EDITORIAL

Mapping Earth's cryosphere and inland waters with satellite radar altimetry

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Originally developed for ocean observations, satellite altimetry has revolutionized our ability to monitor, quantify, and understand the evolution of many components of the Earth system, including the cryosphere (e.g., ice sheets, glaciers, sea ice), inland water, coastal ocean and bathymetry. Among these, inland water and the cryosphere are two key fields that have attracted particular attention from scientific studies. In comparison to performance over the open ocean, the quality of measurements derived by conventional pulse-limited altimeters across highly-variable terrain (i.e., ice sheet margins or rivers located in mountainous regions) is degraded due to the complex radar response returned from such surfaces.[1] The advancement of altimeter instrumentation and processing has, however, enabled the transition from conventional pulse-limited systems to synthetic aperture radar (SAR) altimeters. One of the major advantages of SAR altimetry is the improvement in along-track resolution, from the order of kilometres to a few hundred meters. Further, the advancement of postprocessing techniques (e.g., waveform retracking and slope correction) has elevated the accuracy of the derived elevation measurements. Combining the latest SAR technology and on-the-ground processing, researchers have been successful in deriving elevations for numerous downstream applications (Figure 1). This study introduces the state-of-the-art satellite altimetry techniques for monitoring cryosphere (i.e., ice sheets) and inland water (i.e., rivers), discusses the principal research challenges and opportunities across these two major domains, and provides a summary outlook for future developments in this field.

