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# On the performance of Sentinel-3 altimetry over new reservoirs: Approaches to determine on-board a-priori elevation

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**Key Points:**

- The Sentinel-3A altimeter cannot deliver useful data over many reservoirs (constructed after 2005) in open-loop tracking mode with OLTC V5.

- Defining correct a-priori elevation information is the key to increasing data availability over reservoirs.

- Four approaches are proposed to define the most accurate on-board a-priori elevation.

## Abstract

Satellite radar altimetry has become an important data source supplementing in-situ water level. For practical reasons, a radar altimeter can only record reflected echoes within its range window. Therefore, water surface elevation must fall within the range window. To this end, the Sentinel-3 radar altimetry mission is configured with a new tracking function (i.e. open-loop) to position its range window based on an on-board a-priori elevation of ground targets. We found that Sentinel-3 is unable to observe recently built reservoirs due to the incorrect on-board elevations. To overcome this issue, four approaches are proposed to improve the a-priori elevation for inland water bodies, particularly reservoirs. These approaches can significantly increase data availability of Sentinel-3 over reservoirs and can be used to prepare the on-board elevation of reservoirs and lakes for future missions such as Sentinel-6, Sentinel-3C/-3D, as well as the Surface Water Ocean Topography mission (SWOT).

## Plain Language Summary

Satellite radar altimetry is increasingly being used for hydrological studies. However, it is still challenging to deliver high quality data over inland water bodies, i.e. lakes, rivers, and reservoirs. One of the reasons is that the altimeter cannot easily identify the water surface elevation due to highly variable terrain elevation along the satellite flight path. In other words, the data delivered may not contain valid information for water bodies. To address this issue, Sentinel-3 is configured with a new function which informs the altimeter about the expected elevation of the water surface. However, this function demands a-priori knowledge of the altitude of the ground targets. We present four approaches to improve the a-priori information to increase data availability over inland water bodies, specifically reservoirs.

# 1 Introduction

Dams and reservoirs play an important role in social and economic development. Reservoirs are used to generate hydroelectric power, to mitigate floods, and to secure water supplies for human consumption, industrial use, irrigation, etc. (Nilsson, 2009; Wang et al., 2017; Zarfl et al., 2014; Zhou et al., 2016). Tens of thousands of reservoirs have been built in the past century, and many new reservoirs are still under construction or being planned (Lehner et al., 2011). However, in many cases, reservoir construction requires the relocation of local communities due to the inundation of land. Moreover, reservoir construction and management significantly change flow regimes. Concerns have been raised about the negative impact of reservoir construction on the environment and local communities, especially in the downstream areas, given the background of climate change and population growth (Richter et al., 2010; Zarfl et al., 2014; Zhou et al., 2016). Therefore, reservoir monitoring and management is becoming more critical, particularly for transboundary river basins (J. Crétaux et al., 2015). Reservoir water surface elevation (WSE) is an essential variable because it directly tracks reservoir storage, and thus, water availability downstream of the reservoir. The most newly built dams have been equipped with sophisticated in-situ monitoring systems to obtain long-term and consistent records. Unfortunately, these datasets are not publicly available partially due to geopolitical concerns (Hannah et al., 2011; C. Schneider et al., 2017; Thu & Wehn, 2016). Research assessing the role and impact of dams and reservoirs on society and the environment has so far been limited due to a lack of data, particularly at transboundary and global scales (Mulligan et al., 2020). It is therefore crucial to apply alternative and efficient techniques to collect comprehensive regional-scale reservoir WSE datasets and make them publicly available.

