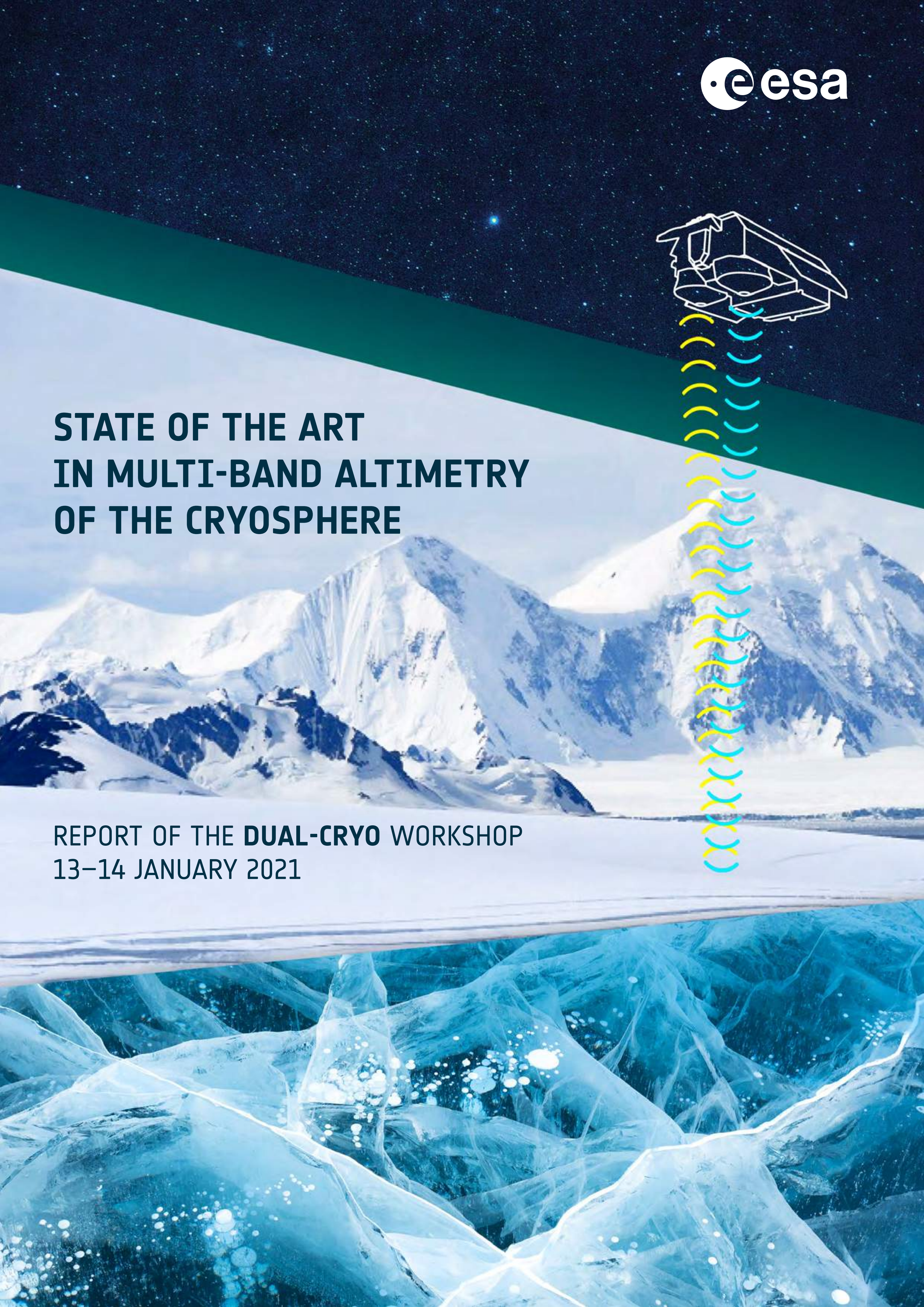

STATE OF THE ART IN MULTI-BAND ALTIMETRY OF THE CRYOSPHERE

REPORT OF THE **DUAL-CRYO** WORKSHOP
13–14 JANUARY 2021

The Workshop on “State of the art in multi-band altimetry of the cryosphere” (DUAL-CRYO Workshop) took place online, on 13/14 January 2021.

Workshop Chairs:

Andrew Shepherd, Univ. of Leeds/CPOM; Paolo Cipollini, ESA
This Workshop Report, which collates contributions from all presenters, has been compiled by Paolo Cipollini (EOP-SME), with the support of Günther March (EOP-SME), in the Earth and Mission Science Division, ESA-ESTEC.

Guidance and encouragement from Michael Kern, former CRISTAL Mission Scientist, are gratefully acknowledged.

Workshop web site:

https://atpi.eventsair.com/QuickEventWebsitePortal/dual-cryo-workshop/website

Cover Image: *A view of Antarctic landscape taken in the vicinity of the Rothera Research Station (British Antarctic Survey) during the CryoVEx/KaREN campaign in 2018. Photo by Tânia Casal, ESA.*

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Rationale and introduction

The Cryosphere plays a critical role within Earth's climate system, both in the radiation budget and in the sea level budgets. Loss of sea ice makes planetary warming worse by causing a reduction of albedo, while loss of land ice from ice sheets and glaciers is a primary contributor to sea level rise. Monitoring and projecting the rate of these losses are key elements of climate research; sustained long-term monitoring, in particular, is essential for understanding and modelling the various processes at play.

Radar altimetry has provided key observations of the Cryosphere with multiple missions spanning more than three decades, complemented by laser altimetry from ICEsat over 2003–2010 and then with ICEsat-2 from 2018 onwards. These space-based observations are a unique component of the monitoring system as they provide synoptic coverage. The resulting long-term record is of vital importance to understand past and present trends in ice loss, and predict future ones. The future Copernicus polaR Ice and Snow Topography ALtimeter (CRISTAL) mission is proposed as part of Copernicus Sentinels' expansion. Its two satellites will provide crucial data on the Cryosphere as primary objective and will bring ice monitoring into full operational realisation within the Copernicus framework, building on the legacy of CryoSat.

Present and future altimeter observing systems use a number of different radar bands: observations in Ku band have traditionally been and remain the workhorse of polar (and ocean) altimetry; some Ku-band altimeters gathered and/or are gathering additional echoes at a lower frequency (S-band on Envisat, C-band on the Topex/Jason series, Sentinel-3 and Sentinel-6) for the purpose of estimating ionospheric path delay, and these echoes convey surface information too. These instruments have been accompanied since 2012 by the Ka-band AltiKa altimeter on CNES/ISRO's SARAL mission, which has shown very promising performance in terms of along-track resolution and comparatively low noise. CRISTAL will feature unprecedented dual Ku/Ka-band capability on the same platform, allowing coincident observations in the two bands to be collected and exploited for a number of primary and secondary objectives. CRISTAL's primary objectives pertain to the Cryosphere: to measure and monitor sea ice thickness and its snow depth, as well as the surface elevation and changes of land ice (glaciers and ice sheets). Laser altimetry from the IceSAT missions provides another independent and complementary view of the ice surfaces. A number of campaigns with in situ measurements and airborne radar and laser measurements have been carried out in the last two decades in the polar regions. NASA's Operation IceBridge (which has completed 11 years of polar surveys) and ESA's CryoVEx campaigns (which started in 2002 and are still active) provided crucial information for calibrating retrievals and aiding the interpretation of the satellite data.

As a fundamental step towards the full exploitation of the wealth of data and information available from the satellite missions and the polar campaigns over the cryosphere, a clear need has recently arisen in the cryospheric science community for **a scientific workshop reviewing the state of the art and prospects of dual-band (and multi-band) altimetry over ice surfaces.** ESA has responded to this need by organising and convening **the Workshop on Dual-band Altimetry of the Cryosphere (DUAL-CRYO).** The workshop objectives were:

- ➜ to review the state of the art in dual-band altimetry of the cryosphere (Ku, Ka, and Laser);
- ➜ to identify the relevant campaign data (in situ, airborne, and satellite);
- ➜ to discuss and summarise processing techniques, algorithms, and limitations for dual-band altimetry of the cryosphere;
- ➜ to identify gaps in the technical knowledge and observational data, and to make recommendations for further studies.

The DUAL-CRYO workshop also served the purpose **of confirming and consolidating the science case for dual-band altimetry from CRISTAL, and promoting this mission's timely and rapid implementation.** This is particularly important given the prospect of a gap in polar observations poleward of 82° latitude, which are at present provided by CryoSat-2 (CS2) and ICEsat-2 (IS2). Though launched in 2010, CryoSat-2 remains in good condition and current calculations indicate the mission could last until the end of 2026, assuming no unexpected failure or incident. ICESat-2 mission status is also satisfactory according to NASA: the mission, launched in September 2018, has been designed to operate for 3 years with a goal of 5 years (and fuel for 7 years). The laser instrument is recognised as the main life-limiting factor. The first of the two planned CRISTAL satellites is planned to be launched in the second half of 2027. Therefore, the possibility of a gap is real and has raised the legitimate concerns of the scientific community.

DUAL-CRYO was held online over two half-days on 13th and 14th January 2021 and had 133 registered participants. More than 100 participants attended simultaneously online over each one of the two days, dedicated to land ice and sea ice, respectively. Each day started with a keynote on the state of the art and scientific readiness of dual band measurements over the respective domain (land ice and sea ice). This was followed by invited or regular contributions based on abstract submission (18 presentations in total). The workshop Agenda is listed in the next page. The online version of the agenda includes links to all workshop presentations and can be found at https://atpi.eventsair.com/QuickEventWebsitePortal/dual-cryo-workshop/website.

The main output of the workshop is this report, which summarizes the status of multi-frequency altimetry of the cryosphere from both satellites and aircrafts, and provides recommendations and a roadmap for improvement of the scientific readiness level of Ku and Ka algorithms over Ice Sheets and Sea ice. This report should also serve as the basis for a community white paper to be collated and submitted for peer review in the near future.

The Kangerlussuaq Glacier, one of Greenland's largest tidewater outlet glaciers, is pictured in this false-colour image captured by the Copernicus Sentinel-1 mission. Meaning 'large fjord' in Greenlandic, the Kangerlussuaq Glacier flows into the head of the Kangerlussuaq Fjord, the second largest fjord in east Greenland.

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DUAL-CRYO Workshop Agenda

DAY 1 – Wednesday 13 Jan 2021

WebEx opens at 13:30 for connection troubleshooting

14:00 – 14:10 Introduction & workshop objectives, **Andrew Shepherd** (Univ. Leeds)

Land Ice (Chair: Mal McMillan)

14:10 – 14:30 **Keynote: State of the art and SRL of dual-band measurements on land ice and ice sheets, Mal McMillan** (Univ. Lancaster) et al

14:30 – 14:50 **Invited contributions** (10' each)

- Comparisons of satellite and airborne radar and laser altimetry over the ice sheets, **Inès Otosaka** (Univ. Leeds) et al
- Greenland ice sheet mass balance 1992-2020 from radar altimetry, **Sebastian Simonsen** (Tech. Univ. Denmark) et al

14:50 – 15:20 **Regular contributions** (7' each):

- Altimetry mission performances over Antarctica: Cryosat-2, AltiKa and Sentinel-3A, **Jérémie Aublanc** (CLS) et al
- Adaptation of the Snow Microwave Radiative Transfer model (SMRT) for altimetric applications in the Antarctic ice sheet, **Ghislain Picard** (CNRS) et al
- Towards a comprehensive analysis of radar altimetry backscattering over the cryosphere, **Frédéric Frappart** (LEGOS) et al
- CryoSURF: Deep Neural Networks to combine elevation measurements over the ice sheet, **Martin Ewart, Alex Horton** (EarthWave) et al

15:20 – 15:35 **Break**

15:35 – 15:45 **Invited contribution**

- Time varying surface penetration bias generated from coincident ICESat-2 and CryoSat-2 observations over Greenland and Antarctica, **Johan Nilsson** (JPL)

15:45 – 17:30 **Discussion:** Identify gaps in the technical knowledge and observational data, and make recommendations for further studies

DAY 2 – Thursday 14 Jan 2021

WebEx opens at 13:30 for connection troubleshooting

Sea Ice (Chair: Eero Rinne)

14:00 – 14:20 **Keynote: State of the art and SRL of dual-band measurements on sea ice, Eero Rinne** (FMI), **Heidi Sallila** et al

14:20 – 14:50 **Invited contributions** (10' each)

- Scattering characteristics and snow depth determination from KuKa Ku- and Ka-band polarimetric, dual frequency, ground-based radar deployed in altimeter mode during MOSAiC, **Rosemary Willatt** (UCL) et al
- Combining ESA and NASA altimetry over sea ice, **Rachel Tilling** (NASA GSFC/U Maryland) et al
- Snow depth on sea ice from airborne Ku/Ka-band and ultra-wide band radars, **Stefan Hendricks** (AWI) et al

14:50 – 15:00 ESA dual frequency campaign datasets, **Tânia Casal** (ESA)

15:00 – 15:10 NASA IceBridge observations in support of 3-band altimetry, **Sinéad Farrell** (Univ. Maryland) / CReSIS Ka-band radar altimeters and data review, **Fernando Rodrigues-Morales** and **Jilu Li** (CReSIS, Univ. Kansas) et al

15:10 – 15:25 **Break**

15:25 – 16:00 **Regular contributions** (7' each):

- Comparing coincident elevation and freeboard of IceBridge ATM, Cryosat-2, and Sentinel-3 over Arctic sea ice, **Donghui Yi** (NOAA) et al
- 25 years of airborne multi-band altimetry - the ESA CryoVEx campaigns and related campaigns in the Arctic and Antarctica, **Rene Forsberg** (Tech Univ Denmark) et al
- Dual-frequency airborne radar measurement for potential estimates of snow depth, **Henriette Skourup** (Tech Univ Denmark) et al
- Baltic SEAL: assessment and perspectives of Ku- and Ka-band sea level retrieval with and without sea ice coverage, **Marcello Passaro** (DGFI-TUM) et al
- Multi-frequency satellite approaches for snow on sea ice: Polar+ Snow, **Michel Tsamados** (UCL) et al

16:00 – 16:10 **Invited contribution**

- Differencing IceSat-2 and CryoSat-2 freeboards, **Ron Kwok** (APL, Univ. Washington)

16:10 – 17:30 **Discussion:** Identify gaps in the technical knowledge and observational data, and make recommendations for further studies

DAY 1 Land Ice

Malcolm McMillan kicked off the session with a keynote talk on the state of the art and scientific readiness of dual-band measurements over land ice, drawing on results from core work by the UK Center for Polar Observations and Modelling and from a number of studies such as ESA-SPICE (Sentinel-3 Performance improvement for ICE sheets), Sentinel-3 Tandem for Climate, and the Polar Monitoring Mission study funded by the CRISTAL Project.

It is useful to start from considering the ideal situation of a flat ice sheet surface, such as the one at the surface of subglacial Lake Vostok in Antarctica. The ice is freely floating over the surface of the lake, providing an almost perfectly flat geometry (the surface slope is typically less than 0.01°), also very smooth (one or two centimetres variation in roughness), which makes it into a very good reference calibration site for altimetry.

The Radar backscatter from this ideal ice surface has been analysed in the SPICE project which looked at waveforms in Ka band from AltiKa, and in Ku band from CryoSat-2 both in Synthetic Aperture Radar (SAR) mode and in pseudo-Low Resolution Mode (pLRM), around a crossover between the two satellites (see Figure 1). In particular CS2 pLRM shows a less steep leading edge of the waveform when compared to CS2 SAR and AltiKa, indicating that in Ku band in pulse-limited mode there is significant volume scattering from the top few meters of the ice.

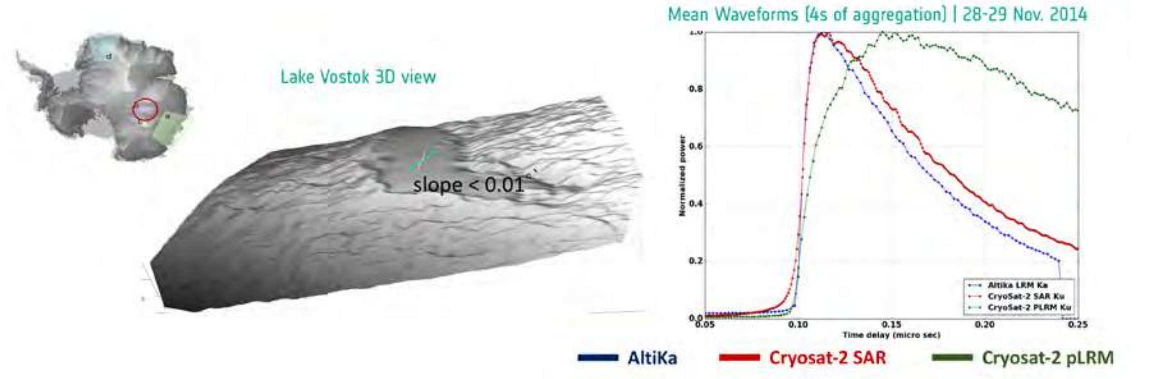


Figure 1 – Mean radar waveforms from the ideal ice sheet surface of Lake Vostok in Antarctica around a crossover between AltiKa and CryoSat-2. Credits: J. Aublanc and P. Thibatut.

