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The Cryosphere Discussions

Brief Communication: Ice Sheet Elevation Measurements from the Sentinel-3A / 3B Tandem Phase

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Abstract. Over the coming decade, the quartet of Sentinel-3 satellite altimeters will provide a continuous record of ice sheet elevation change. To ensure consistency of measurement between each of the four satellites, requires rigorous in-flight inter-comparison. To facilitate this, Sentinel-3B was initially flown in a unique tandem formation with Sentinel-3A, enabling near-instantaneous, co-located measurements to be acquired. Here, we analyse tandem measurements of ice sheet elevation, to show that both instruments operate with statistically equivalent accuracy and precision, even over complex ice margin terrain. This analysis demonstrates that both satellites can be used interchangeably to study ice sheet evolution.

1 Introduction

Long-term continuity of ice sheet elevation measurements is important for understanding the nature and drivers of ice sheet change (Sandberg Sørensen et al., 2018; Shepherd et al., 2019). Polar orbiting satellite radar altimeters have, for the past 30 years, provided such a record, and with it new insight into surface topography, ice mass loss, dynamical instabilities, surface processes and subglacial hydrology (Helm et al., 2014; Konrad et al., 2017, 2018, McMillan et al., 2013, 2016, 2019; Slater et al., 2018). The most recent satellites contributing to this record are the Sentinel-3 series, which provides delay-Doppler altimetry measurements up to a latitude of 81.35°, and with an on-the-ground revisit time of 27 days. Unlike previous polar altimetry missions, Sentinel-3 is part of the operational EU Copernicus Programme. As such Sentinel-3 is composed of four satellites, which together will deliver unbroken coverage until at least the end of this decade. Because of this unique configuration, it is vital that measurements from the four satellites (Sentinel-3A, B, C and D), are systematically compared in-flight, to determine whether their associated streams of data can be treated interchangeably by the scientific and service user community. This is important not only for long term continuity, but also for optimising the use of these data when more than one satellite is operating simultaneously. For example, at a latitude of 75°, adjacent tracks of a single satellite are separated by approximately 23 km, whereas when two identical satellites are flying in their nominal orbits, the across track separation decreases to around 11.5 km.

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The first two Sentinel-3 satellites (-3A and -3B), were launched on 16th February 2016 and 25th April 2018, respectively. To facilitate the inter-comparison of these satellites, Sentinel-3B was initially placed into a 'Tandem' formation with Sentinel-3A, whereby both satellites followed the same ground track (within the across-track control range of ±1 km) with a 30 seconds separation (Clerc et al., *in review*). This configuration was maintained between 7th June – 16th October 2018, so as to acquire several full cycles of data. Over Earth's ice sheets, these measurements are important because they provide contemporaneous (within 30 seconds), co-located (within ~150 metres) and co-orientated (i.e. same track heading and footprint orientation) observations. Such a configuration allows a more robust inter-comparison than is normally possible, because it avoids many of the common challenges associated with instrument inter-comparison, by removing the confounding effects of surface backscattering anisotropy (Armitage et al., 2014), and any spatial or temporal changes in elevation. In this study, we utilise this unique dataset to perform the first systematic inter-comparison of Sentinel-3A and Sentinel-3B (S3A and S3B, respectively) altimetry measurements over ice sheets, and to assess the extent to which these measurements can be used interchangeably by the glaciological community. Specifically, we analyse (1) the consistency of S3A and S3B radar echoes acquired over complex coastal topography, (2) the precision of the S3A and S3B instruments over Lake Vostok, and (3) the accuracy of S3A and S3B elevation measurements as compared to independent reference datasets.