Satellite radar altimetry has been increasingly used to study inland water bodies such as rivers, lakes, and reservoirs on regional to global scales since the 1990s (Asadzadeh Jarihani et al., 2013; Biancamaria et al., 2017; Birkett, 1995; J. F. Crétaux & Birkett, 2006; Frappart et al., 2006; Jiang, Nielsen, et al., 2017c; Jiang, Schneider, et al., 2017; Jiang, Madsen, et al., 2019). The precision of satellite altimetry derived WSE has improved significantly when compared to the first satellite altimeter developed three decades ago (Jiang et al., 2020; Koblinsky et al., 1993; Nielsen et al., 2017). Nowadays altimetry data, acquired by both conventional LRM (low resolution mode) altimeters (e.g. Envisat, Jason-2/-3, SARAL/AltiKa) and SAR (Synthetic Aperture Radar) altimeters, have been broadly explored to study regional water resources (e.g. J.-F. Crétaux et al., 2016; Jiang, Nielsen, et al., 2017a; Papa et al., 2015), lake dynamics (e.g. Baup et al., 2014; Jiang, Nielsen, et al., 2017a; Kraemer et al., 2020), hydrologic modelling (e.g. Hulsman et al., 2020; C. M. M. Kittel et al., 2018; Michailovsky et al., 2013; Pereira-Cardenal et al., 2011), and parameterization of river models (e.g. Domeneghetti et al., 2014; Jiang, Madsen, et al., 2019; R. Schneider et al., 2018). However, none of the altimetry missions are specifically designed for inland water monitoring. It is still challenging to deliver high quality data over inland water bodies.

Partially because altimeters have problems tracking water surfaces of lakes, rivers, and reservoirs, particularly those surrounded by rugged topography (Biancamaria et al., 2018; Desjonquères et al., 2010; Jiang et al., 2020; Martin-Puig et al., 2016). To acquire as much data as possible, different on-board tracking methods have been proposed and tested, such as the Envisat Model Free Tracker, the Jason-1 Split-gate tracker, the Jason-2 Diode/Median tracker, and the Diode/DEM tracker, etc. (Desjonquères et al., 2010; Gommenginger et al., 2011; Martin-Puig et al., 2016). The Diode/DEM mode (i.e. open-loop mode) was first tested on-board Jason-2 and SARAL/AltiKa missions (Desjonquères et al., 2010; Steunou et al., 2015). Currently it is used as the operational mode for Jason-3 and Sentinel-3. The open-loop tracking system can position the range window very efficiently based on a-priori elevation stored on-board. Therefore, it is important to inform the tracking system with the most accurate a-priori elevation information.