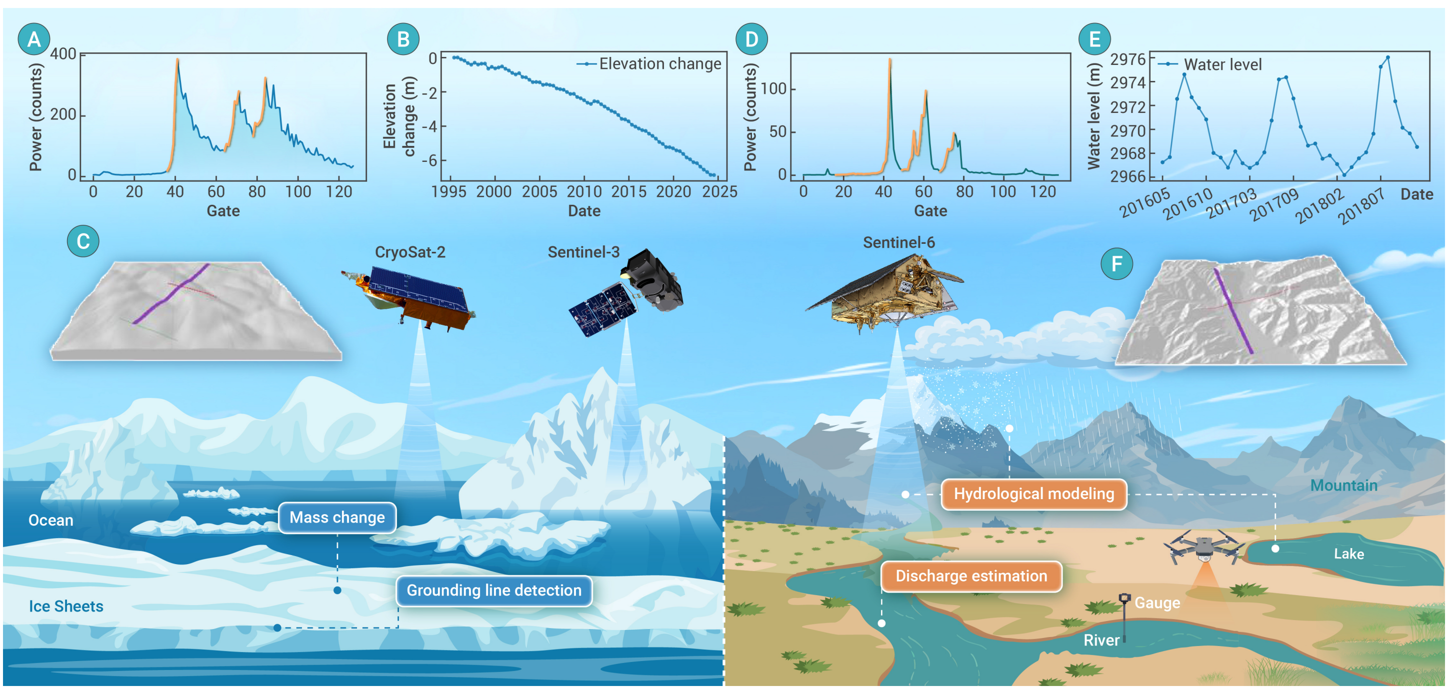

Figure 1. Monitoring cryosphere (e.g., ice sheets and mountain glaciers) and inland water (e.g., rivers and lakes) using radar altimeters (e.g., CryoSat-2, Sentinel-3, and Sentinel-6) with examples of downstream applications: (A) the multipeak waveform over the Russell Glacier in Greenland, (B) the elevation change of the Amundsen Sea Embayment in Antarctica during 1995–2024, (C) the 3D map of the complex terrain of the Russell Glacier, (D) a multipeak waveform (similar to that of the ice sheets) in the Brahmaputra River over the Tibetan Plateau, (E) time series of the water surface elevation during 2016–2018 derived from Sentinel-3A, and (F) the 3D map of the complex terrain for the Brahmaputra River.

CRYOSPHERE MAPPING

As a critical element of the Earth system, the cryosphere is a sensitive indicator of climate change/variability. In this regard, monitoring Earth's cryosphere is important for understanding the climate impact of anthropogenic activities, due to the cryosphere's capability to respond to, and drive, climate change. For the past three decades, satellite altimeters have provided a continuous source of information (e.g., elevation and mass change) on the cryosphere (e.g., ice sheets) and helped to quantify its contribution to sea level rise. Standard methods of retrieving surface elevation using radar altimetry are based upon resolving the Point-Of-Closest-Approach (POCA). Primary postprocessing procedures include waveform retracking and slope correction. Waveform retracking is one of the crucial steps, which serves to identify the deviation of the first recorded echo from the nominal tracking gate, in order to deliver greater range precision. Physical and empirical approaches have been developed for these purposes. Empirical approaches use statistical methods to estimate the range to POCA. Physical approaches model the returned power due to the interaction between the radar pulse and the illuminated surface. Additionally, a slope correction is required across ice sheets to account for the fact that the POCA is typically not located at nadir. The slope correction is performed using either an elevation or slope model, or via a leading edge based method.[2]

In addition to single point measurements from POCA, the SAR interferometric (SIN) altimeter onboard the CryoSat-2 mission launched in 2010 also allows for resolving a substantial number of elevation retrievals using swath processing. Swath processing includes (1) identifying suitable SIN samples based upon the phase coherence, backscattered power, and surface slopes; (2) phase unwrapping using a reference digital elevation model (DEM); and (3) aggregating multiple point measurements into a swath using the range, across-track look angle, attitude of the satellite, and orbit information.[3] Whilst POCA-based approaches capture only a single primary reflection, swath processing has the benefit of providing multiple (up to two orders of magnitude higher) samples across the satellite track, leading to enhanced spatial and temporal coverage (at the cost of higher computational demand). In the context of the upcoming Copernicus Polar Ice and Snow Topography Altimeter (CRISTAL) mission planned for 2027, further innovations of these techniques will be realized for monitoring the cryosphere. On the other hand, although the Surface Water and Ocean Topography (SWOT) mission, launched in 2022, was not specifically designed for cryosphere studies and has limited polar coverage (77.6° latitudinal limit), in regions that it does cover, it still offers potentially valuable insights into ice sheet hydrology and large-scale elevation changes. SWOT's Ka-band interferometry (KaRIn) enables continuous elevation profiles rather than isolated nadir points, making it ideal for reducing data gaps over ice sheet margins and glaciers while capturing surface hydrological networks in polar regions. For downstream applications from all of the aforementioned missions, elevation retrievals can be used for the delineation of the grounding line of ice sheets, the generation of DEMs, and the quantification of elevation change, volume change, and mass change. Ultimately, these observations facilitate a better understanding of the contribution of the cryosphere to global sea level rise.