2 Data & Study Sites

We analysed tandem phase Sentinel-3A and Sentinel-3B SRAL data that were acquired during the summer of 2018; using the most recent ESA Processing Baseline 2.27 of the Level-2 enhanced data product. Our assessment focused on three study sites in East Antarctica; Lake Vostok and Dome C which exhibit relatively low slope topography that is characteristic of the ice sheet interior, and the Spirit site which presents steeper and less uniform coastal topography (McMillan et al., 2019). To assess the accuracy of the Sentinel-3A and Sentinel-3B elevation measurements, we used airborne reference data acquired by the Airborne Topographic Mapper (ATM) and Riegl Laser Altimeter (RLA) instruments carried on Operation IceBridge campaigns (https://nsidc.org/data/icebridge). Further details of these datasets and the method of inter-comparison are given in McMillan et al., 2019.

3 Consistency of delay-Doppler echoes over complex coastal topography

When radar altimeters overfly areas of complex surface topography, the echo return diverges from its classical shape (Ray et al., 2015). This difference can range from a slight distortion of the theoretical waveform shape, to multiple superimposed reflections from distinct surfaces within the doppler beam footprint. Handling these complex waveforms is one of the major challenges associated with processing radar data over regions of complex topography. We therefore used the tandem phase to investigate the consistency of simultaneously acquired S3A and S3B waveforms over an area of complex terrain. Specifically,

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the objective of this analysis was to ascertain whether (1) the complex waveform shape is essentially non-repeatable due to the pseudo-random combination of multiple reflections from within the Doppler beam footprint, or (2) whether the waveform complexity is repeatable, and therefore represents meaningful geophysical information about the surface geometry. This distinction is important, because the former implies that the signal is somewhat degraded; particularly when it comes to making stable, repeatable measurements through time. Whereas the latter implies that, whilst more sophisticated processing may be required, there is useable, physically meaningful information encoded within the complex waveform shape. We therefore analysed tandem acquisitions from a track at the Spirit site, where the satellites made landfall over the Mertz Glacier Tongue (Figure 1). This location is characterised by complex, non-linear topography; with the floating ice tongue bounded on either side by steep topography. We find that the altimeter waveforms present a high degree of complexity, with multiple peaks and a varying shape along the satellite track. Importantly, however, the Sentinel-3A and Sentinel-3B waveforms are extremely coherent, both in terms of their shape (e.g. number of distinct peaks), and the amplitude of the backscattered signal (Figure 1). This suggests that meaningful, repeatable information is encoded within complex waveform morphology, opening up the future possibility of utilising the full waveform to retrieve additional topographic information.

4 Assessment of Instrument Precision at Lake Vostok

Next, we assessed and inter-compared the precision of the Sentinel-3A and Sentinel-3B altimeters by evaluating repeated elevation profiles that crossed the ice surface above subglacial Lake Vostok (Figure 2). This site provides a stable, relatively smooth (at the footprint scale) and low-slope surface that is well established for validation studies (McMillan et al., 2019; Richter et al., 2014). We selected a track that crossed above the central part of the subglacial lake and, for each satellite, we accumulated consecutive cycles acquired during the tandem phase of operations (S3A cycles 34-36; S3B cycles 11-13). Inspecting these data, we find no discernible difference between the measurements made by each satellite (Figure 2). To quantify the precision of both instruments, and to determine whether there was a statistically significant difference in their performance, we computed the standard deviation of all measurements made by each satellite within 1 km intervals along the satellite track. This yielded an estimate of the dispersion of elevation measurements along the satellite track (Figure 2), which averaged 0.094 m and 0.10 m for S3A and S3B, respectively. Testing for significance (5% significance threshold) using the non-parametric Mann Whitney U (Hollander et al., 2015) and Kolmogorov-Smirnov (Massey, 1951) tests for the central values and distribution, respectively, we find that there is no significant difference in the instrument precision of Sentinel-3A and Sentinel-3B.