Sentinel-3 is configured with a new on-board tracking system, i.e. the open-loop tracking function. In principle, this feature can increase data availability over both coastal regions and inland water bodies. However, the static nature of the on-board elevation may result in some practical challenges. Specifically, Sentinel-3A (S3A) is operating based on a pseudo-DEM controlled through the Open-Loop Tracking Command (OLTC) (Le Gac et al., 2019). The OLTC is being periodically updated. The current OLTC on-board Sentinel-3A (operated since March 2019) is Version 5 (V5), which includes ca. 33000 hydrology targets (Blumstein et al., 2019). The OLTC V5 was generated mainly based on inland water masks (the Global Inundation Extent from Multi-Satellites (GIEMS), the Shuttle Radar Topography Mission (SRTM) Water Body Data (SWBD), and the Global Surface Water Explorer (GSW)), the global SRTM DEM and the Hydroweb database (http://hydroweb.theia-land.fr/). The SRTM DEM was measured during an 11-day mission in February of 2000. Hence, the a-priori elevation for many reservoirs built after 2005 is most likely incorrect. As illustrated in **Figure 1**, the altimeter cannot record a complete signal of the water surface anymore since the construction of dams. The altimetry data could be just noise if the WSE of the reservoir rises by more than 30 m (assuming the a-priori elevation is in the middle of the range window). In this study, our hypothesis is that the on-board elevations for newly built large reservoirs are wrong, and thus, altimetry data is invalid.
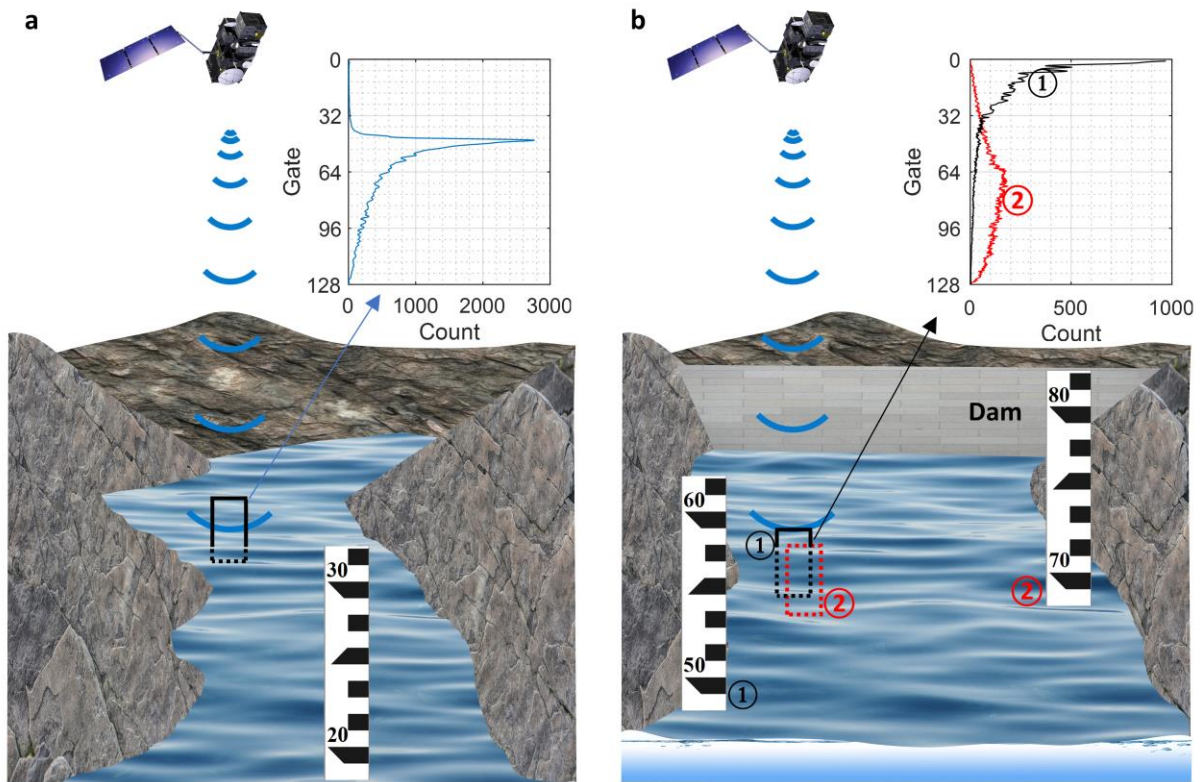
***Figure 1.*** *Schematic presentation of the range window position problem. (a) on-board a-priori elevation correctly represents the ground truth before dam construction. In this case, the range window (solid line indicates portion above, dotted line the portion below the water surface) is positioned correctly. Therefore, the altimeter is able to record reflected echoes from water, and a full waveform (upper-right plot, spanning 60 m) is acquired. (b) After dam construction, on-board a-priori elevation does not represent ground truth anymore. Therefore, the range window is positioned too low (too late in time) to record echoes returned from water surface. Depending on the rise of water surface elevation after dam construction, the recorded signals could be the trailing edge of the waveform (scenario ①:a small portion (solid black line) of the window is above the water surface) or just background noise (scenario ②: the full window (dotted red line) is below the water surface).*

The objective of this study is to examine data availability and the validity of S3A over recently constructed large reservoirs. We investigate waveforms and Level-2 WSE to understand the reason for data unavailability and invalidity. To address this problem, we propose four approaches to improve the a-priori elevation. We expect that the approaches will improve the performance of Sentinel-3 altimeters (Sentinel-3A/-3B) as well as other upcoming satellite altimetry missions (Sentinel-6, Sentinel-3C/-3D) for inland water monitoring.

## 2 Materials and Methods

### 2.1 Reservoir and dam database

The global reservoir and dam database (GRanD) provides a single, geographically explicit, and reliable source of information on reservoirs and dams (Lehner et al., 2011). The latest version, GRanD v1.3, includes a total of 7320 reservoirs globally (storage capacity > 0.1 km$^3$), of which 347 were constructed after 2005. A comprehensive attribute table assembled from numerous sources is available, including the height of the dam, the average depth of the reservoir, the year in which the dam was built, etc. (Lehner et al., 2011). Considering the potential problems with Sentinel-3 data acquisition described in the previous section, we select the reservoirs for this study based on the following criteria:

- Reservoirs intersected by S3A ground tracks;
- Reservoirs built after 2005;
- Reservoirs with a dam height higher than 100 meters;