INLAND WATER MONITORING

Inland waters are a key component of the water cycle and a sensitive indicator of climate change, with significant societal and economic value. The use of satellite altimetry for remote sensing of hydrology encompasses a broad range of domains including rivers, lakes, reservoirs, and estuaries. The utility of altimetry over inland water, particularly over rivers, requires sophisticated postprocessing to derive reliable water surface elevation. First, the delineation of virtual stations (the intersection of the satellite ground track and the river) dynamically as per the season is desirable. Similar to the cryosphere, robust waveform retracking is needed to reliably resolve the appropriate leading edge in complex waveforms caused by multiple reflections from the illuminated surface, specifically for mountainous regions. For inland water, the reflection of radar pulses tends to be locked over water bodies, due to its higher backscattering characteristics, thereby leading to an off-nadir measurement (i.e., a distorted range, also termed the hooking effect). To account for this, attempts have been made to apply a parabolic model to simulate the evolution of the elevation retrievals along-track and thus mitigate this range distortion.

Additionally, Fully Focused SAR (FF-SAR) processing for SAR altimeters can improve the along-track resolution from a few hundred meters towards the ~0.5 m theoretical limit provided by the along-track integration time.[4] This finer resolution allows for smaller water targets to be resolved, in comparison to standard Unfocused SAR processing, thereby reducing the land contamination prevalent in the footprint. One of the primary downstream applications of inland water level estimation is to determine river discharge either using a discharge-water level rating curve or the calibration of a hydrological model using the water level to derive daily continuous discharge estimates.

CHALLENGES OF SATELLITE ALTIMETRY FOR CRYOSPHERE AND INLAND WATER

Despite the significant progress made in radar altimetry instrumentation and processing over the past three decades, challenges still exist for the future evolution of satellite altimetry over cryosphere and inland water surfaces.

(1) The lag in the operationalisation of state-of-the-art algorithms

It can often take several years for the newly developed retracking approaches to be implemented for downstream applications. For instance, Ice-1, the retracker originally designed for ice sheets, has historically been used for inland water retrievals for many operational datasets, despite the development of multiple state-of-the-art retrackers. To address this, frameworks for more rapidly integrating technical innovations within operational systems are now being developed, such as within ESA's Cryo-TEMPO project.

(2) Challenges for data processing and storage

New techniques and instrumentation, such as FF-SAR and the ICESat-2 photon counting laser altimeter are rapidly increasing the volume of data that are available to be exploited. Utilizing higher rate data, for example, SAR and laser altimeters have delivered improved accuracy compared to their traditional LRM counterparts. For instance, ICESat-2 utilizes 6 beams, and CryoSat-2 operates a Pulse Repetition Frequency of 18.181 kHz in SIN mode, compared to the conventional 1.97 kHz in LRM. Managing and analyzing the resulting terabytes of data from these advanced altimeters pose significant technical challenges, requiring robust data processing infrastructure and storage solutions far beyond those needed for traditional altimeters. For example, SWOT's interferometric altimeter further amplifies data generation (on the order of seven terabytes per day). Although modern storage solutions can accommodate large datasets, ensuring long-term data accessibility and integration across multi-mission archives remains a critical issue.

(3) The validation of altimetry products for operational purposes

Currently, there exist many altimetry data sets for inland water (e.g., DIHITI, Hydroweb, River and Lake database). However, the reliability of these datasets cannot be fully validated due to the declining gauging stations globally, making it difficult to convince hydrologists to use them for operational hydrological systems (e.g., flood forecasting).

PROSPECTS OF SATELLITE ALTIMETRY

(1) Synergy with modelling and data assimilation

The integration of satellite altimetry with modelling can improve the spatiotemporal resolution of the key variables. For example, integrating altimeter-derived water levels with hydrological models through model calibration or data assimilation allows for daily continuous discharge estimates and helps make a step toward predictions in ungauged basins.

(2) Integration of artificial intelligence

Leveraging artificial intelligence (AI) with satellite altimetry will be one of the foci of future development. Specifically, classifying diversified and complex waveforms using deep learning prior to retracking may contribute to the reliability of the subsequent elevation retrievals. Further, leveraging AI may help bridge the data gap in hydrological basins that are not well monitored by altimeters, due to the constraints imposed by the temporal and/or spatial sampling of the satellites .[5]

SUMMARY AND OUTLOOK

This study introduces the state-of-the-art technologies currently implemented in satellite altimetry, presents current challenges, and discusses possible future evolutions of altimeters for cryosphere and inland water research. Ongoing efforts will focus on the joint use of advanced machine learning algorithms and modelling to fully exploit the potential of satellite altimeters in monitoring Earth's surface with higher resolution and precision.

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DECLARATION OF INTERESTS

The authors declare no competing interests.