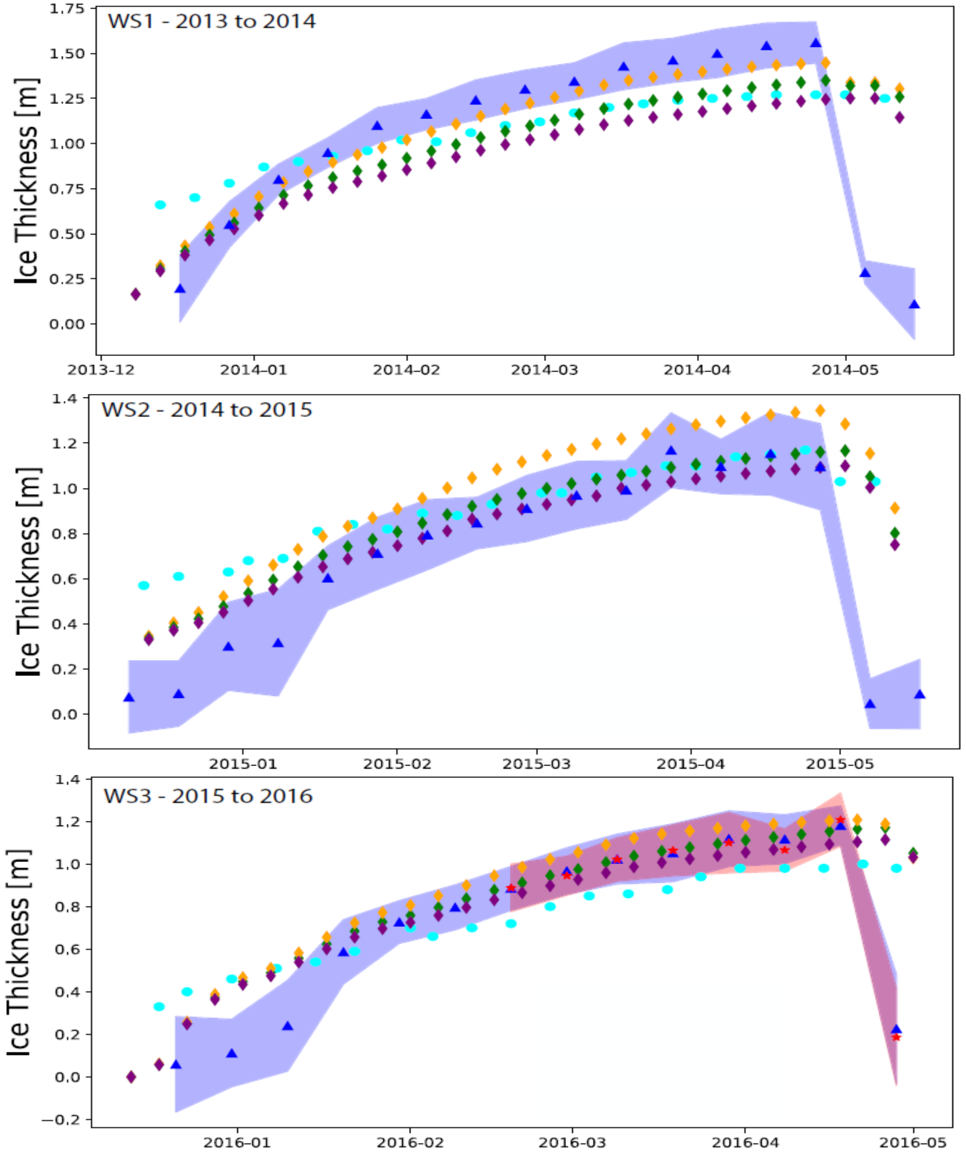
Beginning of the melting season: the snow cover has largely melted from the ice surface (lower reflectance). Peaky waveforms. Heterogeneous and reflecting surface

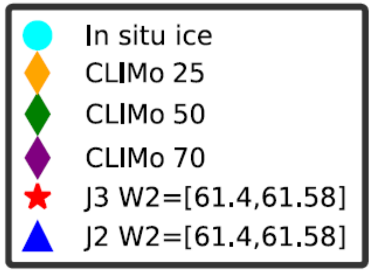
**Take-away message**

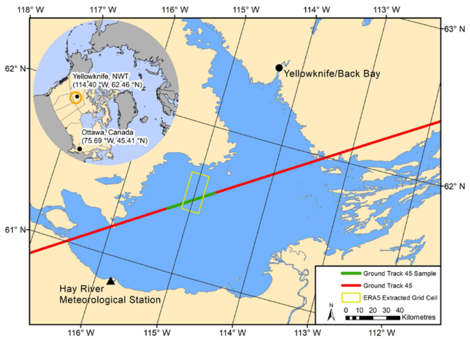
- ✓ LIT estimates from Jason data are fully consistent with MODIS/RADARSAT-2 images
- ✓ LRM_LIT retracker provides reliable estimates of the spatial evolution of LIT and can capture the seasonal transitions, yet it cannot precisely follow the ice evolution in the (snow) melting phase
- ✓ LIT accuracy estimation ~10cm