In this way, 62 globally distributed reservoirs are selected. In addition, another nine reservoirs across different continents are randomly selected to examine the validity of S3A data over these relatively smaller reservoirs. **Figure 2** shows the spatial distribution of the selected reservoirs and the coverage of the open-loop mode before March 2019.
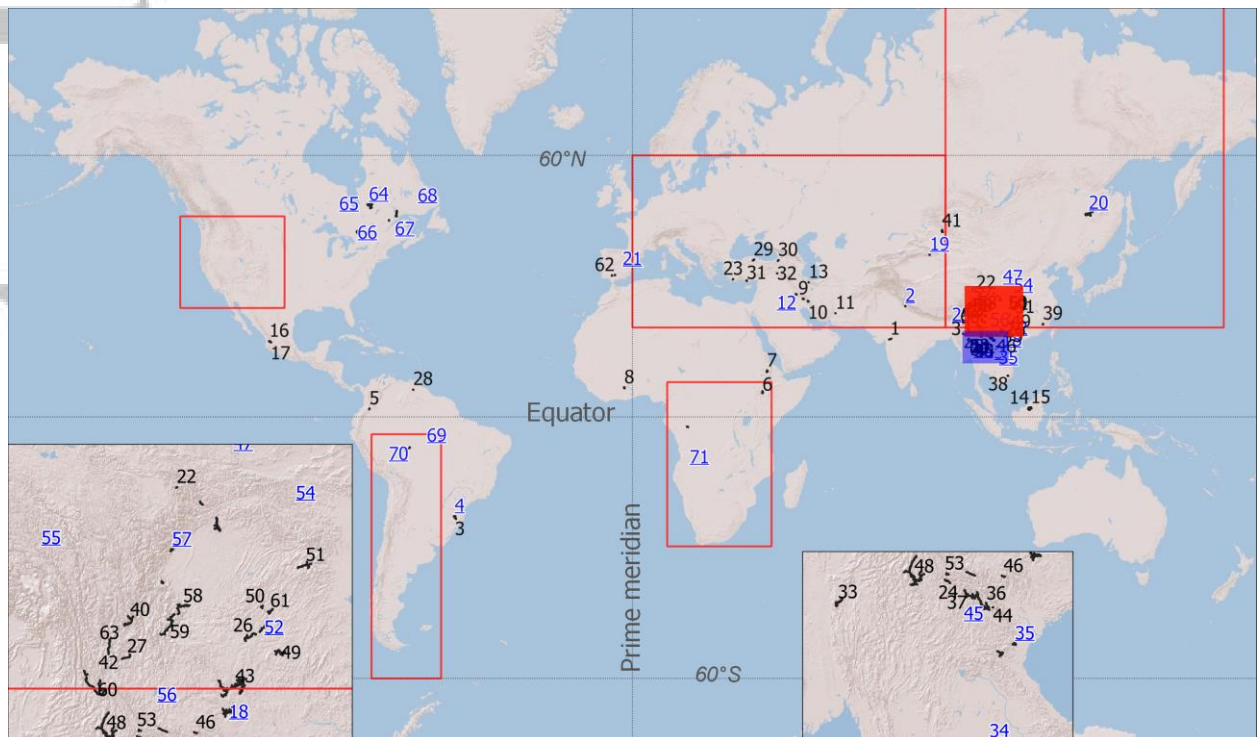


***Figure 2.*** *Locations of studied reservoirs. Left-bottom and right-bottom insets are zoomed views of the red and blue shaded rectangles, respectively. Regions where S3A operated in open-loop before March 2019 are indicated by red boxes, including 37 reservoirs. Other regions were covered in closed-loop. After March 9$^{th}$ 2019, all areas within 60°N - 60°S are covered in open-loop. Labels in blue indicate reservoirs with good performance.*

## 2.2 Sentinel-3A data and processing

S3A altimetry products are downloaded from the Copernicus Open Access Hub (https://scihub.copernicus.eu/dhus/#/home). The enhanced measurement data file used in this study contains Level-1b waveforms and associated parameters as well as the Level-2 standard 20 Hz parameters. Note that before March 2019, S3A operated in both open-loop and closed-loop for different regions, as indicated in **Figure 2**. After March 9th 2019, all areas within 60°N - 60°S are covered in open-loop mode. Thirty-seven reservoirs were located in the regions covered in open-loop, while 34 were in regions covered in closed-loop mode. For predefined open-loop regions before March 2019, a limited number of targets (mostly in France) were defined with an appropriate a-priori elevation. More details about the on-board elevation definition can be found in previous publications (e.g. Le Gac et al., 2019; Jiang et al., 2020) and on the OLTC website: https://www.altimetry-hydro.eu/. Data of both periods are used to explore the behavior of the S3A tracker in different modes.