5 Elevation Accuracy

Finally, we assessed the absolute accuracy of Sentinel-3A and Sentinel-3B ice sheet measurements, by computing elevation differences relative to reference datasets, using the approach described in McMillan *et al.*, 2019. We perform the analysis at

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three different sites (Lake Vostok, Dome C and Spirit) and using the two different retrackers provided in the ESA Level-2 product (the 'ice margin' retracker and the Threshold Centre of Gravity retracker). Across all sites and retrackers, we find that the differences in accuracy between S3A and S3B are always insignificant (5% significance level), both in terms of the absolute biases relative to the reference datasets and also the dispersion of the elevation differences (Figure 3). This indicates that there is no significant difference in the accuracy of the two instruments across any of the sites studied, and that it is reasonable to use data from both satellites interchangeably.

6 Conclusion

This Brief Communication summarises recent analysis of Sentinel-3A/B tandem phase measurements of ice sheet elevation. We find that (1) there is no significant difference between S3A and S3B instrument precision, (2) that there is no significant difference between the accuracy of S3A and S3B elevation measurements, and (3) that both instruments resolve near-identical echoes of the ice sheet surface, even over complex, non-linear coastal terrain. This study demonstrates that both satellites can be used interchangeably to monitor ongoing ice sheet evolution; effectively doubling the spatial coverage of measurements available, now that Sentinel-3B has moved to its nominal orbit. More broadly, it also establishes the value of operating a tandem phase immediately after satellite launch, and indicates that such operations would benefit the Sentinel-3C and Sentinel-3D units in the future.

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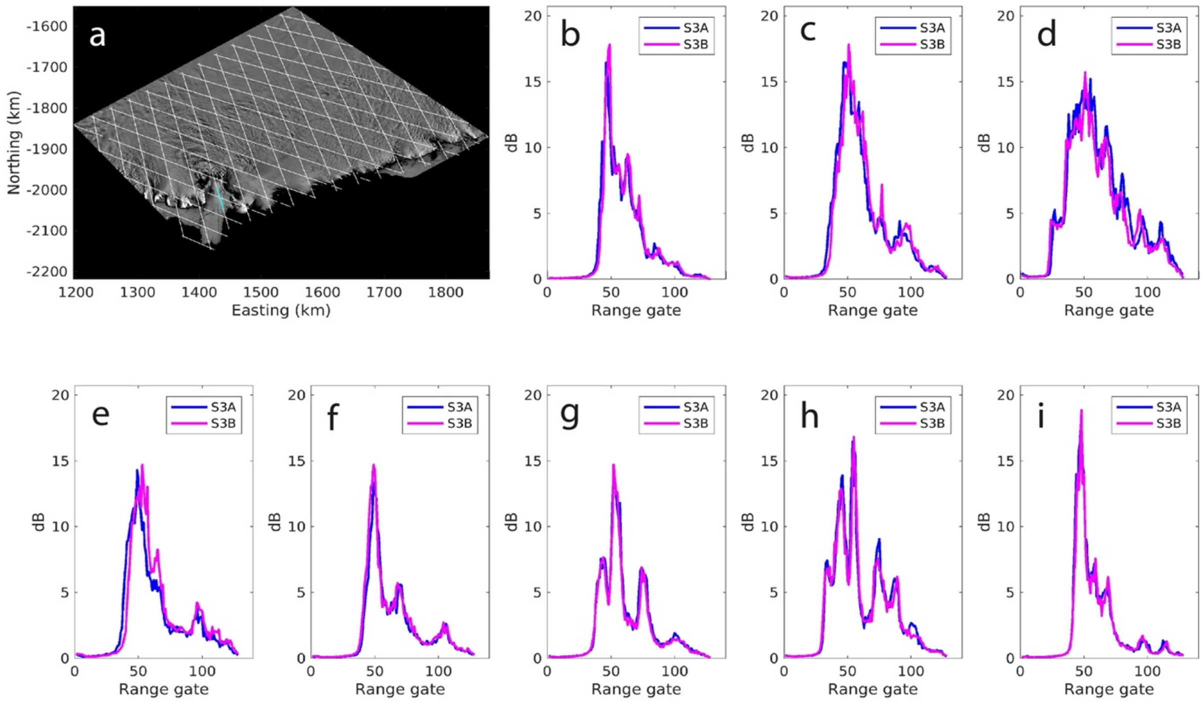