# LIT ANALYSIS OF JASON DATA OVER GREAT SLAVE LAKE

**LIT estimation over 3 ice seasons (2013-2016): Comparison with CLIMo simulations [Duguay et al. 2003] and in-situ data**



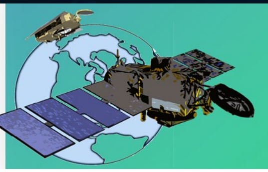



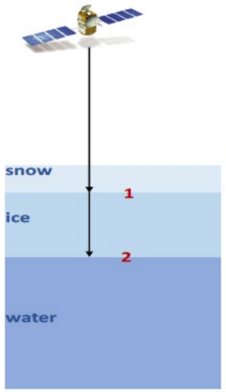

## Take-away message

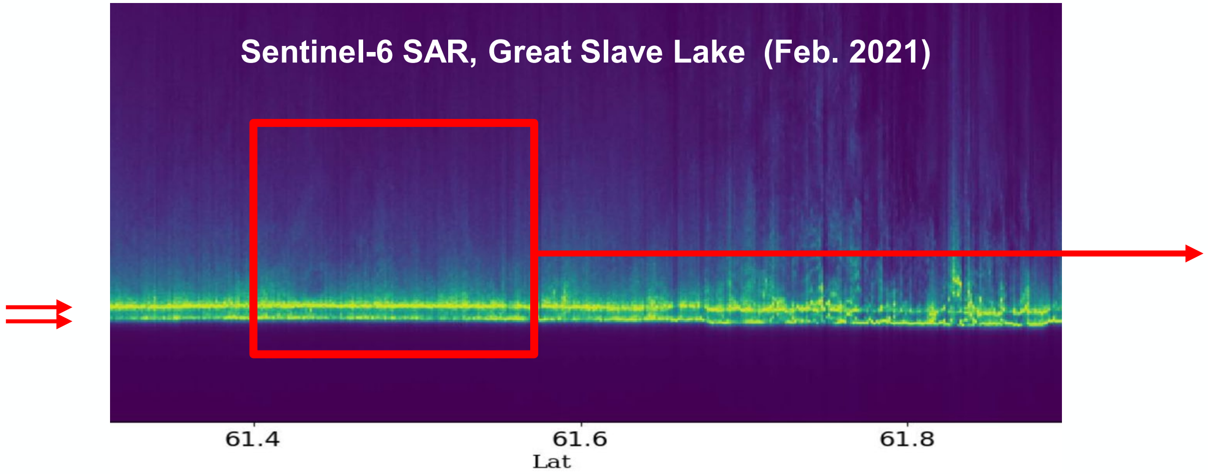
- ✓ LIT estimates from radar altimetry are compatible with thermodynamic simulations and qualitatively in agreement with in-situ data
- ✓ Caveat with in-situ data comparison: in situ are collected near the shore while radar data are from the middle of the lake (expected LIT difference up to tens of cm)
- ✓ The LRM_LIT retracker can capture the inter-seasonal LIT variation

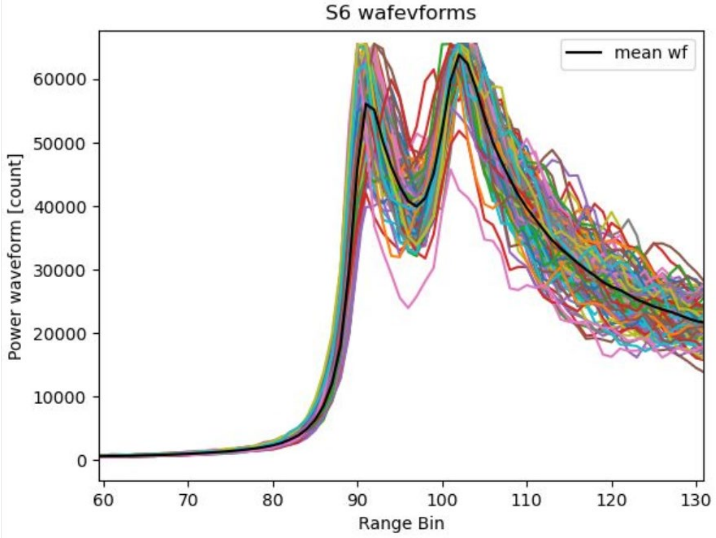
# LIT SIGNATURE ON SAR WAVEFORMS



**Double peak** on SAR waveforms (different signature in contrast to LRM) over ice covered lakes due to the backscattering of the radar wave at the snow/ice interface (1) and at the ice/water interface (2). **The <u>peak separation is linked to the ice thickness</u>**