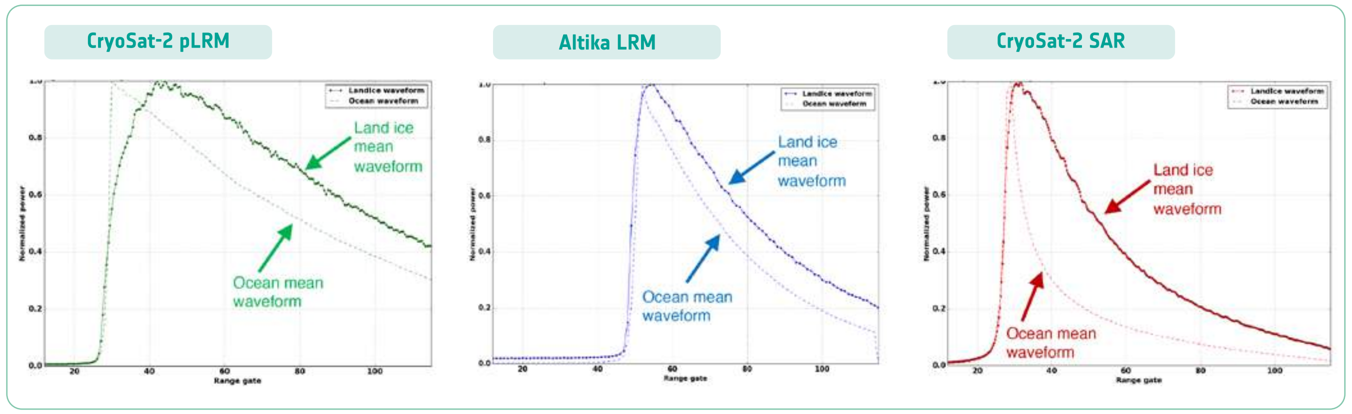


Figure 2 – Comparison of mean radar waveforms at Lake Vostok with typical mean waveforms over the open ocean , for CryoSat-2 pLRM (left panel), AltiKa LRM (middle panel) and CryoSat-2 SAR (right panel). Credits: J. Aublanc and P. Thibaut.

The extremely low slope and roughness of this site make a comparison of the average waveforms in each band and radar mode with the corresponding ocean mean waveforms particularly meaningful. All three comparisons (Figure 2) show the effect of volume scattering in the trailing edge portion, but the CS2 pLRM waveforms over ice depart from the ideal surface scattering case very noticeably, already on the leading edge portion. This is in line with theoretical expectations from published literature, that indicated larger penetration for this band.

The issue of penetration can be investigated further by bringing in some coincident IceSat-2 laser altimeter data in Spring 2019 and looking at the difference over the IS2-CS2 crossovers. We can assume that IceSat-2's ATLAS laser, which operates at a wavelength of 532 nm in the green region of the visible spectrum, tracks very accurately the surface of the ice, i.e. penetration is negligible. The mean difference with the CS2 pLRM is −0.22 m, so the radar is ranging longer than the laser indicating penetration, and the standard deviation is 0.08 m. The comparison of laser with Sentinel-3 SAR altimetry shown that in SAR mode the scattering horizon is closer to the surface so the results are unbiased with respect to laser, with again a standard deviation of 0.08 m.

Observations of this kind must be extended in time to allow a look at the evolution of the ice sheet in order to measure its contribution to sea level rise. This also allows the important assessment of how the biases between altimetry and laser evolve in time, in dependence of the ice and surface characteristics. The comparisons of altimetry from S-3A and -3B and IS2 over Vostok over 11/2018 to 02/2020 show a remarkable consistency between the two altimeters and a modest annual cycle in the bias to IS2 (see Figure 3). The same seasonal cycle is visible in the comparison with CS2 which however is 22 cm lower. The reasons for such a cycle are matter of current investigation and could include both the insensitivity of the altimeter to the snow layer fluctuations (which are instead detected by the laser) or changes in the scattering properties of the surface.

Current campaigns such as CRYO2ICE are allowing us to dig deeper in this issue and investigating those differences. These results clearly indicate a need for dedicated integrative studies of multiple sensors operating simultaneously, to leverage their full potential, and are important to define the science case for future dual-band or multi-band satellite missions, such as CRISTAL. Some knowledge might also be obtained by comparing S3 C-band signals versus Ku-band signals especially when S3 was in LRM, i.e. at the beginning of S3A/S3B missions, which should yield more confidence on the uncertainty of the measurements. As for the effect of the radar mode, i.e. the different response between SAR mode and LRM, insight can certainly be derived from the S3 tandem mission during which we have a full cycle of S3A in SAR and S3B in LRM, which should be analysed in detail (this will also be crucial to intercalibrate LRM and SAR observation to form the long-term data record).

McMillan further discussed the current knowledge gaps. The status of knowledge is reflected in the maturity of the processing steps, which can be measured in terms of Scientific Readiness Level (defined in the ESA SRL Handbook, 2015). Quantifying the SRL implies identifying the algorithms that currently exist, assessing their maturity i.e. whether they are still experimental or to what extent they are routinely used, and how traceable they are to references from the supporting literature. This will also highlight needs for future algorithm development/refinement activities.

Capturing complex topography especially such as the one of glaciers and ice sheet margins requires the adoption of open loop tracking, in which the receiving range window of the altimeter for a given position and orbital altitude of the satellite (derived from the instrumentation used for precise orbit determination) is positioned according to pre-computed altitude values in a reference Digital Elevation Model (DEM) stored on-board. Open loop tracking should be in principle very efficient on rough terrain, but needs adequate resolution to follow the terrain at the resolution afforded by SAR altimetry. Open loop tracking is not yet definitely proven in orbit, as shown by Sentinel-3, which had a 80% tracking failure over the ice margin where open loop was tested during the commissioning phase. Still, Sentinel-3 data provide a valuable source of data to be exploited to improve this approach. The crucial issue for a development of open loop tracking for future missions is to establish whether it is sufficiently agile to capture the surface response over complex terrain, and whether it can capture both Ku and Ka responses. It should be noted that global glacier monitoring is a primary objective for CRISTAL, therefore a functioning open loop will be critical to ensure success, and the DEM (and its management on-board) needs to be thought carefully in this context, especially for the limited on-board memory.

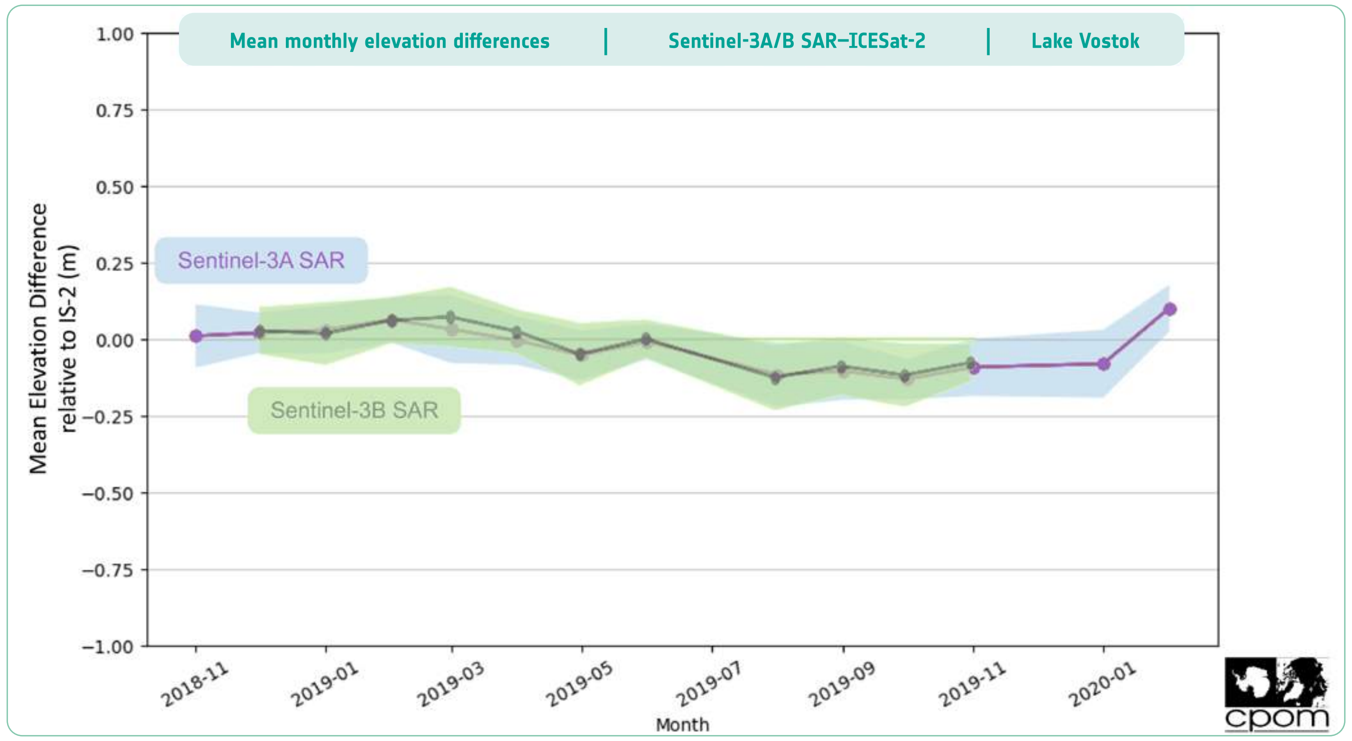


Figure 3 – Comparison of Sentinel-3A and Sentinel-3B elevations with laser elevations from ICEsat-2 at Lake Vostok over 11/2018 to 02/2020. Credits: CPOM

Ka SAR altimetry processing has a low SRL as it has not been done before for a satellite mission, irrespective whether unfocused or fully-focused (FF). For the Ku band, unfocused SAR processing can now be considered mature in view of the experience gained with CS2 and S3. The tandem phase of S3A and S3B has also demonstrated a remarkable consistency of the Ku-band SAR acquisitions from the two altimeters over complex terrain, as shown in the S-3 Tandem for Climate data over East Antarctica. This consistency is an essential prerequisite for the quantitative exploitation of the data. However, a Ka SAR altimeter will have a different SAR footprint (typically 100 m along-track by 5 Km across-track, as opposed to 270 m x 12 m for Ku) so we should expect significant differences in the Ka waveform w.r.t the Ku waveform, and this poses challenges for the integration of the two measurements, namely for the estimation of penetration depth over complex terrain, as illustrated in Figure 4. While in a simple case the penetration can be estimated by differencing the ranges at the point of closest approach (POCA), when topography is complex with slopes exceeding several tenths of a degree, it may happen that the POCA in the Ku footprint lies outside the Ka footprint and therefore it is different from the POCA in Ka band. In this case the ranges cannot be differenced. This is a situation likely to happen in glaciers and in the steep ice margins; its proper treatment will require better understanding of how much power is returned from the sides of the antenna beam, as well as how the sensitivity of the Ka/Ku waveform coherency on surface slope. If interferometric information is available (as will be the case in Ku band for CRISTAL), that could hold the key to solve or mitigate this problem. For the interferometric approach we have a body of knowledge from CryoSat-2 that will be exploited for CRISTAL, from which we expect many more swath processed data over land ice.

Fully-focused SAR altimetry (Egido and Smith, 2018) is still in its infancy, and data processed with this technique over the ice sheets are few. FF has the potential of achieving very high along-track resolution, as shown in the Lake Vostok example at 8 m in Figure 5. Therefore, the challenge is how to derive and exploit meaningful information.

Inès Otosaka provided a practical illustration of the perspectives in multi-band altimetry of the cryosphere by drawing examples from three case studies.

A first study in West Antarctica has been looking at the ice sheet elevation, and elevation change over time, from a combination of Ka-band (AltiKa), Ku-band (CS2) and laser altimetry from the Operation IceBridge (OIB) Airborne Topographic Mapper (ATM). The region has been experiencing widespread thinning and ice imbalance. Most of the laser data were collected in the ice margin, where terrain is steep.

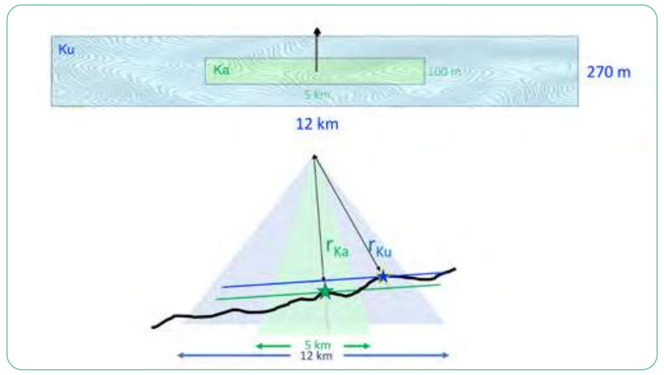


Figure 4 - Illustration of the impact of the different SAR altimetry resolution cell in Ku and Ka band over complex topography. The top panel shows typical footprints, based on a −3dB beamwidth of 1.04° for Ku band and 0.43° for Ka band. The bottom panel illustrates a situation where the POCA in Ku band falls outside the Ka main antenna beam, inhibiting the estimation of penetration depth from the difference in ranges to POCA..

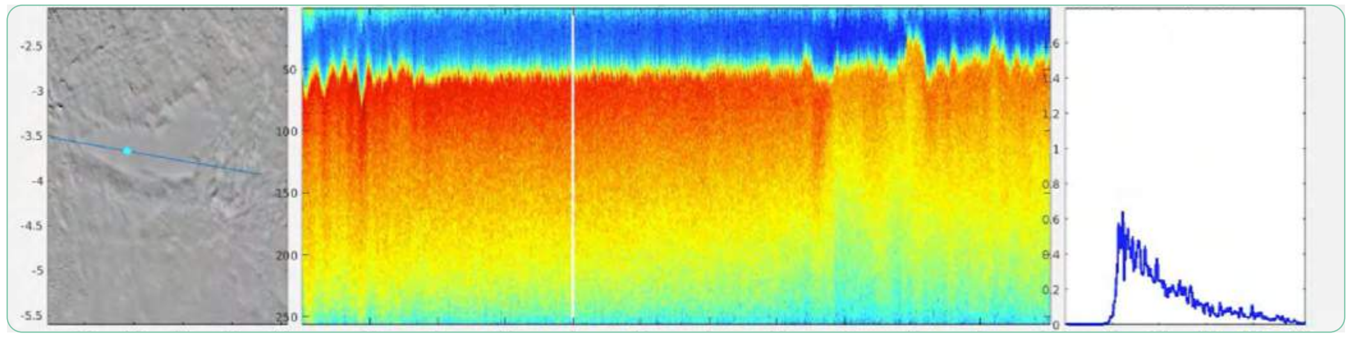


Figure 5 –A segment of an overpass of CryoSat-2 data over Lake Vostok (left panel); radargram of the transect processed with fully-focused SAR altimetry techniques to an along-track resolution of 8 m (middle panel); the single FF-SAR waveform at the location indicated by a vertical line in the middle panel (right panel). Credits: A. Egido.

In more than half of the locations the slope exceeds the half antenna aperture of AltiKa (i.e. the situation depicted in the bottom panel of Figure 4) and in those locations the difference AltiKa-OIB is 5.5 m (note that it is positive) compared to 2.3 m in regions of low slope. In terms of elevation change rates show a good agreement between AltiKa and OIB with a median of −3 cm/yr. A comparison with CS2 over a much wider area than that covered by OIB found a median AltiKa–CS2 of −0.1 cm/yr with a std of 13.4 cm/yr, showing that radar penetration does not seem to affect the retrieved trends in elevation in this particular case.

The analysis of detailed profiles of slopes and elevation change over OIB flight lines (Figure 6) shows that AltiKa struggles to survey elevation change over complex terrain such as along the grounding line of the Getz Ice Shelf, compared to CryoSat-2 and OIB laser altimeter. Differences in retrieved trends appear therefore to be mainly due to differences in operational modes and footprint rather than to changes in penetration depth with frequency. A more dedicated experiment in Antarctica would help to better understand differences between Ka- and Ku-band satellite altimetry.

The fluctuations in airborne radar penetration driven by surface melting have been studied along the Expédition Glaciologique Internationale Groenland (EGIG) line in West Central Greenland, with data from a CryoVEx campaign using the ESA airborne Ku-band interferometric radar (ASIRAS), as well as radar Ka (KAREN) and airborne laser scanner (ALS), in combination with firn cores and using firn models to aid the interpretation. The campaign confirmed that fluctuations in radar penetration are correlated with fluctuations in densities, such as a density peak in summer 2012, twice the density of the previous summer, that contributed to the formation of a strong scattering horizon close to the surface of the ice sheet and decreased by more than 6 m the radar penetration depth. It is encouraging that, despite these large fluctuations in penetration, radar (ASIRAS) and laser (ALS) surface elevations agree to within 20 cm when suitable retracking algorithms (threshold retrackers) are used instead of standard Offset Centre Of Gravity (OCOG).

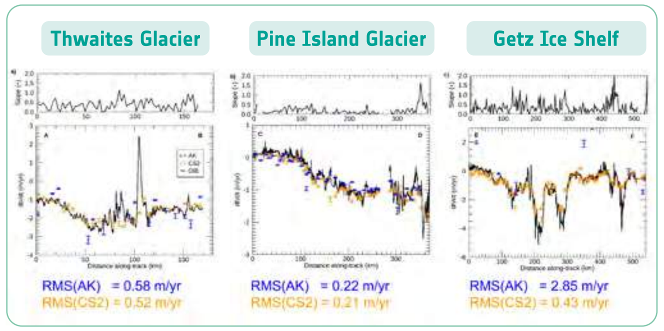


Figure 6 –Comparison of trends in elevation derived from ATM, CS2 and AltiKa over OIB flight lines in three different Antarctic regions (bottom panels). The top panels show the terrain slope. The RMS differences between each altimeter and the laser are reported for each transect. Credits: Otosaka et al.

The comparison of perfectly coincident profiles in Ku and Ka band in Figure 7 shows the much reduced volume scattering in Ka band, with the KAREN-derived penetration depth about half of the one from ASIRAS. The combination of deeper penetration and higher bandwidth of ASIRAS (1 GHz, compared to 600 MHz for KAREN) yields a much more detailed rendition of the individual ice layers, including the denser 2012 layer.