Figure 1: Repeatability of Sentinel-3A (S3A) and Sentinel-3B (S3B) tandem acquisitions over the Mertz Glacier in East Antarctica, along pass number 344. a. The locations of Sentinel-3 tracks (in white) over the Spirit site in East Antarctica. The turquoise dots mark the location of the waveforms shown in panels b-i; corresponding to every 20th acquisition (~ 7 km intervals along track), and the background image is the MODIS Mosaic of Antarctica (Haran et al., 2006). b-i. co-located (within 150 m), contemporaneous (within 30 seconds) and co-orientated waveforms acquired by Sentinel-3A (blue) and Sentinel-3B (magenta), showing the repeatability of complex multi-peaked waveforms.

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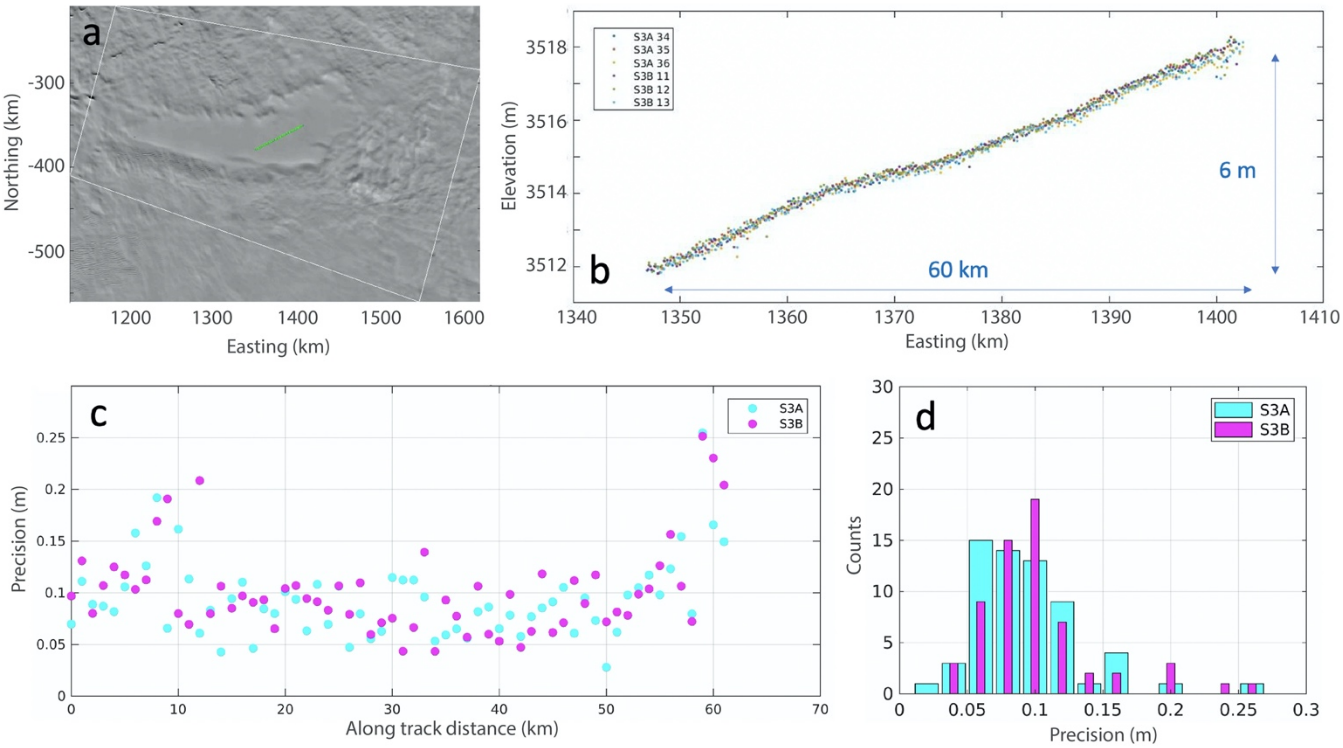