**<u>SAR LIT retracker [A. Mangilli, P. Thibaut, C. Duguay & J. Murfitt, in preparation]</u>:**

- Same approach as for LRM (physical retracker, analytical model) but different modelling based on SAMOSA formalism (Ray et al. 2015). Optimization step: Weighted Least Square Estimator, Levenberg-Marquardt fit.
- **First analytical modelling of SAR waveforms with LIT signature**

# PRELIMINARY ANALYSIS OF SENTINEL-6 SAR DATA

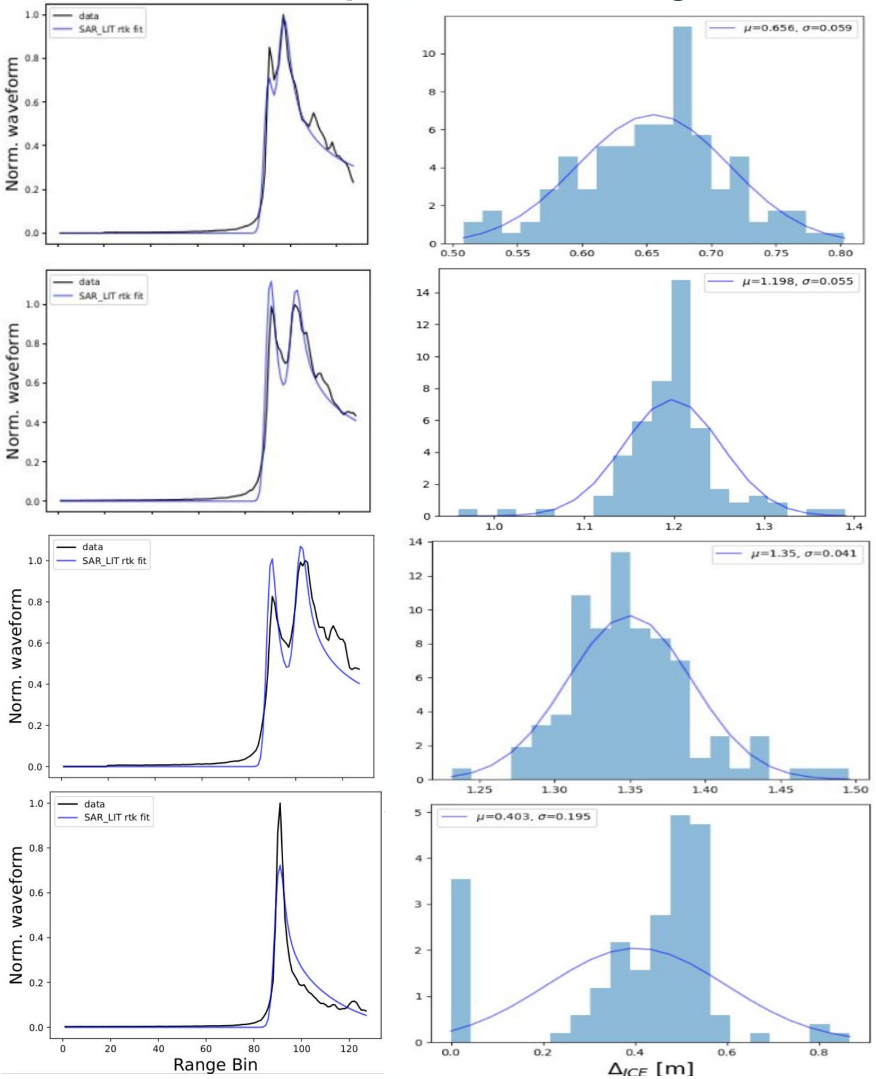
**SAR-LIT fit example** **LIT histogram**