For the first step to select potential measurements of reservoir water surface elevation, the water occurrence map (occurrence > 10%) of the Global Surface Water Explorer (Pekel et al., 2016) is used. A low threshold of 10% is chosen for two reasons: 1) water occurrences are expected to be low for new reservoirs; 2) a lower threshold ensures that a higher number of potential measurements are pre-selected.

To assess whether the range window is positioned reasonably, we investigated waveforms along each pass. The waveform shape (i.e. the presence of the leading edge if it exists) and the maximum power are good indicators of data validity and quality (Le Gac et al., 2019; Jiang et al., 2020). Specifically, we first construct a new waveform by taking the gate-wise median value of all waveforms over a reservoir. The rationale is the assumption that all these waveforms contain one common peak that corresponds to the reservoir water surface, even though individual waveforms may be contaminated by other bright targets (Jiang et al., 2020). Note that waveforms were first adjusted by the Automatic Gain Control (AGC) values (available in the product) to make them comparable. Secondly, based on the maximum power (40000 counts, based on our statistics) and the corresponding gate position (between 4 and 125) of the constructed waveform, we assess the data validity of each pass. Here, we assume that the leading edge occupies 2 - 3 gates. If the maximum power occurs between gate 4 and 125, we treat this peak as the leading edge, thereby classifying the waveform as valid. The corresponding pass is classified as successful in terms of range window positioning. In the end, a success rate is calculated for each reservoir based on the number of valid passes and total passes in the period. If the data is missing for a given pass, this pass is also classified as invalid.

The actual range window position can be inferred from the tracker range (available in the dataset), which is the distance between the antenna and nominal tracker point. Applying all associated corrections, the elevation of the nominal tracker point can be obtained and compared with DEMs, e.g. the up-to-date TanDEM-X DEM (https://tandemx-

science.dlr.de/). In principle, if the range window does not contain the water surface of the reservoirs, then the water surface echo is not recorded in the waveforms. Thus, the delivered data is invalid, and in most cases, the signal power is relatively low.

To retrieve the WSE of a reservoir, potential measurements selected from the first step are further processed. Here the first outlier removal procedure is based on the backscatter coefficient ($\sigma^0$). A backscatter coefficient ($\sigma^0$) threshold of 30 dB is used to remove obvious outliers (C. Kittel et al., 2020). Note that $\sigma^0$ and the orthometric WSE are estimated using the OCOG retracker. Furthermore, outliers within each pass are removed using the median of absolute deviation (Jiang, Andersen, et al., 2019). The remaining data points are used to construct time series using tsHydro (Nielsen et al., 2015).

2.3 Approaches to define the a-priori elevation for new reservoirs

Four approaches are proposed and summarized in *Table S1*. Here, we discuss these methods in detail. The most appropriate a-priori elevation of inland water bodies can be obtained from satellite altimetry. Although the closed-loop mode is not ideal, the altimeter can deliver quite a lot of valid data in closed-loop if the topography does not change too abruptly. Therefore, the first approach is to make use of the S3A data collected in closed-loop (with the exception of areas tracked in open-loop mode; refer to **Figure 2**) during the first approximately three years (before March 2019). The second approach uses other satellite altimetry missions to derive WSE time series. CryoSat-2 and AltiKa (drifting phase) data are used here because of their dense ground tracks. Similar data processing procedures are used for S3A. Once the time series is available, the optimal range window position can be determined.

However, not all studied reservoirs are successfully sampled by CryoSat-2 or AltiKa. In these cases, we propose to estimate WSE based on the dam heights available from the GRanD database. The top of the range window can be set at the same elevation as the crest of the dam. The rationale behind this approach is that the normal water level (an optimum highest reservoir water surface elevation) is usually lower than the dam height by a few meters (Sun et al., 2011). Recall that only the height of dam is available; therefore, in order to obtain the elevation of the crest, dam base elevation is approximated using the ACE2 DEM, which represents the ground elevation before dam construction.