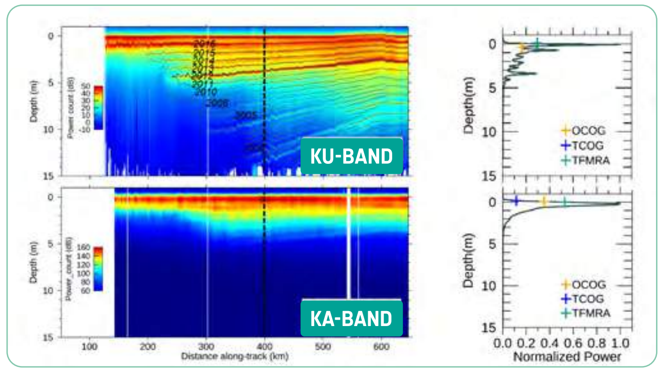


Figure 7 – Radargrams (left) and waveforms (right) along the EGIG line, in Ku band from ASIRAS (top panels) and in Ka band from KAREN (bottom panels). The waveforms are those at the location indicated by the dashed vertical line in the radargram, and have superimposed the elevations estimated with three different retrackers (OCOG,TCOG and TMFRA). Note the detailed layering structure captured in particular by the Ku band, with the prominent peak corresponding to the 2012 melt. Credits: Otosaka et al.

Elevation changes in Northwest Greenland have been estimated by satellite Ku band from CS2 and a dense network of airborne laser altimetry measurements from OIB. As shown in Figure 8, there is an overall good agreement in rates of elevation change (mean CS2–OIB 6.5 cm/yr, std 31.1 cm/yr) but large differences remain locally, close to the margins of the ice sheet. It should be recalled that even small differences in the retrieved rates, such as those quoted above, translate into significant volume and mass changes that can reach 15 km3/year over the CS2 SARin area in this region. It would be beneficial to add to the comparison AltiKa data, which are available over this region and time frame. The challenge highlighted from all these case studies is how to disentangle the effects of radar penetration, surface roughness, terrain topography, sensors' resolutions and spatial sampling when comparing satellite radar altimetry from different instruments and airborne laser altimetry. The selection of the retracking algorithm is also important and studies should be conducted on the performance of the various algorithms in both Ku and Ka band. This looks particularly promising over regions with plenty of quasi-coincident laser data that can be used as a benchmark, such as West Antarctica and Northwest Greenland. Extending the time series of Ku and Ka observations should then allow a more complete assessment of the trends in radar penetration in Ka- and Ku-band signals.

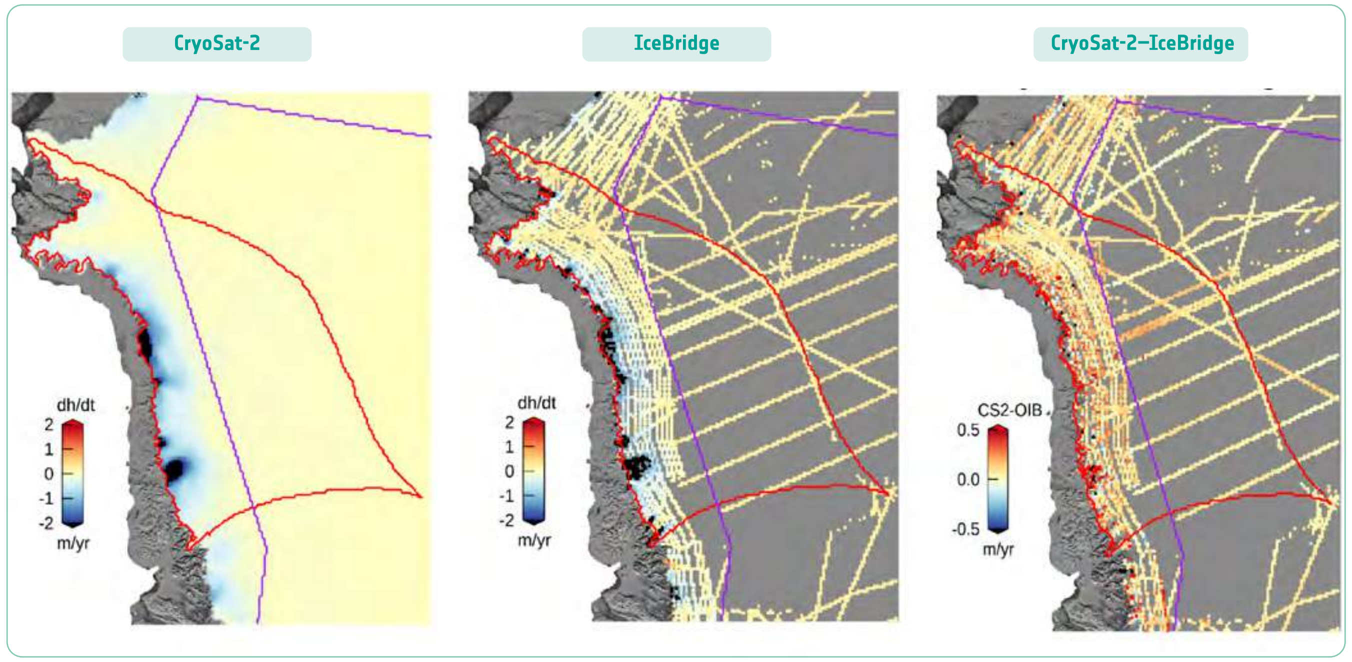


Figure 8 – Comparison of rates of elevation change from satellite Ku band from CS2 and airborne laser altimetry from IceBridge ATM in Northwest Greenland. Credits: Otosaka and Shepherd

Sebastian Simonsen dwell on the main objective of altimetry over land ice: establishing the ice mass balance. The loss of land ice from ice sheets and glaciers is a primary contributor to sea level rise. This makes land ice monitoring key to understanding and predicting sea level. Therefore, the crucial issue is to establish the ice mass/volume budget from space. Early efforts over Greenland, using Envisat altimetry and ICESat Lidar data over 2003-2009 (Sørensen et al, 2015) already showed a discrepancy in the rates of ice loss (ICEsat −240 Gt/yr, Envisat −177 Gt/yr) that is interpreted as changes in penetration. The derivation of an ice sheet mass balance from Lidar requires accurate modelling of the Firn air content and the density (Sørensen et al, 2011).

The similar approach can be applied to 25 years of elevation data, which are now available from Ku-band radar altimetry and are being used in the ESA Greenland Ice Sheets Climate Change initiative and in the Copernicus Climate Change Service. When compared with laser and other independent estimates of mass change rate (see Simonsen slide 7) we see differences in part due to penetration, and in part due to the fact that the bigger altimeter footprint does not capture the rapid ice loss seen at the margin of the ice sheet.

The firn compaction and the corresponding changes in radar scattering horizon can be modelled; but the changes in penetration depth can also be compensated with a radar processing approach (Slater et al, 2019) trying to deconvolute the radar waveform and get to the surface scatterers.

A simpler approach is to calibrate the mass change from Altimetry in each location against the mass change computed from Lidar over 2003-2009, and then extend the calibration factor to the whole altimetry time series using some supervised machine learning that takes into account radar sensing mode and surface slope. With this approach Simonsen et al (2021) have been able to derive the Greenland Ice Sheet mass balance over 1992-2020, showing 12.1±2.3 mm sea level equivalent since 1992, with more than 80% of this contribution occurring after 2003, as shown in Figure 9.

A comparison of ice surface elevations from Ku from CS2 (Level 2 processing) and Ka from AltiKa (off the shelf product) (see Simonsen Slide 13) has been done separately for each of the Greenland provinces over 2013-2017; normally the Ka elevations are higher but in some cases we see an inversion: this is a clear call for further investigations on the causes of these different scattering horizons (which may constitute an opportunity to elucidate processes, including the investigation

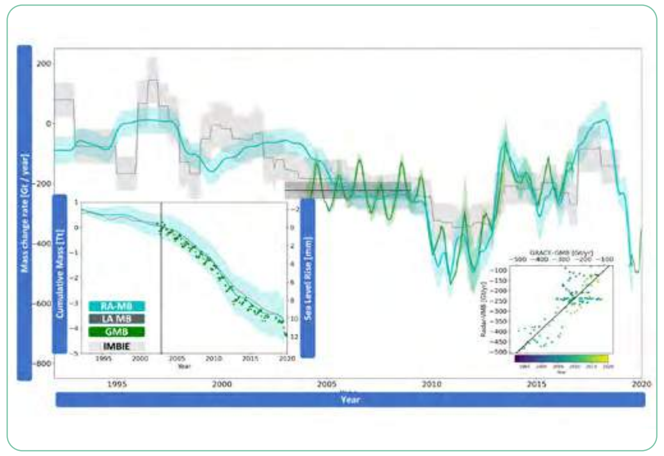


Figure 9 – Greenland ice Sheet mass balance from radar altimetry (RA-MB), compared with laser altimetry (LA-MB), GRACE-based estimates (GMB, also resolving the annual cycle) and from the IMBIE study).
Credits: Simonsen et al. (2021)

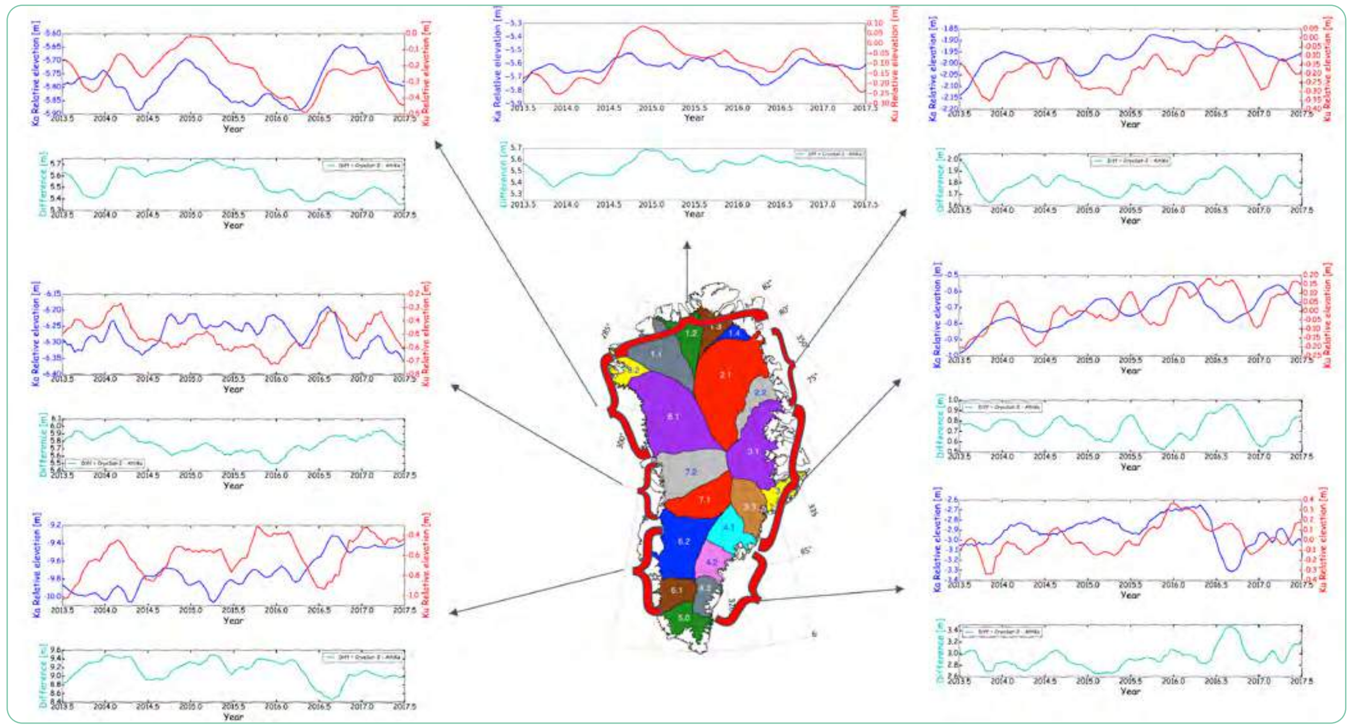


Figure 10 – Mass balance for the various basins of the Greenland ice sheet. The panel pairs show the timeseries of relative elevations from AltiKa (redline) and CS2 (blue line) altimetry, and their difference (cyan line). Credits: Simonsen et al (2021).

of the impact of specialised retracking).

Jérémie Aublanc gave further details on the work carried out on Lake Vostok, which is an excellent calibration site for radar altimetry as the surface is very flat (0.025% slope, resulting in ~2 cm slope-induced error) and stable in time. Aublanc et al have used it for an investigation of waveform retracking, using a Threshold Peak Retracker and adjusting the threshold T as an attempt to compensate for the impact of volume scattering in the radar altimetry elevations and capture the surface elevation at snow/air interface.

In their retracking scheme Aublanc at al chose for AltiKa T=50% Pmax; for C2 LRM and S3 pLRM T=25% of Pmax (a value based on previous literature) to account for the higher volume scattering; for S3A SAR T=80% of Pmax as the leading edge appears to be quite insensitive to volume scattering. When compared with GNSS and ICEsat at crossovers there retracking thresholds provide a vertical alignment within ~6 cm between the 3 missions. Altimetry underestimates surface elevation by 20-25 cm compared to GNSS and ICESat, interpreted as due to signal penetration into the snowpack (volume scattering). Sentinel-3A SAR mode has the lowest precision (std 19.9 cm from ICEsat) due to the high (80%) retracking threshold position on the leading edge, which makes it more sensitive to speckle noise and volume scattering, while AltiKa is the most precise (std 8.4 cm from ICEsat), even if retracking threshold (50%) is higher compared to LRM/pLRM Ku (25%). Seasonal surface elevation variations due to surface/snow change have also been noticed over lake Vostok (Lacroix et al., 2009). These are more noticeable in Ku compared to Ka, even with with the 25% low retracking threshold in LRM/pLRM.

A comparison has also been done between CS2 SARIn data over Antarctica and ICESat-2 at crossovers. After editing the CS2-IS2 bias is ~-10 cm with a std of ~50 cm. Performances get better over linear surfaces exhibiting clear leading edge waveforms (such as over Antarctica's interior) and in such situations the snow/air interface corresponds in average to a 60-65% threshold.

The impact of radar wave polarisation also remains to be investigated in more detail.

The effect of snow structure can be investigated with a modelling approach. **Ghislain Picard** presented the Snow Microwave Transfer Model (SMRT), a model for snow microstructure signature in the microwaves, i.e. "grain size scattering" which recently has had an altimeter module added in the framework of the ESA Polar Monitoring Study (PMS) for CRISTAL. The altimetry SMRT module is being validated on frozen lakes in project LIAM and on sea ice in project AKROSS. SMRT is a highly structured modular model, with the different steps of radiative transfer calculation clearly separated, so that each module can be easily reformulated. The waveforms are computed in two steps, first computing the vertical profile of backscatter (still approximated as first order backscatter), and then distributing in time according to the horizontal spread and delay of the waveform. The module has originally been developed for LRM altimetry over simple topography, but in combination with the AltiDop simulator developed in PMS it is possible to relax those approximations. It has been validated with in situ data (density profile, snow grain size profile and surface roughness). Simulations have been conducted in S, Ka and Ku band: in all cases it is possible to simulate not just the total signal, but also the separate contributions from surface, volume and interlayer interface scattering, as shown in Figure 11.

Surface backscatter dominates at all the frequencies, volume scattering is larger at Ka band, but penetration depth is much less than at the lower frequencies (penetration is about 20-40 cm at Ka band; this is in line with 40-80 cm observed with passive microwaves). Interface scattering is negligible in Ka, but not in Ku and S.

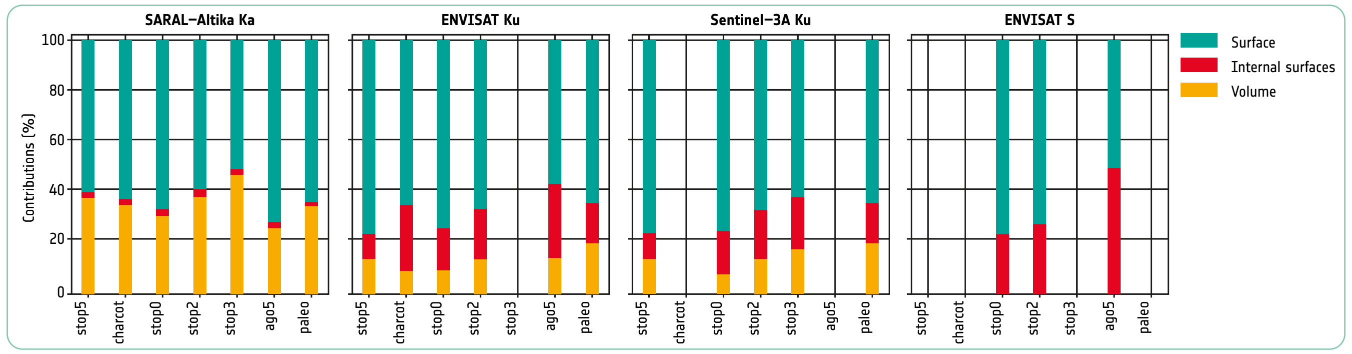


Figure 11 – Percentual contribution to the altimetric signal from surface, internal interfaces and volume scattering for different altimeters and frequency bands, as simulated by SMRT. Credits: G. Picard.

With swath-processing we need to think no longer in terms of simple penetration depth at nadir, but rather in terms of the penetration (and therefore the bias) varying with incidence angle, as a consequence of the varying surface/volume scattering. SMRT accounts for the surface reflectivity dependency to the incidence angle. The volume scattering is assumed to have a small dependency on the angle.