Figure 2: Assessment of Sentinel-3A and Sentinel-3B instrument precision at Lake Vostok site. a. Location of the ground track crossing the central part of the lake (shown in green), which was used to assess precision; the background image is taken from the MODIS Mosaic of Antarctica (Haran et al., 2006). b. Repeated elevation profiles acquired during Sentinel-3A cycles 34-36 inclusive and Sentinel-3B cycles 11-13 inclusive. c. The standard deviation of Sentinel-3A and Sentinel-3B elevation measurements in 1 km intervals along the satellite track. d. The distribution of the 1 km-interval standard deviations for Sentienl-3A and Sentinel-3B; there is no significant difference in S3A and S3B precision at this site, at the 5% significance level.

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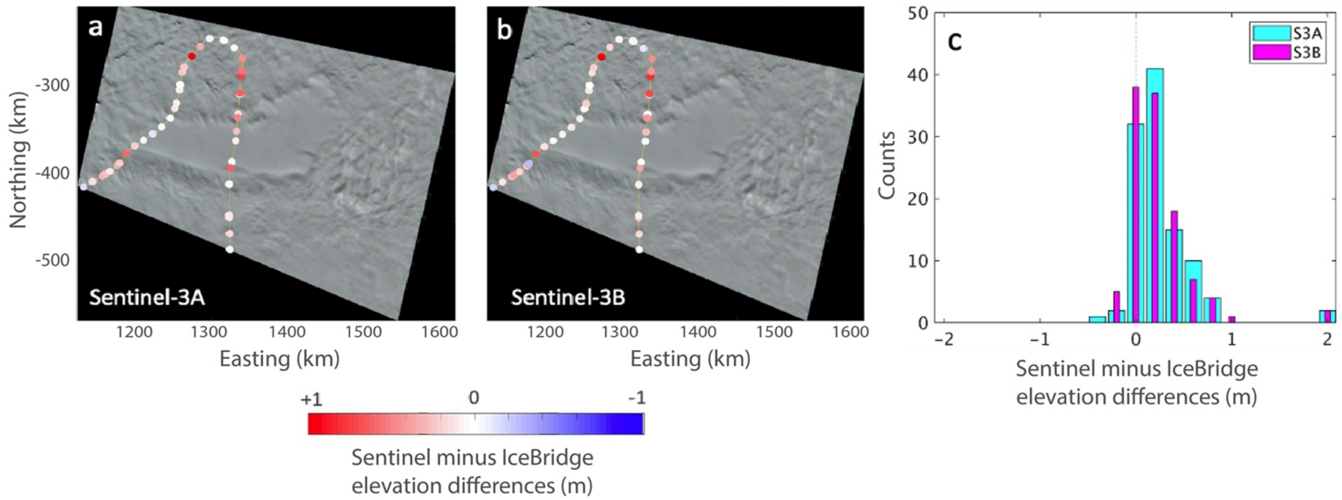

Figure 3: Inter-comparison of Sentinel-3A and Sentinel-3B accuracy at the Lake Vostok Validation site. a. Sentinel-3A minus IceBridge elevation differences, b. Sentinel-3B minus IceBridge elevation differences, c. the distributions of Sentinel-3A and Sentinel-3B minus IceBridge elevation differences. Results shown are for the TCOG retracking solution provided within the ESA Level-2 product, and for acquisitions made during cycle 34 (S3A) and cycle 11 (S3B) within the tandem phase. The background image in panels a and b is taken from the MODIS Mosaic of Antarctica (Haran et al., 2006).