December

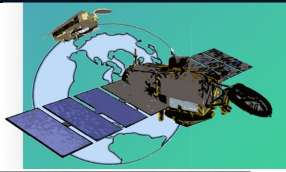
February

March

End of April



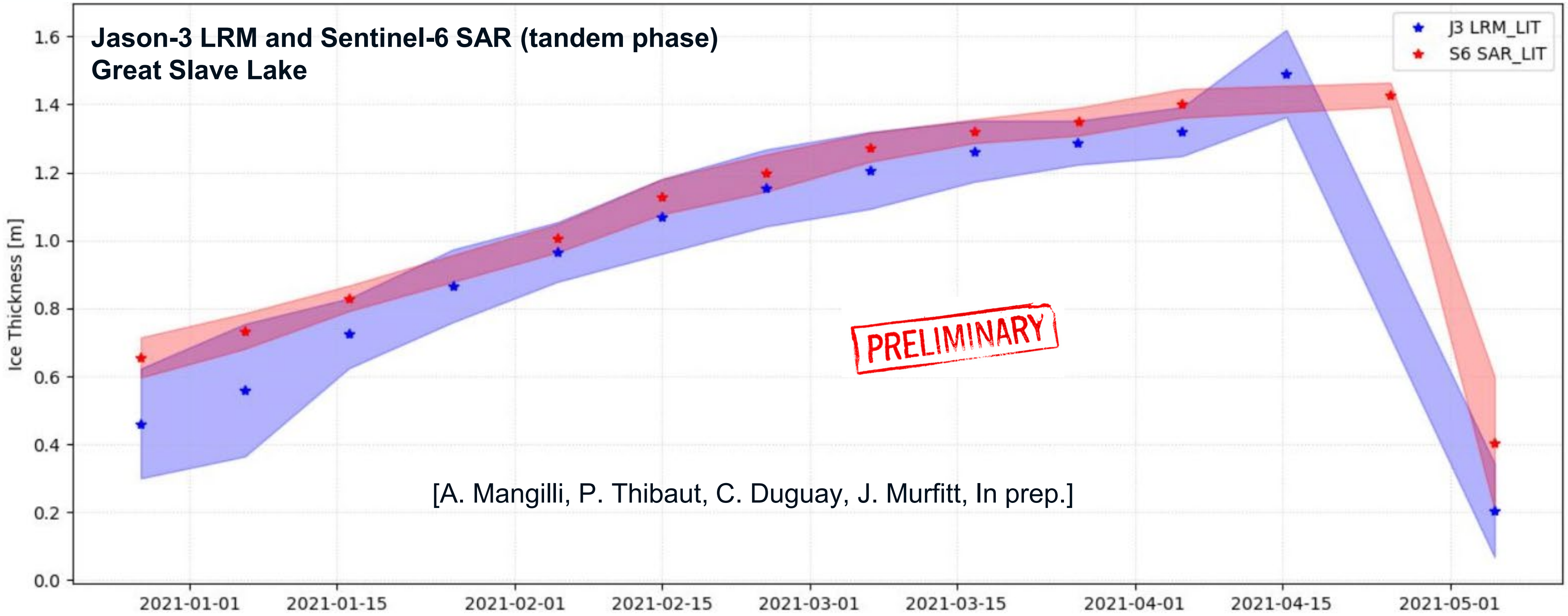

PRELIMINARY

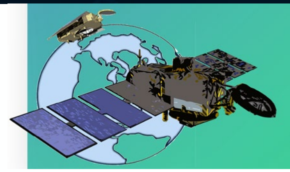


**Preliminary results:**

- ✓ The first implementation of the SAR_LIT retracker provides consistent LIT results when applied to S6 SAR data
- ✓ Significant improvement of the LIT estimation accuracy (~5 cm compared to ~10 cm of LRM_LIT)

# PRELIMINARY ANALYSIS OF SENTINEL-6 SAR DATA



__Preliminary results are promising:__ the LIT estimation is consistent with J3 LRM_LIT estimates. **Significant improvement on the accuracy of the LIT estimation**

__Work in progress__ to improve the fit (and model) accuracy + validation on simulations and comparison with LIT estimates obtained from LRM Sentinel-6 data and thermodynamic CLIMo simulations

# CONCLUSIONS AND PERSPECTIVES

- **Lake Ice Thickness (LIT) is an important variable in the context of climate change** that needs precise and continuous monitoring.
- In the frame of the **ESA CCI-LAKES** project, we developed and validated a **new method for the estimation of LIT** from radar altimetry data, the LRM_LIT retracker **[Mangilli et al. TGRS 2022]**, which is a powerful tool for LIT trend studies and monitoring
- Development of the **SAR_LIT retracker** is underway (**ESA S6JTEX project**). Preliminary results are very promising. Next steps: validation and assessment of the accuracy of the SAR LIT estimations and comparisons with LRM results

## PERSPECTIVES:

- **LIT ECV** variable **CCI-LAKES Phase 2** (starting in June 2022): long LIT times series will be produced (LRM_LIT retracker) on relevant target lakes using LRM altimetry data (Envisat/Jasons/Sentinel-6)
- Include LIT estimation outputs in the products on specific targets for monitoring and improving lake analysis as the presence of lake ice and its growth can bias the estimation of other variables, such as lake water level.

# Thank you!