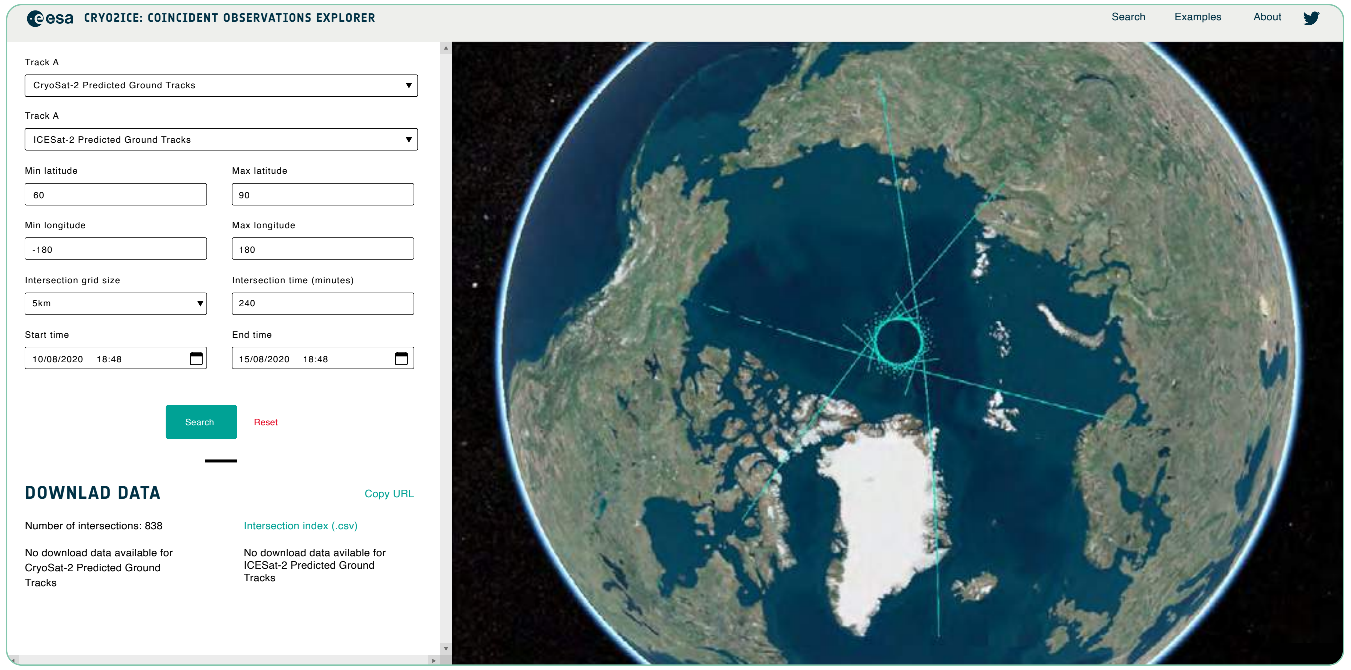
We also see that total backscatter is increasing from the coast to the interior, due to bigger grains and rougher surface. The model could be in principle used to investigate sensitivity of retracking to various parameters and whether it is possible to resolve the ice layers. Dronning Maud Land was suggested by M. Drinkwater as a suitable place for validation.

It should be noted that in SMRT it is also possible to account for the effect of different moisture content, like the presence of wet snow. A comparatively more difficult condition to represent in the model is the percolation of water into dense firn. This can be solved with some approximation.

Frédéric Frappart presented some work carried out at CTOH/LEGOS towards a comprehensive analysis of radar altimetry backscattering over the cryosphere, that includes a backscatter analysis of AltiKa data over sea ice carried out by C. Soriot (including the K-band channel of AltiKa radiometer, at 23 GHz), therefore more relevant to the discussion in Day 2 of the Workshop. Frédéric mentioned that they are soon starting to analyse the backscatter in Sentinel-3 Ku/C observations, that can be used for water/ice discrimination over Arctic lakes. The combination of Cryosat-2 Swath Altimetry with Operation Ice Bridge and IceSat-2 is also being attempted with a Neural Network Approach, which was presented by **Alex Horton**. The resulting model yields 'adjustments' that correlate with penetration depths. Coincident ICESat-2 and CryoSat-2 observations can be conveniently extracted with the Cryo2Ice Coincident Observations Explorer (Figure 12) at cryo2ice.org.

The time varying surface penetration bias and the factors that affect it have been studied by **Johan Nilsson** using coincident ICESat-2 and CryoSat-2 observations for Greenland and Antarctica.

The main source of uncertainty in deriving the mass balance of ice sheets from altimetry is the penetration the radar signal into the firn column, which varies in time and space and in dependence of the firn conditions. This induces large errors in the retrieved elevation. A correction for this effect is difficuly to quantify, due to the lack of an adequate model describing



CRYO2ICE: COINCIDENT OBSERVATIONS EXPLORER

Track A: CryoSat-2 Predicted Ground Tracks

Track A: ICESat-2 Predicted Ground Tracks

Min latitude: 60

Max latitude: 90

Min longitude: -180

Max longitude: 180

Intersection grid size: 5km

Intersection time (minutes): 240

Start time: 10/08/2020 18:48

End time: 15/08/2020 18:48

DOWNLAD DATA

Number of intersections: 838

No download data available for CryoSat-2 Predicted Ground Tracks

No download data avilable for ICESat-2 Predicted Ground Tracks

Figure 12 – Screenshot of the CRYO2ICE Coincident Observations Explorer. Credits: Alex Horton / cryo2ice.org

the scattering horizon, and the paucity of validation data sets. The launch of ICEsat-2 in September 2018 offers the unique opportunity to compare the laser measurements, that capture the snow-air interface with high fidelity and dense sampling, with radar altimetry measurements from CryoSat-2. Therefore, this allows an investigation of the penetration bias and its spatial and temporal variations.

The variations of the bias create artificial trends and seasonality in the long-term data record of mass balance, as clearly seen by looking at uncorrected time series from the various altimeters at Lake Vostok and around NEEM Camp in Greenland (Figure 13). While for Antarctica the dominating effects are the seasonal variations in snowfall and snow properties (so that the seasonal cycle dominates the uncertainty even after a scattering correction is applied), for Greenland these seasonal effects are eclipsed by melt event such as the major event in summer 2012, where the transition from volume to surface scattering was very rapid and challenging for the retracking (even with good retracking this is not totally accounted for). Nilsson et al, 2016 use the radar waveforms itself as a proxy for the influence of external factors. They first retrack CS2 with different retracking threshold on the radar waveforms and investigate the sensitivity of these different thresholds to change in some parameters extracted from the shape of the waveform (backscatter Bs, leading edge width LeW and trailing edge slope TeS). These parameters are directly linked to changes in surface conditions and can be used as a proxy to describe surface properties. Results confirm that the penetration bias varies virtually linearly with the retracking threshold. Over Greenland there is little dependence from changes in the upper firn layers, due to the higher content of moisture, and as a consequence the waveform parameters are poorly correlated with the time series. Over Antarctica, the penetration bias is much more affected by the surface conditions (winds causing changes in surface roughness, with a big increase in backscatter in Jan/Feb 2019 being reflected in a clear reduction in the penetration depth.

Nilsson et al's work improves our understanding of how altimetry signals interact with snow, firn and ice. This in turn benefits firn modelling and our understanding of ice sheet climatology such as long-term snow accumulation, necessary for converting ice sheet volume to mass. In the end this knowledge can be leveraged to improve our corrections of the historical, long-term radar altimetry record and in the end sea-level rise projections.

Discussion

The discussion following the various presentations moved from the realisation of what we already know and have solutions for, on the basis of the existing results.

The aim of deriving the ice sheet elevation is to achieve a reliable estimate of surface elevation change and mass balance. We have been deriving elevations over ice sheets for many years from Ku-band altimetry, and also more recently from Ka altimetry, and combining those with laser altimetry. Therefore, there is already a lot that can be done by using the available data and literature and revisiting them in terms of the latest findings, for instance on the effect of different threshold levels in retracking.

We know with confidence that there is a difference between the Ku and Ka signals (and also between measurements in LRM and SAR mode). While many studies are trying to correct that difference by modelling and compensating for the volume scattering, the past lack of process-based knowledge has also resulted into a number of empirical corrections, and a vast library of algorithms has been developed and tested to that effect. However, the growing availability of in situ and airborne data now calls for a change of approach. There is valuable information in the signal difference that allows us to explore – and gain understanding on – the sub-surface processes (such as the low-permeability 'ice slabs' that have expanded the Greenland ice sheet's total runoff, studied by MacFerrin et al., 2019), and this must be pursued further. A key step to this exploitation is the development of flexible processing schemes, providing a choice of retrackers.

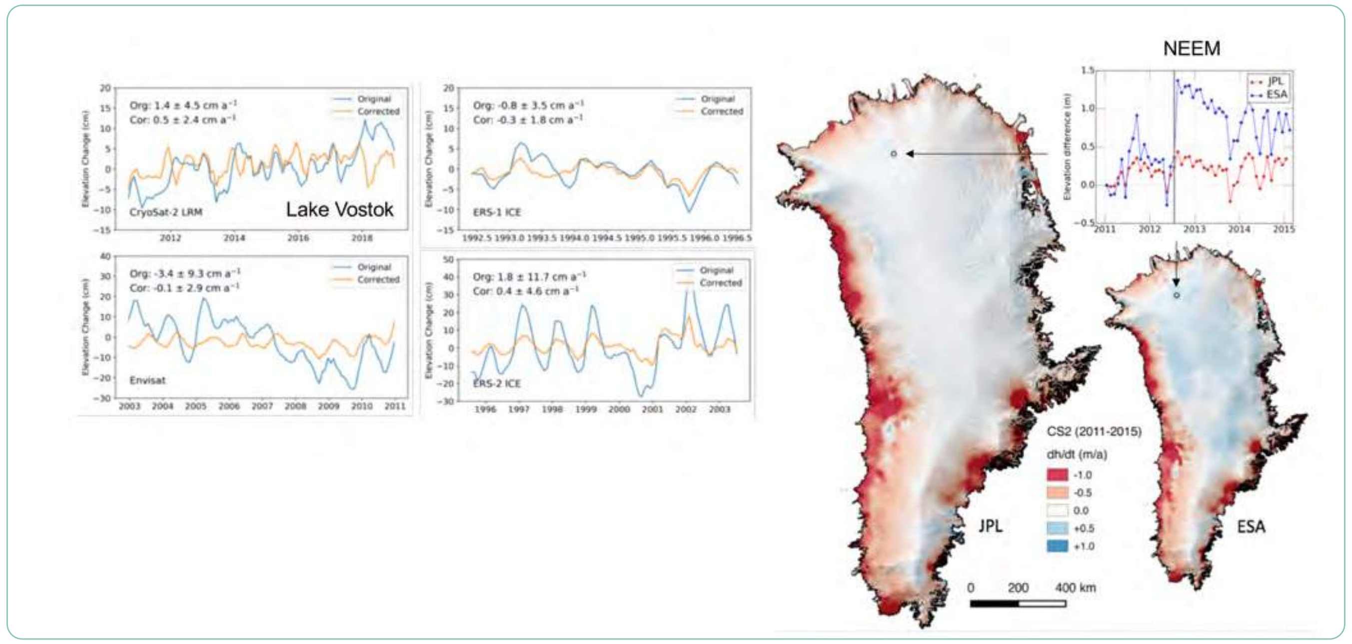


Figure 13 –Time series of elevation change from various altimeters at Lake Vostok (left 4 panels), in the original format (blue lines) and after correction with the technique by Nilsson et al (red lines). Elevation change rates from CS2, and the time series at NEEM Camp showing the effect of the 2012 melt on the uncorrected (ESA) series (right panel and images). Image credit: Nilsson et al. (2016).

The improved understanding goes in step with advancement in modelling. This can also benefit from the good previous understanding of the passive microwave properties of the snow pack, which was also gathered in the 36 and 37 GHz channels.

Topography (especially in non-interferometric mode data) and surface roughness effects need to be investigated further, as they are still a big part of the uncertainty, and we need to improve the processing chains to reduce that uncertainty. For surface roughness, a big help now comes from IceSat-2, which has the resolution necessary to characterise that roughness, that could be extracted from the lower level products and also allow us to look at crevasses. The newest high-resolution DEMs like REMA or from TanDEM-X may also be of some help. One of the difficulties in translating the information from airborne data into information relevant to the interpretation of the satellite data due comes from the differences in footprints, and IS2 may help to bridge that resolution gap. Simulation of the roughness effects is now possible with the coupling of SMRT with AltiDop. For the impact of roughness with direct facet-based simulations, recent work led by J. Landy (also mentioned in M. Tsamados' talk on day 2), even if focusing on sea ice, might be relevant.

Another important issue is to ensure consistency of the reprocessing of different missions over time. For instance ESA has been flying three classes of altimeters in Ku band alone: pulse-limited, SAR and SAR interferometric. Differences in the estimates due to the different radar mode should be reconciled. One possible framework to carry out this activity is the Fiducial Reference Measurement framework, where the inter-comparison of different instruments and modes is made over the same surfaces and against well-characterized in situ measurements.

We have most of the tools that we need; however in some cases the Level 1 and 2 processors have not kept up with the advances that have been published in the literature. The products that are emerging from radar altimetry mission could certainly be improved by incorporating into the processors some of the corrections that have been discussed.

We concluded that dual-frequency altimetry of land ice offers a number of scientific opportunities, on the estimation of surface and sub-surface processes, and holds the key to the consolidation and improvement of the long-term ice mass balance estimates from the altimeter record. Some of the new parameters like snowfall on ice sheets could be operationalised as part of Climate Services. Others will be more experimental, such as firn air content, which would be extremely valuable for firn models. The availability of dual-band measurements from the same platform with CRISTAL will remove a further cause of error, i.e. the temporal mismatch between observations (which has already been reduced for the Ku/laser case by the CRYO2ICE campaign).

Conclusions and Recommendations

There is a strong case to run a study to consistently process airborne and satellite Ka/Ku/laser data over some test sites (e.g. Amundsen Sea, NW Greenland, and a mountain glacier location to include glaciers that are one of the objectives of CRISTAL), exploiting all available data in the archives and bringing in modelling as needed. This should aim at disentangling the effects of radar penetration, terrain topography, surface roughness and spatial sampling bias. Special care must be taken for Ka data. Indeed, the ground systems for Ka data over ice are less mature. There is only a year's worth of a dedicated AltiKa ice sheet product from CNES/CLS. A positive feedback from the community would support refinement and extension of this product. Therefore, some effort must be put into assessing the consistency of airborne Ka and AltiKa data. Airborne Ka data are also available from CReSIS/U Kansas (see Jilu Li's summary in the sea ice section).

The proposed study should be conducted with a range of retracking approaches, as this will define the retrieval and its quality. Efforts should also be put on physical retrackers that go beyond the fitting of the leading edge and exploit the information contained in the trailing edge of the Ku (in different radar modes) and Ka waveforms to capture the information about the properties of the subsurface layers. Some insights can also come from looking at dual-band echoes from past altimeter missions, such as the simultaneous Ku- and S-band observations in the initial years of the Envisat mission (see for instance work by F. Remy and co-authors).

With those premises it is clear that dual-frequency will not only improve land ice elevation and elevation change retrieval, but also allow innovative work on firn properties.

View of the oceanographic vessel RV Polastern next to 'Ice Floe 2.0' during Leg 5 of the MOSAiC International Arctic Drift Expedition on 8 August 2020. This mosaic image, taken from a height of 250 m, shows the large quantity of scientific instrumentation deployed on the ice floe including Miss Piggy, a red coloured tethered balloon that collects in situ meteorological data.

Credits: Alfred Wegener Institute / Steffen Graupner, Charles Finkenbeiner

DAY 2 Sea Ice

Eero Rinne introduced the session with a keynote talk about SRL and open questions in multi-frequency altimetry over sea ice. The talk revolved around the implementation of sea ice products from CRISTAL, starting by asking what products we would build based on today's knowledge, in the near future, or even in 20 years from now (when the second CRISTAL satellite is expected to be still operational). Afterwards, the talk focused on how we could improve the methodology based on current or future in situ activities, crucially exploiting the complementary information from ICESat-2 data.

For sea ice, it assumes particular importance to remember the wide range of user needs. On one side there are those requirements for quality controlled, sustained long-term observations advocated by science users such as the climate research community, which are similar to those for land ice and are non-time-critical; but on the other side there are the needs from operational users such as the winter navigation industry interested in the thickness of sea ice affecting operations and safety at sea, who demand latencies of the order of 2 hours. Long time series and climatology are still relevant to the operational users for planning purposes.
Sea ice is a more heterogeneous target than land ice, and collocated measurements require both instruments to fly on the same platform (or within minutes of each other). The SRL of sea ice thickness (SIT) retrieval for the Ku band, especially in SAR mode (delay-Doppler mode), is very high (SRL=9, meaning mature, validated and with well-quantified user impact). Several SIT algorithms for Ku band exist (a general diagram is shown in Figure 14), where different choices are made on:

- ➜ retracking
- ➜ surface type classification
- ➜ auxiliary data

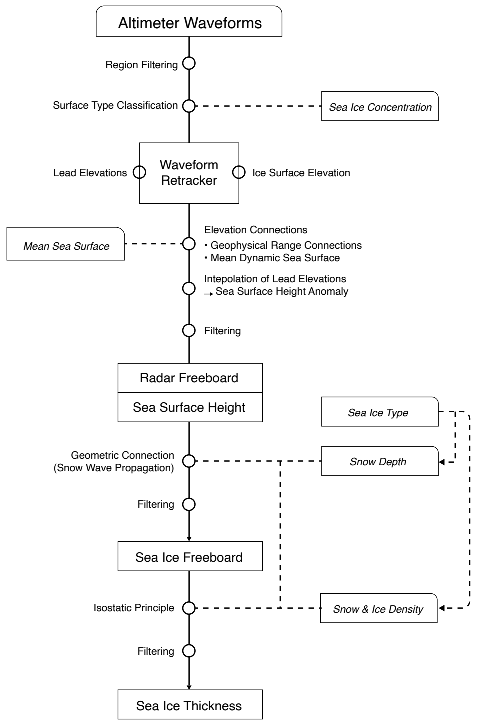


Figure 14 – General schematic diagram of an altimeter L2 processor for sea ice.Credits: E. Rinne

Ka-band algorithms for SIT are much less mature, but exist (despite the lack of any SAR mode Ka data). Many of the choices mentioned for the Ku case and shown in the schematic in Figure 14 have not been tested on (LRM) Ka data, and their suitability for the Ka case should be investigated. The smaller SRL for Ka is not unique to the Level 2 sea ice products, but stands for Level 1 processing as well.