The fourth approach is based on the TanDEM-X DEM, which is currently the most recent, accurate, and publicly available global DEM (Wessel et al., 2018). This global DEM is based on data collected between December 2010 and January 2015, representing the latest

global terrain heights. The lowest point along the satellite ground tracks crossing each reservoir is chosen to represent the reservoir water level.

## 3 Results and discussion

### 3.1 Performance

The majority of the studied reservoirs are located in Asia and the Eastern Mediterranean Region (**Figure 2**). **Figure 3** demonstrates the waveforms and range window positions corresponding to four scenarios that we observed in the S3A dataset for the entire period. The power of a waveform generally indicates whether the reflected echoes are valid. As shown in **Figures 3b** and **3c**, valid signals are much stronger than the invalid ones, which are essentially background noise. This is corroborated by the range window position. The range window (the green area in **Figure 3d**) is positioned too high before March 2019 or, in other words, too early to record the signals bounced back from the water surface. The current elevation is appropriate, and the range window encompasses the water surface. Note that both passes were in open-loop in this example and, therefore, an appropriate a-priori elevation is vital to acquire valid signals.

Unfortunately, the current open-loop configuration does not deliver useful data over most of the studied reservoirs. As demonstrated in the second row of **Figure 3**, the range window is positioned too low to capture the waveform peaks (**Figure 3g**). On the other hand, the closed-loop successfully captured the water surface (**Figure 3f**). However, the closed-loop is not robust, and data is sometimes invalid or completely unavailable due to the loss of tracking. In this particular case, the reason for the wrong window position in open-loop is that the a-priori elevation for this reservoir is not defined. The onboard tracker simply uses the elevation of the previous target along the ground track.