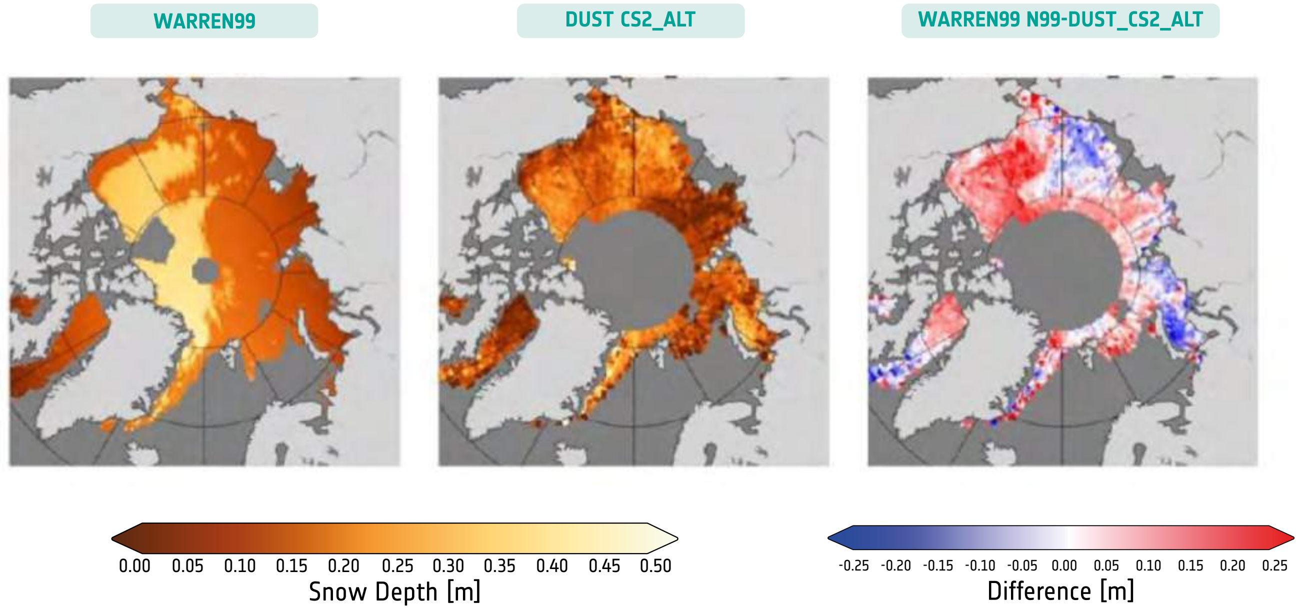


Figure 15 – Examples of snow depth product for April 2014 from Warren climatology (left panel), ESA DuST from CryoSat-2 and AltiKa (middle panel) and their difference (right panel). Credits: UCL

However, much work remains to be done with dual-frequency for snow thickness retrieval, which is a primary mission objective for CRISTAL. Snow retrieval with a combination of LRM AltiKa and CryoSat-2 has been published (Armitage & Ridout 2015 which also used OIB airborne laser data; Guerreiro et al. 2017; Lawrence et al. 2018), and the ESA dual-altimeter snow thickness (DuST) project also generated a snow depth on sea ice product from CryoSat-2 and AltiKa that is broadly in agreement with the climatology, as can be seen in Figure 15. However, CRISTAL's IRIS altimeter is to operate in SAR mode for both Ku and Ka bands: this will make the difference in footprint size much smaller than the case with LRM AltiKa and SAR mode CryoSat-2. The effect of ambiguous penetration depths would still stand even if the footprints were identical (which, even for IRIS, is not the case). Thus, building and validating a snow thickness algorithm will still require coincident, large scale airborne measurements of snow thickness as well as theoretical work on the effect of surface roughness, snow grain size etc. on the range for both channels.

There are two ways of approaching the retrieval of snow depth:

- ➜ the empirical approach is based on taking the difference of the ranges in the two bands (which will also crucially depend on the retrackers used), finding the empirical relationship with snow thickness, possibly using a few waveform parameters and some auxiliary data as additional correction terms in the relationship. This would be the likely approach to be used if CRISTAL were to fly now as it has been demonstrated in the studies mentioned above;
- ➜ a theoretical approach is also possible, by properly understanding the effects of frequency, surface roughness, difference in footprint size, radar penetration, and building a physically-based inversion model to derive the snow depth.

A fundamental help for algorithm derivation comes from the availability of in situ and airborne data, despite the fact that on sea ice, satellite/airborne colocation is challenging and in situ measurements are expensive. Several airborne campaigns in support of dual-frequency or multi-frequency, i.e. CryoVEx Arctic campaigns 2017 (Skourup et al. 2019) and 2019, and CryoVEx Antarctic campaign 2017/18 (Hvidegaard et al. 2020), have been flown in the past few years and are reviewed in this workshop. As for in situ data there is now a new exciting data set from the MOSAiC expedition (Stroeve et al, 2020) with a Ku/Ka radar setup (see R. Willatt's talk below). We will definitely need more in situ radar setups like this to provide long time series covering the seasonally and geographically varying conditions in the radar response of the snowpack.

Rosemary Willatt provided details on the determination of scattering characteristics and snow depth from the KuKa, Ku- and Ka-band polarimetric, dual-frequency, ground-based radar which was deployed in altimeter mode during the MOSAiC campaign. The key uncertainties in sea ice thickness retrieval come from the snow cover and its surface and volume conditions, including the presence of ice crusts and ice lenses, the grain characteristics and the moisture and brine content.

	Ku-band (~CryoSat-2)	Ka-band (~ALTIKA)
Frequency	12-18 GHz	30-40 GHz
Range resolution	2.5 cm	1.5 cm
Antenna beamwidth	16.9°	11.9°

*Figure 16 – The KuKa radar used in MOSAiC, in altimetry configuration (stare mode), with the main specifications of the two channels.
Credits: Stroeve et al, 2020; Stefan Hendricks*

The impact of these features has become more significant in recent years, with the relative increase in first year ice w.r.t. multiyear ice, due to the Arctic amplification of global warming. This means that the assumption, often made in the past, that the Ku-band signal would propagate across the snow pack and the scattering would primarily arise from the snow/ice interface may no longer hold for present and future conditions. In other words, in the Ku signal there is more information about the snow pack than previously thought.
The MOSAiC expedition was conducted by the Polarstern research icebreaker which spent an entire year, starting in September 2019, drifting across the Arctic trapped in Sea ice. Measurements carried out during MOSAiC therefore allowed the observation of the evolution of physical snow characteristics and its scattering properties over time. The KuKa radar, whose picture and specifications are shown in Figure 16, had some deployments on the ice floe around Polarstern in 'stare mode', i.e. the altimetry type, straight-down, nadir-looking mode (other measurements were taken in multi-angle oblique-looking scatterometer mode, but are not relevant here). The KuKa instrument channels have much wider bandwidths than Cryosat-2 and AltiKa, resulting into a very high range resolution (Figure 16) that allows a more detailed comparison of the radar signal with what is seen in the physical snow characteristics.
The geometry of KuKa measurements is obviously different from that of the satellites. The footprints of CryoSat-2 (pulse-limited or SAR) and AltiKa (pulse-limited) include ice ridges, leads and metre-level topography. KuKa is ground-based, towed around along transects of the length of the order of kilometres, and its antennas are only ~1.5 m above the ground (see Figure 16). It is a beam-limited radar with footprints of ~40 cm in Ku band and ~30 cm in Ka band so the footprints only encompass topography at a few cm level. Even if KuKa cannot replicate the satellite viewing geometry, it yields crucial information on the response of the ice pack at different frequencies, which can then be related to the snow characteristics. It also allows measurement at co-polarization (VV) and cross-polarization (HV). A simulator for KuKa is being implemented at UCL.

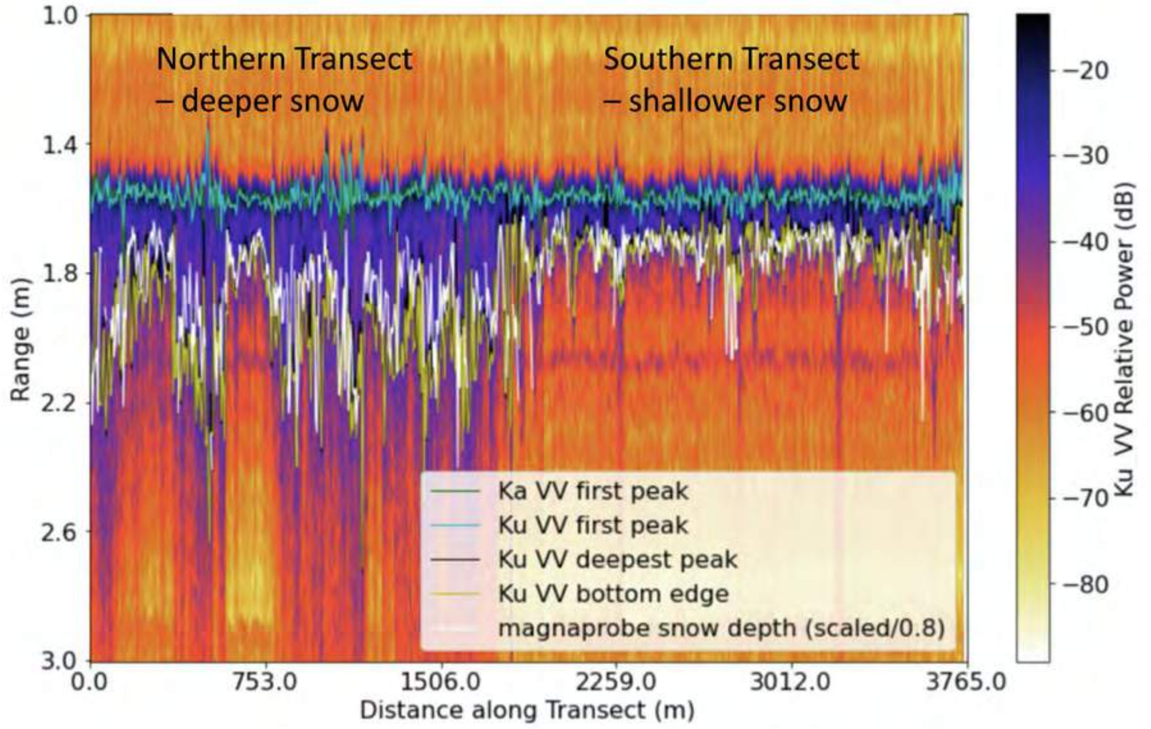


Figure 17 – Ku-band co-pol (VV) radargram for the KuKa instrument along two consecutive transects with different snow conditions taken during the MOSAiC expedition on 16 January 2020. The superimposed lines show some peaks from a peak-picking algorithm applied to the Ku and Ka co-polarization waveforms, as well as the snow depth measured from an automatic snow depth probe (magnaprobe). Credits: UCL

Results from the KuKa radar, which are being analysed, seem to confirm that the Ka band sees the air/snow interface very well, but that interface is captured also by the Ku band, which captures other structures in the snow pack and the snow/ice interface. The high dynamic range and resolution of the instrument, accompanied by very low speckle noise (which means there is no need for averaging over large segments) pave the way to advanced approaches for the extraction of the information such as deconvolution and AI/machine learning, that are currently being investigated at UCL. It was noted by S. Farrell that in order to carry out the deconvolution, the side lobes of the instrument should be characterised; this has been partly done, using a metal plate as target. Figure 17, however, shows an example result from a simple peek-picking approach that finds various peaks in the waveforms, superimposed on the Ku-band co-polarization radargram (similar to the kind of radargram that we would get from CryoSat). The figure refers to two consecutive transects with rather different snow depths (mean depths of 0.26±0.12 m in the left half and 0.15±0.8 m in the right half); worth noting is the very encouraging agreement of the Ku VV deepest peak (black line) with the snow depth measured by an automatic probe (magnaprobe, white line). These data are also being analysed to extract useful information on their typical length scales, to select the best averaging for the comparison.

A very intriguing finding is that the correlation of the snow depth from the magnaprobe snow probe with the radar-derived snow depth increases when the radar depth derivation is made using the difference between the co-pol (VV) Ka first peak and the cross-pol (HV) Ku deepest peak. When the KuKa observations are degraded to mimic the lower bandwidth of the satellite altimeters (320 MHz for CS2, 500 MHz for AltiKa), this correlation with magnaprobe depths remains good only if, again, the radar derivation is made using co-pol Ka and cross-pol Ku (i.e. not for the co-pol/co-pol case). These results call for further investigations on the exploitation of polarization information, but in the discussion it was recalled that the current CRISTAL design has the same polarisation than CS2 and it will be linear polarisation (same for Ka and Ku) co-pol (HH); introducing cross-pol at this stage would be a major change in the CRISTAL instrument current RF architecture, and the much lower power in cross-pol would be challenging. The inclusion of polarimetry could be recommended for future evolutions of the constellation of polar altimetry missions.

Analysis is also ongoing using snow pit data, as well as density values from snow models, including SMRT. A proposal is in preparation by J. Stroeve for deploying KuKa at the Rothera Station in Antarctica over winter. On the whole, it was concluded that, by virtue of its characteristics, KuKa is a well suited instrument for campaigns in support of CRISTAL science.

Rachel Tilling talked about combining ESA CryoSat-2 and NASA ICEsat-2 altimetry over sea ice. Since the launch of ICEsat-2 in September 2018 we have had a unique opportunity to combine radar and laser measurements over the polar sea ice cover, year-round, up to 88° north and south. This combination offers many opportunities for exciting research, a few of which were presented.
One of the possible measurements from space is the sea ice floe length, quantified by its proxy chord length, i.e. the distance along-track between the first and the last measurement in a continuous sequence of echoes discriminating the floe. Floe length is useful to get a better representation of the sea ice floe size distribution, which is an important parameter influencing processes in the Arctic and Antarctic, such as sea ice melt rate, wave propagation, ocean-atmosphere exchanges, ice dynamics and others. Floe length is also useful to reconcile SIT estimates between different satellite missions as it allows for accounting the different geometric sampling. This has been demonstrated with Envisat and CryoSat-2 by Tilling et al, 2019, who showed that Envisat's coarser resolution made it more sensitive to lead within the footprint and, therefore, caused to miss some of the smallest and thinnest sea ice floes. This analysis is now being repeated with CS2 and IS2, taking advantage of the even higher IS2 resolution. Figure 18 shows some preliminary results from this activity, i.e. the chord length (a proxy for floe length) of Arctic ice floes over the winter 2018/2019. The two satellites see the same geographical pattern over multi-year ice, but the chords from IS2 are consistently longer. This is puzzling because a small difference could be expected as the narrower IS2 footprint should be much less sensitive to the contamination by small leads, but not to the extent seen in the figure. This result questions how the different satellites sense the sea surface. For example, when floes break up and the leads start to refreeze the resulting floe may be seen as a floe in IS2 processing, but not in CS2, calling for a better definition of floes and leads.

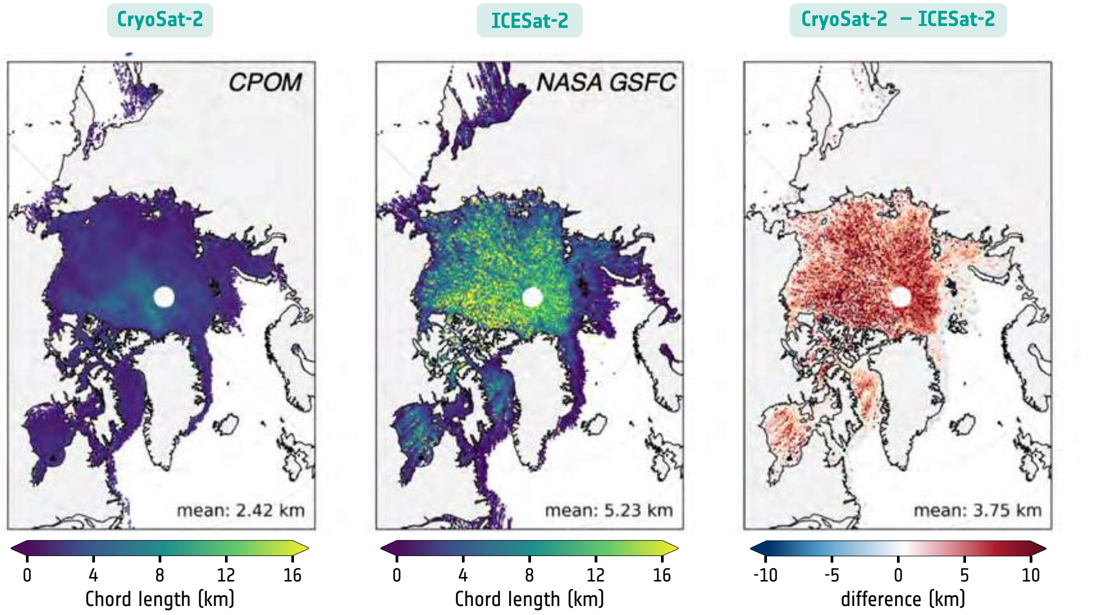


Figure 18 – Arctic sea ice chord lengths (a proxy for floe length) over November 2018 to April 2019 from CryoSat-2 (left panel), ICEsat-2 (middle panel) and their difference (right panel). The ICEsat-2 data used are the ATL07 sea ice surface height, which aggregates data from 150 photons with an effective resolution of 30 m to 70 m. Credits: Alek Petty (NASA GSFC/UMD), CPOM

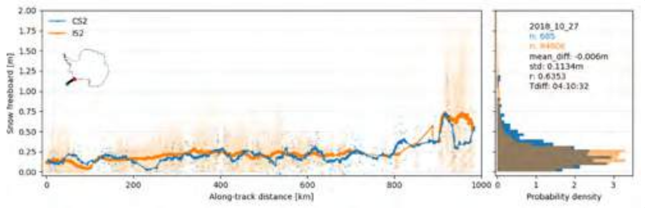


Figure 19 – Snow freeboard computed from CryoSat-2 (blue line) and ICEsat-2 (orange line) over overlapping orbits in East Antarctica (shown in the inset map) in October 2018, and their distributions and statistics (right panel). Credits: Steven Fons (NASA GSFC/UMD)

Another notable research activity enabled by coincident radar and laser measurement is on Antarctic snow freeboard. While in the Arctic the simpler sea ice situation sees a cold, dry snow cover with a positive freeboard, so that we can assume that CS2 will range to the snow/ice interface and give the ice freeboard, in the Antarctic we get far more precipitation so the sea ice surface can get depressed under the water level – essentially we have a negative ice freeboard, which may result in flooding and wicking (drawing of water by capillary action) of the ice. Even without a negative freeboard, because of larger precipitation the snow is more layered than in the Arctic, and the scattering horizon for the radar data is more complex. The CS2 and IS2 orbit overlaps are allowing S. Fons at NASA GSFC to check the ability of the CS2 snow freeboard retrieval algorithm – a waveform fitting method to retrieve the air/snow interface over sea ice. Comparisons with IS2 snow freeboard, like the one shown in Figure 19 for October 2018, show that CS2 is capturing the mean snow freeboard reasonably well , even if missing the smaller scale variability.

Orbit overlaps between CS2 and IS2 have been much more frequent since July 2020, when ESA slightly raised the orbit of CS2 to put it into a resonant orbit with IS2 as part of the ESA/NASA CRYO2ICE campaign, meaning that the two satellites' ground tracks meet every 1.5 days within a few hours (typically ~3 hours) on the polar regions, and sample the same ice. The excellent agreement between the two instruments is confirmed by the surface height anomalies retrieved from the ice leads, which agree at 1-cm level away from the coast, and at 2 cm level closer to the coast, where there are fewer leads.

These results highlight the issue of how to make meaningful comparisons between different instruments. Should we have a unified method for inter-comparisons of data with different resolutions (e.g. CS2/IS2, CS2/airborne)? This is a question that is very relevant to CRISTAL. Furthermore, is the ~3-h

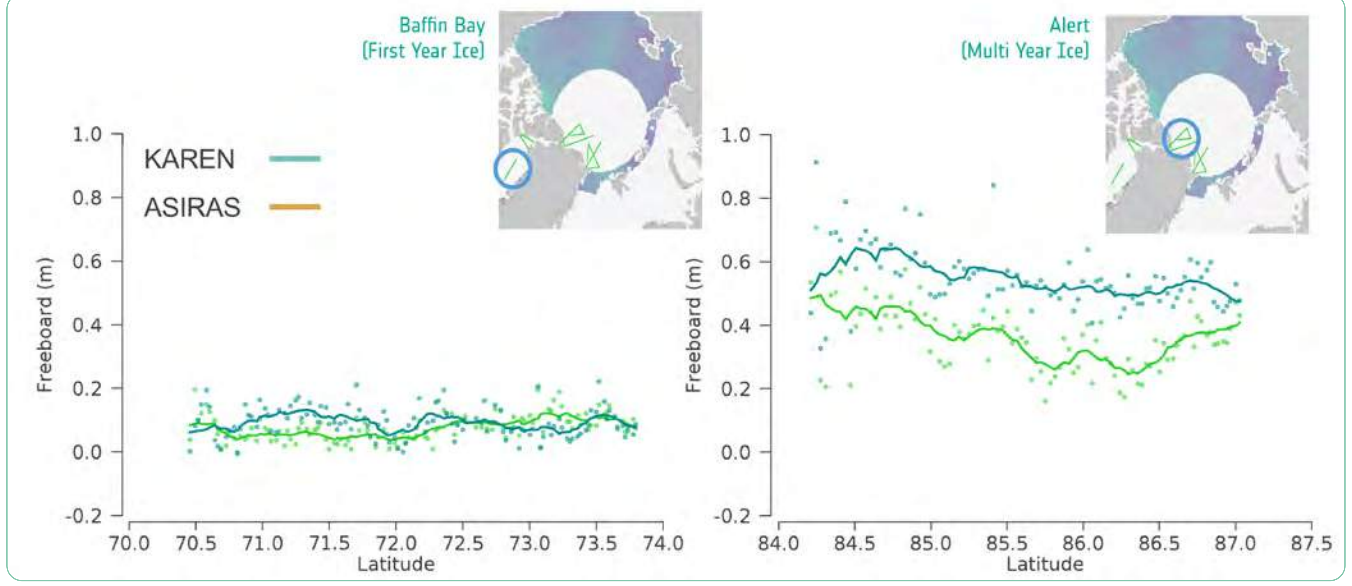


Figure 20 – Airborne dual-band altimetry freeboards from KAREN and ASIRAS collected during the CryoVEx 2017 campaign over two transects with different ice age. Credits: Robert Ricker, AWI

separation still useful for sea ice, which has relatively fast dynamics? A lot can happen to the ice in three hours even if a drift correction is applied. In the ensuing discussion it was recalled that ESA is planning a dedicated activity on this topic, following presentations and recommendations from the World Meteorological Organization (WMO) Global Cryosphere Watch "Sea Ice Satellite Products Inter-comparison" workshop (Nov. 2019), and the recent Sea Ice Cal/Val session at the ESA/EC 2020 European Polar Science Week (Nov. 2020). The workshop on inter-comparison was prompted by the WMO Polar Space Task Group, and the idea, as with ESA SnowPEx (Satellite Snow Product Intercomparison and Evaluation Exercise) is to intercompare all products from satellite, airborne and in situ measurements (where available). It was also suggested that the synergy with other sensors (imaging SAR, but also optical from Sentinel-3) should be exploited.

Stefan Hendricks touched on scales intermediate between in situ and satellites, presenting results on snow depth on sea ice from airborne Ku/Ka-band and ultra-wideband radars from a number of campaigns such as ESA CryoVEX, ESA Cryo-seaNICE and the AWI IceBird Program.

Hendricks recalled the challenges of measuring snow depth on sea ice, where dual-band altimetry is the driver for remote sensing. The challenges are the heterogeneity of sea ice and snow layer, the surface roughness effect on backscatter, the snow distribution and stratigraphy, the issue of bridging the resolution and coverage between in situ and remote sensing. Airborne observations can provide this bridging and have two sets of objectives:

I) method development and validation (for which we usually employ airborne data that are modelled after satellite ones, for instance ASIRAS after CryoSat-2) ;
II) providing reference measurements (usually with dedicated 'ultra-wideband' snow radars)

The first airborne dual-band Ku/Ka experiment was conducted as part of the CryoVEx 2017 campaign with collocated measurements of Ku-band (ASIRAS, operated in SAR mode) and Ka-band (KAREN) radar altimeters over sea ice. A laser scanner was also present, to provide information on the snow surface and surface roughness. Data analysis was carried out in the Cryo-seaNICE project. Figure 20 provides an illustrative example of the measurements. Range and freeboard differences between Ku and Ka band are seen and correlate with snow depth, but below expected value. Over multi-year ice off Alert the range difference (~ 19 cm) does not seem to capture the full snow depth (~ 28 cm from OIB measurements). Over the first-year ice in Baffin Bay, KAREN and ASIRAS freeboard do not show significant difference. This can be due to limitations in sensor capabilities (range resolution) and to issues with the waveform interpretation: empirical retrackers were used for the retrieval and there is certainly scope for reviewing this approach.
To gather reference measurements of snow over ice surface, AWI have been running in 2017 and 2019 the IceBird series of campaigns in which an airborne Airborne Laser Scanner is

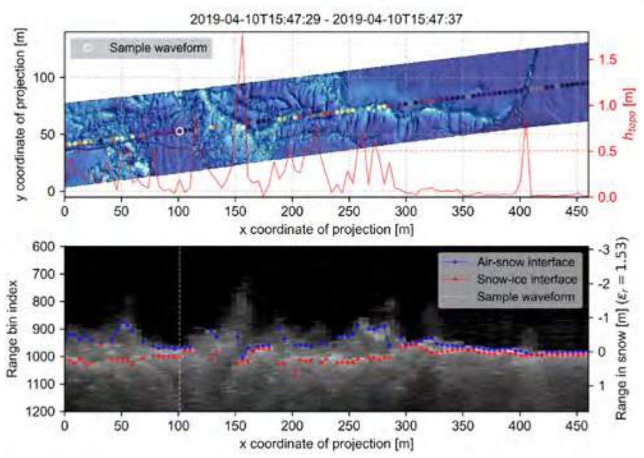


Figure 21 – (Top panel) Ice floe surface topography map from the Airborne Laser Scanner, and the corresponding topography profile at the centre of the swath (red line). The superimposed circles are the measurements of the elevation of the air snow-interface from the ultra-wideband radar, whose radargram is shown in the bottom panel with the detected interfaces. Credits: Arttu Jutila, AWI.

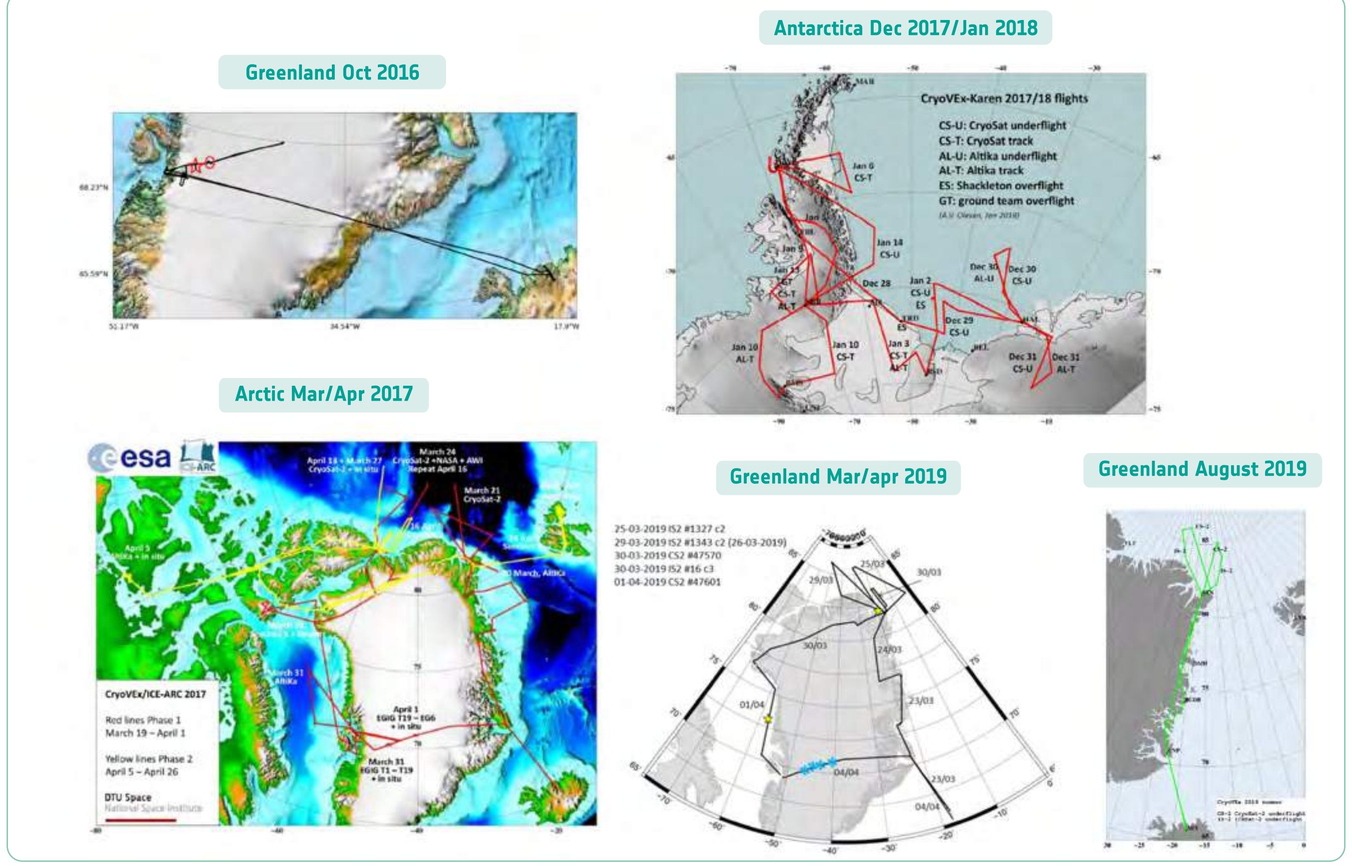


Figure 22 – CryoVEX evolution campaign locations and tracks since 2016. Credits: Tânia Casal, ESA with inputs from DTU teams.

accompanied by an ultra-wideband snow radar (FMCW radar, quad-polarized, 2-18 GHz with specifications comparable to NASA OIB and high performance: range resolution in snow 1.14 cm, across/along-track footprint 2.6/1.0 m for a low altitude (200 ft) survey at 110 kn) (Jutila et al., 2021). After coherent noise removal and range sidelobes deconvolution, the radar waveforms are very clean. The validation of snow depth from this radar against few available in situ data on first-year ice has yielded a bias of only 0.64 cm, and RMSE of 3.98 cm. The IceBird instrument setup is completed by the EM-Bird, a towed sensor based on electromagnetic induction sounding that measures the combined thickness of the sea ice and its snow layer. In the discussion it was noted that it should be easy to install the AWI/IceBird snow radar (and the similar CReSIS radar, for that matter) on other aircrafts, for instance the BAS Twin Otters.

Early results from the IceBird snow radar, obtained with a custom air-snow and snow-ice interface detection algorithm (open-source *pySnowRadar* package) show success retrieval rates of ~80% over complex floe surface topography like in the example shown in Figure 21. There is now a pressing need for extensive validation of this kind of observations, which has not yet been possible due to the COVID-19 pandemic. Evaluation against Ku/Ka/Laser satellite data is also only starting now.

The conclusions from this presentation are that sea ice remains a challenging surface for radar altimetry. For instance, the effects of surface roughness and snow distribution and accumulation are not yet fully understood for different satellites, radar footprints and frequencies. The key parameter is the resolution, both spatial and in range, whose enhancement can potentially improve process understanding at all scales.

In the chat discussion, Julienne Stroeve suggested that it would be interesting to compare the *pySnowRadar* algorithms with those used by Rosie Willatt for her analysis. Arttu Jutila and Josh King said that their approach is an adaptation of the pulse peakiness method by Ricker et al. (2014), the code repository including the picker is online, and all is needed is a wrapper to translate the KuKa format to the one expected in pySnowRadar.

Tânia Casal gave an overview of the ESA dual-frequency campaigns data available in the ESA archives (see link).

The CryoVEx series of campaigns has a long heritage. CryoVEx started in 2002 with a Ku-Band radar (D2P from John Hopkins Univ.) and a laser system. Since then there has been an ESA campaign in the Arctic roughly every one to two years. They were repeated campaigns to capture the temporal changes in snow/ice geophysical characteristics (sea ice campaigns in 2002, 2003, 2006, 2008, 2011, 2012, 2014; land ice campaigns in 2003, 2004, 2006, 2007, 2008, 2011, 2012, 2014, 2016) and these campaigns were planned to address CS-2 before and after launch mission objectives (cal/val). After more than a decade of exceptional performance, the airborne version of SIRAL, ASIRAS, ESA's Ku-band radar built by RST, has been discontinued in 2020. From 2011-2017, there was collaboration with NASA and Operation IceBridge in the form of several joint underflights of CS-2. For logistical considerations most of these Arctic campaigns were carried out in the spring. Since 2016, a new Ka-band radar system, KAREN (owned by MetaSensing), has been added to the airborne instrumentation suite to address future dual-frequency mission objectives. The locations and tracks of these "CryoVEx evolution" campaigns are shown in Figure 22.

Coordinated and collocated ground, aircraft and satellite experiments were run for sea ice campaigns in 2017, 2018 and 2019, and land ice campaigns in 2016, 2017, 2018 and 2019. These no longer took place only in spring: summer campaigns took place in Antarctica in the austral summer 2017/2018, and the first summer Greenland campaign in 2019. In the summer of the 2019 campaign, KAREN and ASIRAS have been replaced by the CReSIS Ku/Ka-Band radar and its use is envisaged for future campaigns given the very promising results obtained. In the meantime new collaborations were also established with CNES and LEGOS to carry out underflights of AltiKa, and with JAXA who provided L-band radar imagery from ALOS-2.