The position of the leading edge of the waveform can indicate whether the range window is well-positioned. The third row of **Figure 3** exemplifies cases where the leading edge reveals a poorly positioned range window. At the shown target, the altimeter detects the water surface in closed-loop mode (**Figure 3j**), but fails in open-loop mode as revealed by the waveform. Clearly, the leading edge is missed due to the low position of the range window. The range window aligns well with the ground topography as indicated by the two DEMs. However, the elevation dataset is outdated due to the sharp rise of water level after dam construction. In this case, only the trailing edge of echoes is within the range window. Similarly, the fourth row of **Figure 3** shows a problem with the current elevation. Although no a-priori elevation is defined for this reservoir prior to March 2019, the altimeter worked well using the elevation of the previous target and useful data were delivered. However, the update introduced faulty elevation, and the reservoir is no longer correctly monitored.
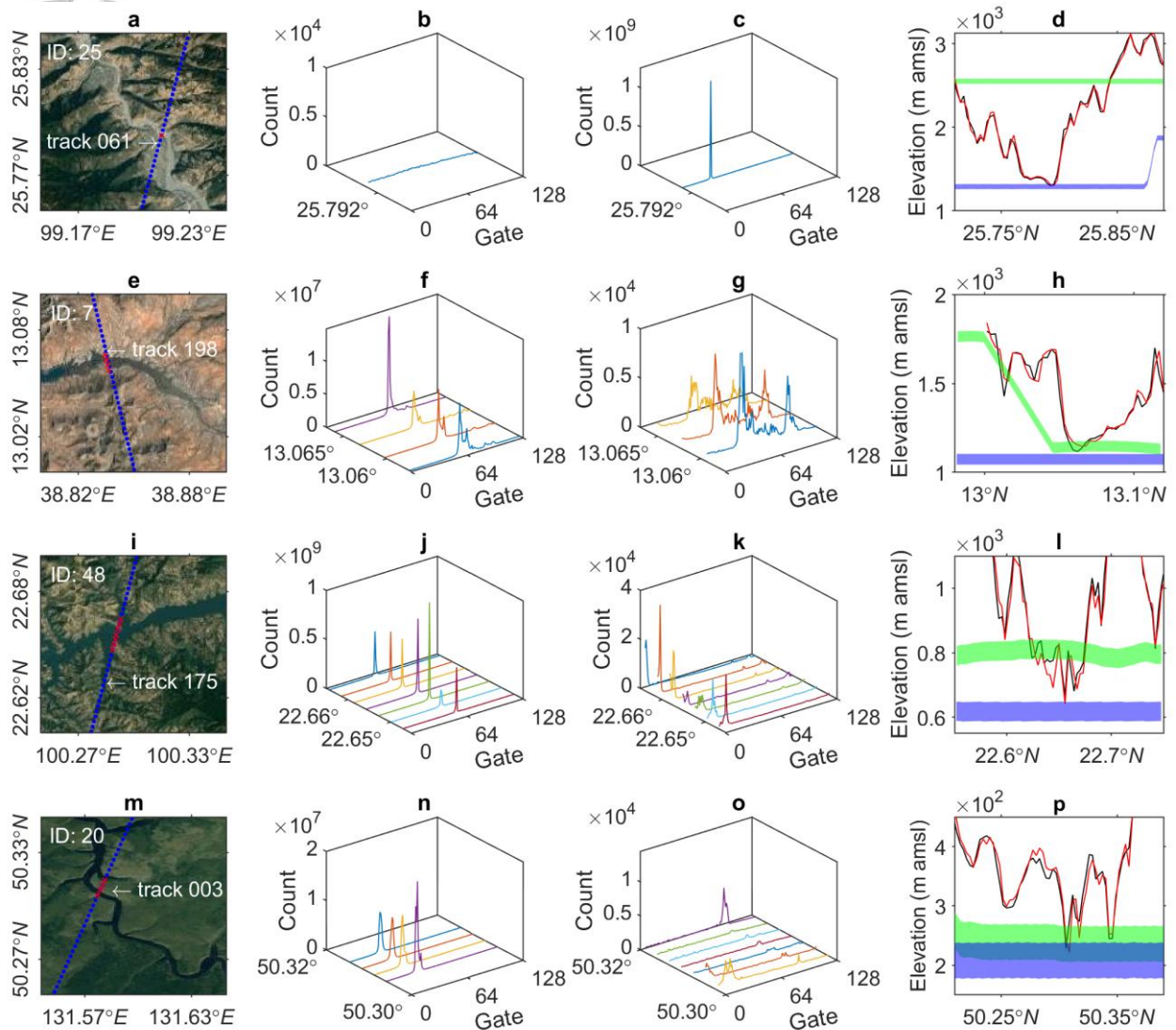
*Figure 3. Selected Level-1b waveforms and Level-2 measurements to illustrate four different scenarios. The first column indicates the location of the reservoir of each scenario. The second column shows waveform in either closed-loop or open-loop before the update of on-board elevation. The third column shows waveform acquired in open-loop with current new a-priori elevation. The last column shows the range window position before and after the update of a-priori elevation (shaded area; green and blue correspond to waveforms shown in column 2 and 3, respectively) and DEM (solid line; ACE2 in black and Tandem-X in red) of corresponding ground track. The first row shows that S3A failed to deliver valid data in previous open-loop while it works well in current open-loop. The second row shows that S3A can occasionally detect reservoir in closed-loop, but fails to deliver valid data without a-priori on-board elevation. The third row demonstrates that valid data were acquired when S3A operated in closed-loop while invalid data are delivered in open-loop. The last row shows the scenario that valid data are available in previous open-loop mode, but no valid data are available in current open-loop mode. Abbreviation amsl stands for above mean sea level.*

Based on the success rate of data acquisition, the performance statistics of S3A are summarized in *Table S2*. As expected, S3A did not deliver consistent valid data over the majority of the reservoirs. The success rate is above 50% only at 25 reservoirs (see the blue ID in **Figure 2**). Except for the 14 reservoirs without an a-priori elevation, most of the current

elevations are too low. This is especially true for reservoirs with a very high dam. Here, the range window is badly positioned and results in a low probability to capture the signals reflected from water surface. Due to large seasonal fluctuations of the water level, a fixed elevation cannot guarantee a 100% success rate of data acquisition. This partially explains the lower success rates of the majority reservoirs (*Table S2*). Comparatively, the closed-loop mode does not perform much worse; 28 of 34 reservoirs have at least 10% of valid data. However, only 30% reservoirs have more than 80% of valid data. This corroborates the lack of robustness of the closed-loop mode. Nevertheless, the closed-loop outperforms the open-loop in terms of success rates (see the first two columns in *Table S2*). This suggests that the closed-loop may be a good choice if a-priori information is unavailable or unreliable.