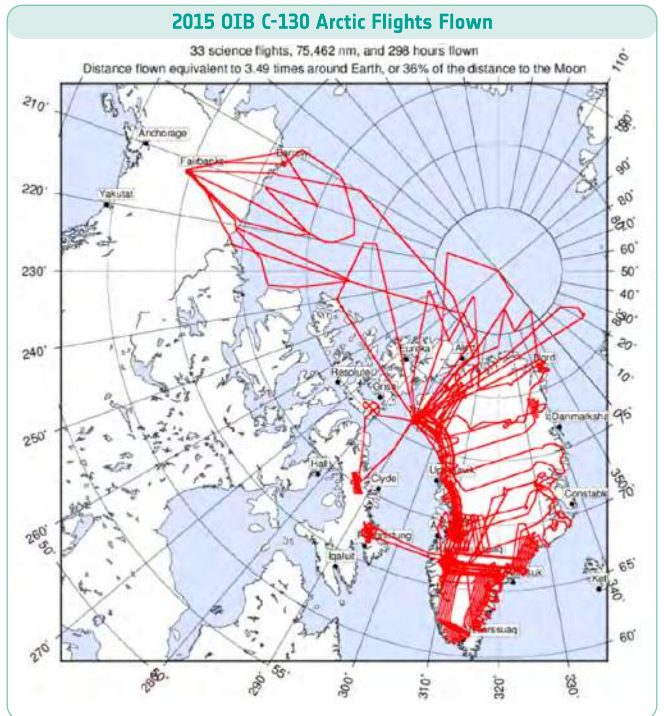


Figure 23 – Operation IceBridge flights in 2015. Credits: NASA GSFC/UMD

Ground-based radar measurements up until 2019 have been taken with the Ku-band ground penetrating radar from Andrew Shepherd's group at Univ. Leeds. Now, there is great potential from the new KuKa dual-frequency radar managed by Julienne Stroeve's team from UCL/Univ. Manitoba. KuKa data collected during the MOSAiC expedition have been presented in Rosie Willatt's talk and will be available through the ESA Archives later on in the year of 2021. The archives already contain all CryoVEx campaigns up to Antarctica 2017/2018, while data from 2019 spring and summer campaigns are expected to be added by Q2 2021. Each dataset has been assigned a DOI (ESA is encouraging users to refer to it for traceability) accompanied by a direct link to the data repository with the only requirement being to supply a very concise explanation of the planned data use. For each campaign, additional information and the full Campaign Report are also available.

Sinéad Farrell provided information on the NASA IceBridge Observations in Support of tri-band Altimetry, taking as an example the very extensive 2015 OIB campaign whose flight tracks are in Figure 23. The instrumentation included: ATM, Snow radar, Ku- and Ka-band radar. Two in situ field sites over sea ice were also overflown.

Fernando Rodrigues-Morales reviewed the CReSIS Ka-band radar data used in OIB, including an instrument overview. The NASA OIB 2015 campaign employed a large and heavy (70 kg) Multi-band Instrument Package (snow radar, Ku, Ka, each with a 6-GHz bandwidth). More recently CReSIS have develop a much more compact system (two modules for a total of ~25 kg) with comparable performance and compatible with much smaller aircrafts, which is shown in Figure 24. This compact system was used also for the ESA/CryoVEx 2019 spring and summer campaigns.

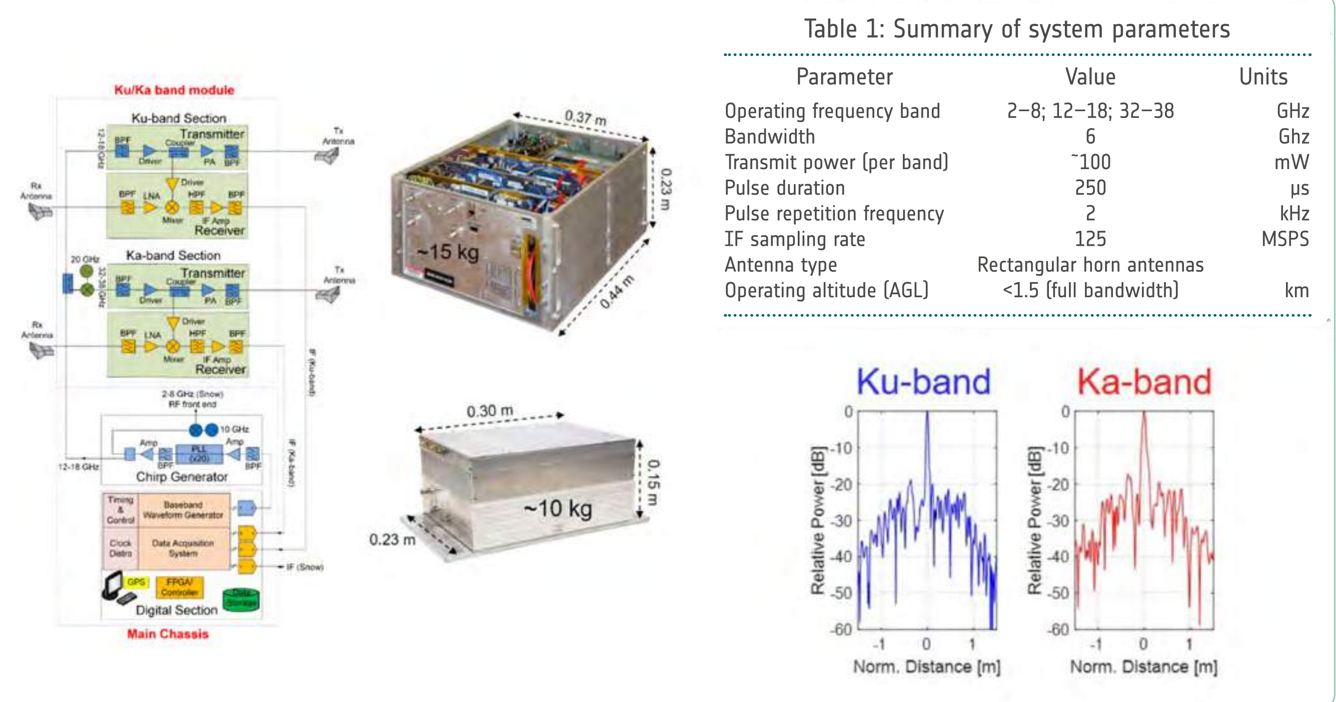


Table 1: Summary of system parameters

Parameter	Value	Units
Operating frequency band	2–8; 12–18; 32–38	GHz
Bandwidth	6	Ghz
Transmit power (per band)	˜100	mW
Pulse duration	250	μs
Pulse repetition frequency	2	kHz
IF sampling rate	125	MSPS
Antenna type	Rectangular horn antennas	
Operating altitude (AGL)	<1.5 (full bandwidth)	km

Figure 24 - Schematic and main specifications of the CReSIS Multi-UWB Compact System. Credits: CReSIS

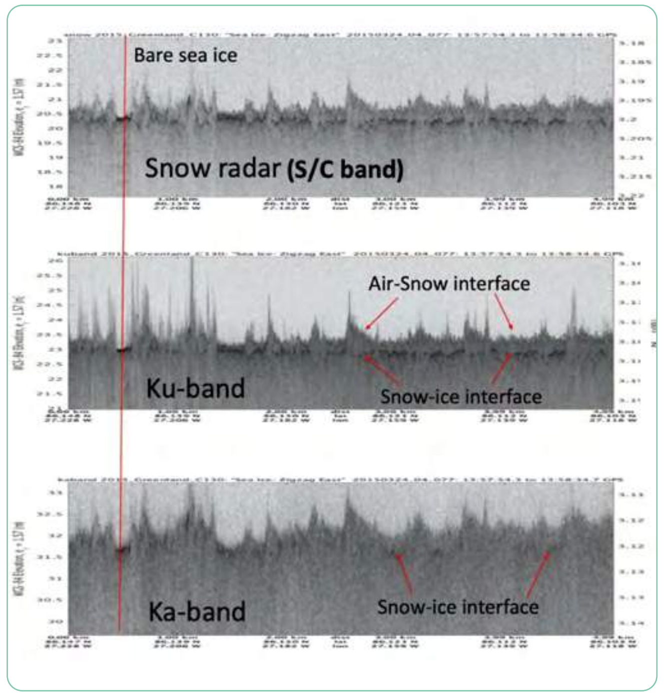


Figure 25 – Example of radargrams from the CReSIS Multi-UWB Compact System over sea ice. Credit: CReSIS

Jilu Li followed on by showing some results for the CReSIS system, in particular on how the Ka band compares with the Ku band and snow radar (S/C band) over the various surfaces. Figure 25 shows an example of the three radargrams over sea ice. Some penetration of the Ka signal in the snow can be seen in the lower panel, where the snow-ice interface is visible in places. Over land ice some layering is also visible in Ka band in dry snow conditions.

Some waveform comparisons of the CReSIS waveforms against AltiKA waveforms at crossovers have also been attempted. There is a broad consistency, but further conclusions are made difficult by the much lower vertical resolution of the satellite altimeter. The snow grain size estimation is one very useful potential application of the Ka-band data (Li et al., IGARSS 2020). Indeed, snow grain size can be inferred by the significant volume scattering in the Ka-band signal. His estimated snow grain size at the Greenland summit is 0.17 mm and it is in good agreement with snow pit measurements.

Donghui Yi showed some work on comparison of coincident elevation and freeboard of IceBridge ATM, Cryosat-2, and Sentinel-3 over Arctic Sea Ice. The work, carried out by the team led by A. Egido has the main purpose of calibration and validation of Fully-Focused (FF) SAR altimetry retrievals. It was recalled that ATM has two conical scanning laser altimeters (narrow angle of 2.5° and wide angle of 15° both with a footprint size of 1 m from 1500ft). ATM elevation and freeboard and IB snow depths were compared, using the methods in Yi et al 2019, with elevations and freeboards from standard CS2 and S3 products, over several years of overlap. A consistent set of corrections were applied to the different data to avoid biases. The authors also used cluster analysis to separate floe an lead in ATM data (they have processed all iceBridge ATM data over the Arctic in this manner; they still have not looked at Antarctic data, but are planning to do it in the next year). The probability density function (PDF) of the surface height is calculated from ATM elevation and modelled using the probability density function of the exponentially modified normal distribution (exGaussian), which fits both rough (with a long exponential tail) and smooth (more narrow Gaussian-like PDF) sea ice roughness. The results of the ATM vs CS2 lead elevation show the distinct effect of adopting different retrackers, with differences up to 0.45m. This dependence on retrackers is even greater for the mean floe elevation, with variations up to 0.75 m amongst retrackers. Comparison of the mean freeboard at the snow/ice interface after correction for snow depth shows a broad match between ATM and the various retrackers, with mean biases varying between −9 cm and +7 cm.

Results so far confirm that radar altimeter-derived 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 also ends up being retracker dependent. The study will now be extended to include FF-reprocessed elevations from CS2 and S3 (so far NOAA have processed a full season of CS2 data in FFSAR, and some limited tracks of S3A and S3B. Their plan is to process all available CS2, S3A and S3B data).

Rene Forsberg went back to the topic of campaigns, summarising 25 years of airborne multi-band altimetry ESA CryoVEx campaigns and related campaigns in the Arctic and Antarctica. Those campaigns have been developed from

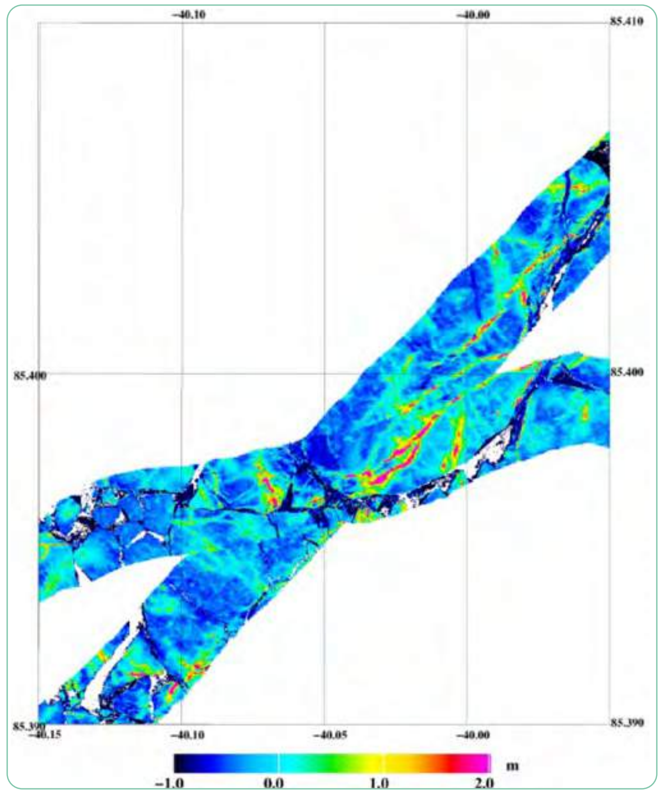


Figure 26 - Example of laser scanning of sea ice in the Arctic Ocean north of Greenland, clearly showing some ice ridges. The swath width is 300 m, with ice thickness of 2-3 m. Credits: DTU Space

relatively small budgets, and with manpower often funded (such as the case for DTU) out of national programs. The usual Twin Otter nicknamed "POF" (from its registration number) is very versatile (and has a fascinating history) and in many cases it allows landing very close to the interesting ice features. The typical instrumental configuration as mentioned by Tânia Casal in her talk was with the Riegl LMS Q240i scanning Lidar (one example from this instrument is shown in Figure 26), ASIRAS (which is now stored at DTU and still functioning), and since 2016 a Ka-band radar (Metasensing KaREN or the CReSIS radar). Particularly significant was the CryoVEx-KaREN campaign in Antarctica in 2017/18 combined with ice cap and sea ice ground truthing by U Leeds/UCL. DTU also have a very versatile Penguin B Lidar drone, allowing year-round operations with 300 km range, 5 cm accuracy. Rene concluded summarizing the plans for future campaigns, in particular CryoVEx 2022 should include Station Nord, Eureka and the EGIG line, with the new CRESIS broad-band snow radar and Canadian ground truth teams. CryoVEx campaigns continue to deliver reach data series over ice caps and sea ice for validation and research.

Marcello Passaro presented the results from the Baltic SEAL project, relevant here as they provide an assessment and perspectives of Ku- and Ka-band sea level retrieval with and without sea ice coverage. The two main issues are to correctly classify the radar returns coming from open water or sea ice, and to avoid biases due to different algorithms used in different situations (sea ice vs open ocean, Ku band vs Ka band, coast vs open ocean). The Baltic sea is a great site for validation and a laboratory for processing strategies as it has plenty of sea ice and coastal locations. Technical University of Munich have developed an homogeneous set of routines for all missions/instrument modes (Ku, Ka, LRM, SAR, FF-SAR) and all environments (including sea ice). They start with an unsupervised waveform classification, using a machine learning approach which only uses some background information over nilas ice and is validated against optical and SAR imagery; then they perform waveform retracking and finally multi-mission cross-calibration. The retrackers used are ALES+ (physically-based) and ALES+ SAR (empirical); the latter is available on the ESA GPOD platform which would be a great platform to exploit in view of comparative retracking studies for CRISTAL. An ALES+ FF-SAR retracker is also being tested. Validation of the sea level results against tide gauges is very encouraging. The correlation values are good for both CS2 SAR and AltiKA LRM, and crucially remain the same also during the sea ice cover period (i.e. using lead elevations). So it appears that their processing classifies and flags correctly sea ice returns, and the processed data (which also include the elevations computed by retracking those sea ice returns and not yet exploited) are now available for research via the website.

Henriette Skourup presented Dual-frequency airborne radar measurements from the CryoVEx campaigns for potential estimates of snow depths, with comparison with in situ work. In the NW-track of the CryoVEx March/April 2017 Arctic campaign (Skourup et al., 2019), there was extensive ground work, and CS2 and OIB overpasses, allowing a comparison of satellite, airborne and in situ-derived snow depths. This study is showing a similar underestimation of snow depth using airborne Ku/Ka as shown by Stefan Hendricks with errors in the region of 10-20 cm (Figure 27).
Skourup also showed some results from the CryoVEx 2017/18 Antarctica campaign (Hvidegaard et al., 2019) where derived ALS-ASIRAS and KaREN-ASIRAS snow depths are compared with in situ data collected from the Shackleton research vessel. There is an indication that the Ka-band signal has some penetration in the snow. During the same campaign some interesting in situ tests were carried out by R. Tilling in various configurations, some involving the use of a metal plate.
The conclusions were that retracking needs further investigation, and we need to better exploit the campaigns data that are available. Then it is necessary to compare with satellites (linking satellite footprint to airborne and in situ measurements). At the moment there are no processed sea ice freeboards from satellites available to scientists over Antarctic sea ice.

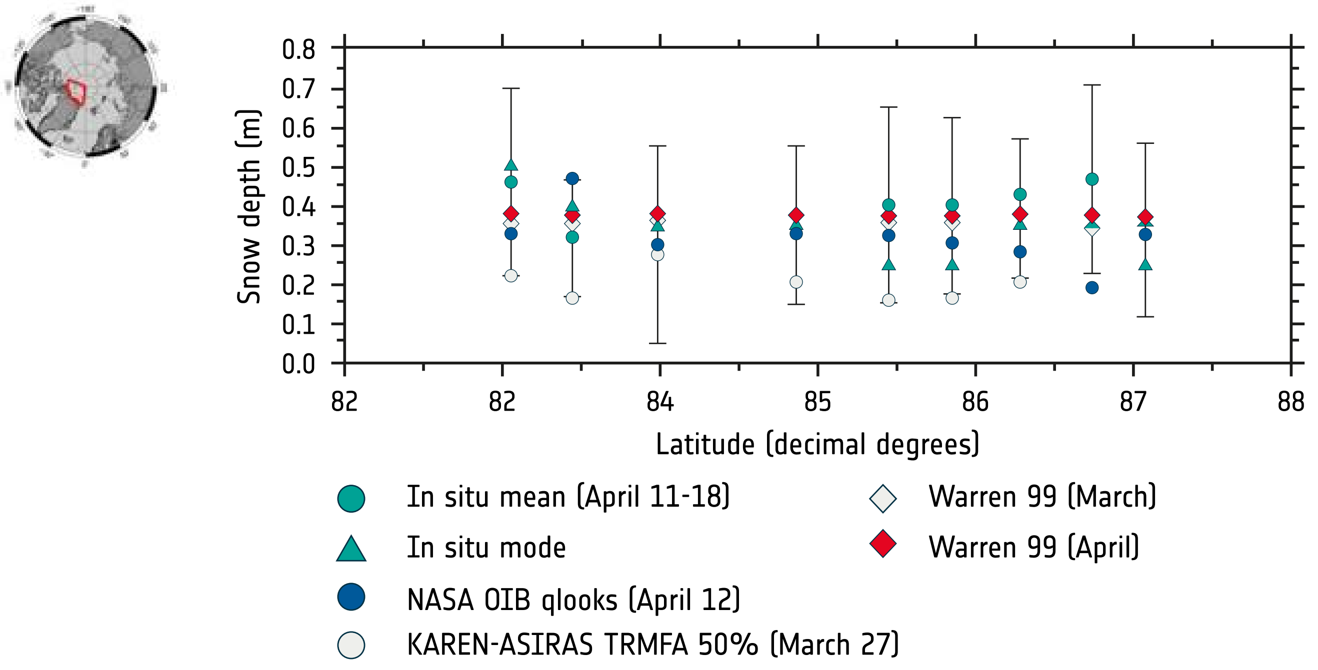


Figure 27 – Comparison of satellite, airborne and in situ snow depths from CryoVEx 2017. Credits: H. Skourup

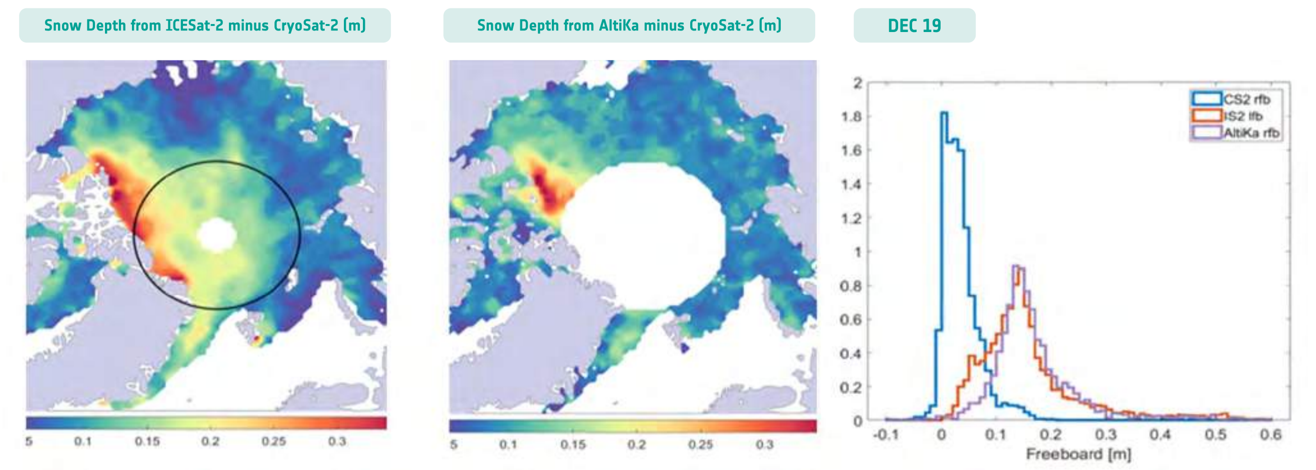


Figure 28 – Results from the facet-based numerical model approach: (left panel) snow depths in Dec 2019 from ICEsat-2 laser minus CryoSat-2 freeboards; (middle panel) the same from AltiKa minus CryoSat-2 freeboards; (right panel) histograms of the freeboards for the three sensors, showing the excellent agreement of laser and Ka band. Credits: Jack Landy, UiTromso/Bristol Glaciology Centre

To illustrate the specific problem of footprint comparison, Skourup showed some results from the ESA CryoVal Sea Ice project, where the scatterplots of elevations from the various airborne sensors versus the CS2 freeboards, averaging airborne data over the CS2 SAR footprint (300mx1600m), show very little or no correlation. The best correlation is found by averaging both datasets at 50 km, a comparatively long scale when we consider that transects are typically 300 to 500 km long. This issue will need further analysis.
Michel Tsamados showed challenges and solutions from the ESA/EXPRO+ POLAR+ Snow project on multi-frequency satellite approaches for snow on sea ice, that has just started. The project explores both the Ku/Ka and Ku/Laser approaches. The challenges tackled in POLAR+ Snow are the comparison of empirical vs physical retrackers, the calibration and bias correction to retrieve the ice freeboard and snow freeboard, the fusion of the information and the error analysis. The different assumptions on Ku/Ka/Laser penetration need to be revisited. There are several possible strategies. The first one is to empirically calibrate the radar freeboards against auxiliary data, such as in situ and airborne measurements, which are flexible and fast. However, the disadvantage is that such calibration is normally not stationary in time. An alternative approach (Guerreiro et al., 2016) is to physically represent and understand the radar freeboards, also degrading the CS2 SAR footprint (whose range retrieval is not much impacted

	Parameter	Estimated Importance		Scattering Mechanism
		Ku-band	Ka-band	
Snow	Air-snow interface roughness	Low	High	SS, R
	Snow temperature	Low	Low	VS
	Snow liquid water	High	High	VS
	Snow density	Med	Low	VS
	Snow grain size	High	High	VS
	Snow salinity	High	Low	VS
	Fresh ice lenses	Med	Med	VS, SS
	Snow depth	Med	Low	VS
Sea Ice	Snow-ice interface roughness	High	Low	SS,R
	Sea ice temperature	Low	Low	SS
	Sea ice salinity	Low	Low	SS
	Large-scale tipography	High	High	SS, R

Table 1 – Impact of various parameters on the measurements in Ku and Ka band, and the relevant scattering mechanism: volume scattering (VS), surface scattering (SS) and reflection (R). Credits: Robbie Mallett, UCL

by surface roughness) to match the AltiKa LRM footprint. In this way, there should be a comparable impact of surface roughness on the range estimation on both retrievals, which may balance out each other. A third approach is to directly simulate the echo footprint and the interaction with the topography, as in the facet-based numerical model proposed by Jack Landy et al., 2019. This is very promising as it simulates realistically the components to the echo from actual topography, and opens the way to investigations that exploit AI methods and inversion schemes aiming at gaining information at sub-footprint level. Converting the 3D facet-based model to 2D and integrating the radar echo over distribution of surface slopes, rather than surface heights, enables a more accurate application to pulse-limited altimetry missions and yields a Ka-band freeboard in good agreement with Laser, and therefore consistent snow depths (see Figure 28).

The challenges in the vertical domain due to volume scattering, scattering by the interface surfaces and reflection are summarised in Table 1. All the parameters in the table intervene to modify the signal to some extent. Yet another possible approach is to tune' the geophysical inputs to the SMRT model (see G. Picard's talk on day 1) in order to match model output to observations.

Tsamados concluded citing latest research on Innovative fusion and AI algorithms to combine the various missions. Despite all the challenges, he believes that with the knowledge we are gaining with the existing and past altimeters, we should be ready for a very useful operational snow product from CRISTAL. Once we have snow products, it is possible to assimilate those into sophisticated, state of the art sea ice and climate model (i.e. at the Met Office).

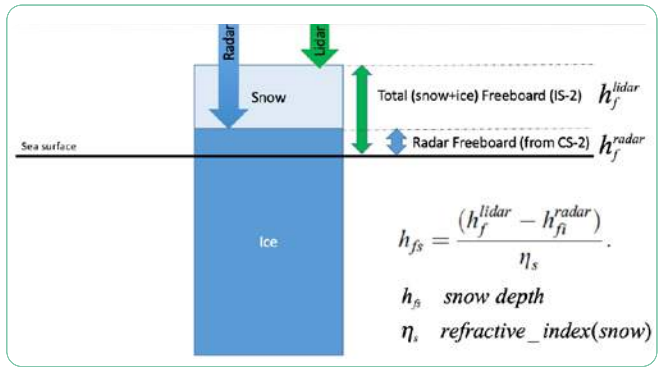


Figure 29 – Principle of snow depth measurement from coincident lidar (ICEsat-2) and Ku-band radar (CryoSat-2) observations. Credits: Ron Kwok

Ron Kwok concluded the presentation session by showing progress and on-going work on snow depth derivation from CryoSat-2 and ICEsat-2 freeboards, that exploits the opportunity of having them in orbit at the same time. Kwok first recalled the measurement principle (Figure 29). We assume that the lidar sees the air-snow interface and the radar gives the freeboard at the snow-ice interface. Their difference divided by the refractive index of snow gives a first-order measurement of the snow depth, provided the differences in sampling can be somehow overcome or accounted for. This idea was first explored at basin scale by Kwok and Markus (2018) using ATM and CryoSat-2 freeboards alongside the snow radar-derived freeboards. When the difference between the two freeboards from laser and radar is regressed against the estimates of snow depth from the OIB snow radar (Figure 30), the regression slope is related to the snow density and refractive index. The slopes of ~1.2 can be translated in a value of density, which is consistent with what expected for the Arctic Ocean.

Kwok et al. (2020) have used this approach to derive Arctic snow depth and sea ice thickness from ICESat-2 and CryoSat-2 freeboards. The relevant dataset is available on the PANGEA archive. An equivalent study for the Antarctic has just been published (Kacimi and Kwok, 2020). Antarctic conditions are more challenging resulting into some still unexplained biases that are highlighted in the paper. The question is now how to verify/validate these snow depth retrievals. It must be recognized that absolute accuracies are difficult to be established. Time-variable behaviour must be looked at and spatial/temporal anomalies (patterns that are unexpected based on climatology or expected behaviour) should be attributed to atmospheric forcing or other sensible physical arguments. Sometimes IS2 and CS2 freeboards are not correlated, or they are negatively correlated, especially in the Antarctic, and an explanation of why this happens can be attempted on based of a number of physical processes as discussed in Kacimi and Kwok (2020). It is also useful to look at extremes in retrievals, to assess the sensitivity of the differencing to geophysical processes.

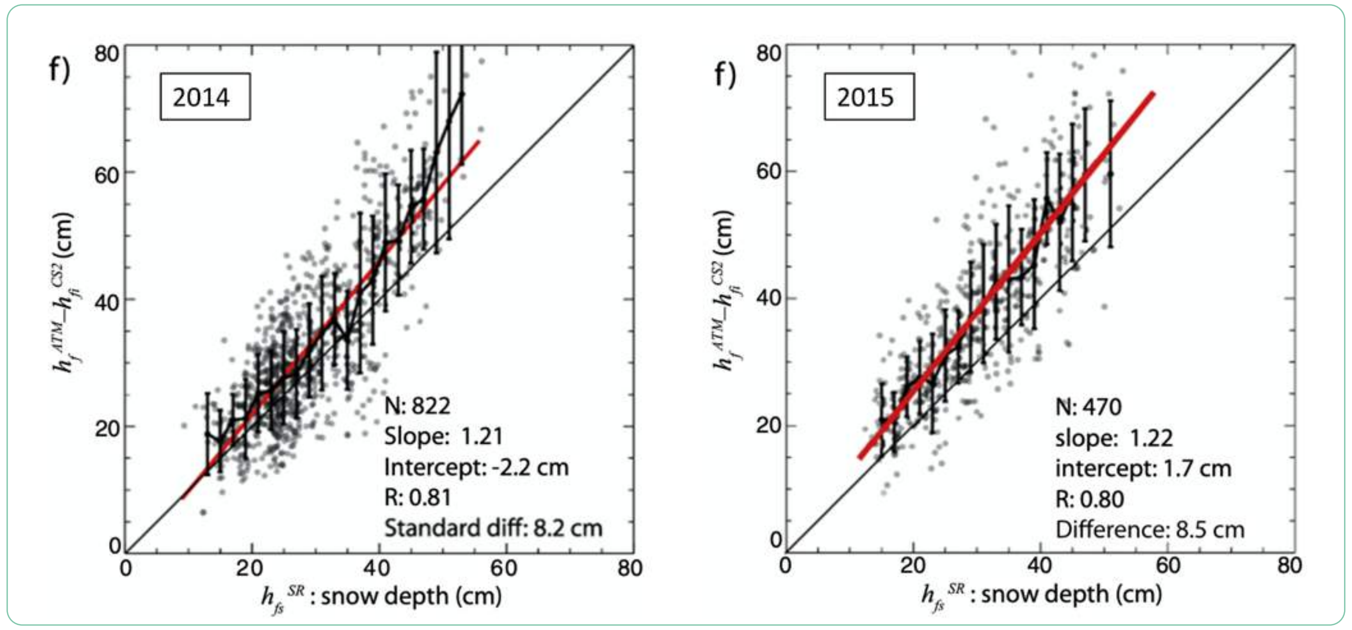


Figure 30 – Scatterplot and regression of ATM-CS2 difference against the snow depth from the show radar from OIB campaigns in 214 (left panel) and 2105 (right panel). Credits: Kwok and Markus (2018)

Kwok concluded by showing some examples that warrant further investigation. For instance, from the CS2/IS2 retrieval of snow depths over the Arctic in the winter 2018/19, there is a anomalously thick snow layer at the end of winter (April 2020 composite) in the Chukchi Shelf region. This could be explained by noticing an anomaly over December to February in the number of cyclone events and cyclone-associated snowfall from the ERA-interim reanalysis. Another example is from the September 2019 composites of Antarctic snow depth and sea ice thickness, which both show anomalously high values in the Amundsen Sea and Bellingshausen Sea, and can be explained as a result of ice convergence due to an atmospheric low over the Ross Sea that pushed the ice towards along the Amundsen/Bellingshausen coast. This convergence increases the tails of the thickness distribution, but why is there correlated changes in snow as well? This is currently being investigated on the basis of possible phenomena (ice cover closed so no snow loss into leads; and/or increased snowfall).

As a conclusion, we need to better understand the evolution of brine in the snow layer. There is increasing evidence of biases in the ice freeboard estimates from CS-2 due to salinity at the snow-ice interface, especially in the Antarctic where due to snow flooding there can be brine up to heights of tens of centimetres. There is an urgent need for coordinated measurements of time-varying snow properties (salinity, density, temperature and grain size) especially in the Antarctic for developing simple models usable in snow depth/thickness retrievals from altimetry. Work is continuing in particular on the refinement of retrievals by looking at profiles of salinity, grain size and density, and examining the seasonal and interannual variability.

Discussion

So what algorithm(s) could we adopt for dual-frequency snow depth retrieval if CRISTAL were to fly now? While for Ku-band retrieval we have useful experience from CS2, for SAR Ka-band data we would have to learn. It is possible that algorithms for Arctic and Antarctic may be different.

A key point coming up from todays' discussion is the benefit of using the three bands together to aid with the interpretation of the Ka-band signal. The information from the smaller laser footprint is useful to derive the smaller-scale surface roughness elevation. Also, the lead discrimination of the SAR Ka-band instrument will presumably be much better than the Ku instrument because of the smaller footprint.

Then, there are additional challenges in generating the near-real-time products that are needed by some users (e.g. winter navigation, weather forecasts).

As for land ice, retracking is a key aspect, and the volume scattering information in the signal (in particular in Ku band) should be exploited further, accounting for the various effects in physically-based waveform models.

Wave motion and swell contribute to uncertainty in sea ice measurements: could this be mitigated with a dual-band approach? This is another aspect that needs further studies. We recall that the SIT uncertainty requirements for CRISTAL are 10 cm uncertainty over 25-km segments.

Another factor contributing to the overall uncertainty in sea ice measurement is the uncertainty on the density of the ice, which altimeters cannot resolve, so additional work will be needed to provide a separate estimate of this quantity.

Conclusions and Recommendations

A very positive aspect of the research on the altimetry over sea ice is that work on scattering horizons and snow depth is already largely published. This suggests that a lot can be achieved by reviewing the papers that are already in the literature.

A dedicated sea ice Ka/Ku/Laser study, such as the one suggested for land ice, is needed, with the advantage that it can be largely completed from analysis of existing data sets in both the Arctic and Southern oceans. Crucial effort then should be dedicated on the improvement of the retrackers.

Future campaigns should target as a priority some CRYO2ICE IS2/CS2 overpasses. The challenge for campaigns is to get personnel on the sea ice. Finding a good snow layer is not trivial – for instance in Antarctica in summer there is very little, but as it has been learnt in previous campaigns the collection of snow, surface roughness and topography information on a two-dimensional grid (therefore needing occupation of a station for some time) is essential for validation. Note that not only the roughness of the air/snow interface is important, but also the roughness of the ice/snow interface whose measurement is a complex task involving extensive physical sampling of the area with snow pits, which is time consuming and requires deployment of a good number of personnel.

Finally, the analysis needs to be properly resources both in terms of software tools to process the data and link these to the satellite scales, and in terms of personnel. Far too often we do not have the manpower to look at all the data from the campaigns, and it is hoped that with the advent of a mission with primary cryosphere objectives such as CRISTAL there will be resources for an extensive analysis of the data already collected.

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