## 3.2 Determination of a-priori elevation

Based on altimetry measurements, Sentinel-3, CryoSat-2, and AltiKa provide a result for 47, 53, and 44 reservoirs, respectively (see *Table S3* and time series in *Figure S4*). They show very good agreements with correlation values of nearly one, although biases exist between different altimeters. Unlike Sentinel-3, CryoSat-2 and AltiKa in long-repeat (geodetic) orbits have much denser ground tracks, and thus, monitoring more hydrology targets. These datasets (likely high resolution due to the SAR/SARIn mode or Ka-band) also show a high potential of preparing elevation for other missions, such as Sentinel-6.

As presented in **Figure 4**, the time series can clearly show the maximum water level as well as the dynamics of the water levels. The WSE derived from CryoSat-2, AltiKa, and S3A are in excellent agreement. In spite of the rugged topography, CryoSat-2 captured the sharp rise of the WSE due to the construction of dams (**Figure 4a** and **c**) as well as the drawdown (**Figure 4d**) in 2016 due to extreme drought. These examples also highlight the value of altimetry for reservoir monitoring. However, CryoSat-2 has difficulty observing WSE when the reservoir is close to empty. In the example illustrated by **Figure 4b**, both S3A and AltiKa observed the low WSE while CryoSat-2 did not. We found that the CryoSat-2 observations of this reservoir are very noisy during these low-level periods.

In general, this approach allows us to properly define an a-priori elevation with consideration of water level dynamics. This is extremely important when the amplitude of the seasonal variation is significant (see examples in *Figure S3*). Seasonal WSE changes might be of the same order as the range window size, i.e. 60 m. That is, a static range window position may not be appropriate at all times, missing either peaks or troughs. Therefore, the determination of an a-priori elevation could prioritize the high-level condition to monitor flood risk. Furthermore, under low-level conditions, the water surface extent of reservoirs becomes narrower; thus, it is difficult to obtain useful data.

However, for some reservoirs, there is not an available valid time series of the WSE. In this case, we have to rely on the information of the dam height and the global DEM. As shown in **Figure 4**, the approach based on the dam height is always applicable. If the top of the range window is set to the elevation of the dam crest, the WSE at the high-level condition

can be guaranteed, but the WSE at the low-level may be missed if the seasonal variation is more than 60 m. A compromise is therefore needed. The results provided by this approach generally agree with the others approaches (*Table S3*). However, if a reservoir is still filling up and has not yet reached the desired operating level, the estimate based on the dam crest elevation will over-estimate actual WSE. Moreover, the accuracy is also affected by the accuracy of the global DEM given that the elevation of the dam base is derived from DEM.

Comparatively, an a-priori elevation derived from a global DEM is less accurate mainly because of the static nature of a DEM dataset. As shown in **Figure 4**, the a-priori elevation derived from the TanDEM-X is inappropriate. Even if the TanDEM-X elevation is used as the end of the range window, the WSE in high-level condition cannot be guaranteed. It is worth noting that the conditions under which the DEM data were collected (i.e. high-level, low-level or in-between) are unknown. Without this information, it is difficult to set the range window. Among the four investigated approaches, the results provided by the DEM-based approach are the worst. For only 16 reservoirs, the actual WSE falls within 30 m of the estimated WSE (*Table* S3). This also indicates that current OLTC V5 contains unreasonable elevations based on global SRTM DEM. For some more shallow reservoirs, the approach works well, but those are exceptions. Recall that, nine reservoirs with dam height smaller than 100 m (69 m in reality) are also selected. The OLTC V5 values of these reservoirs are mostly appropriate and are generally in agreement with results provided in this study (*Table S3*).

Apparently, a priori elevation defined based on the altimetry-derived WSE is the most accurate. It is worth noting that the first two approaches probably do not work well over small reservoirs, for which altimetry measurements are usually of low quality. In this regard, the ICESat-2 laser altimeter, which has much higher resolution and precision, can be very helpful to obtain the WSE dynamics after two years of operation.

Beyond the approaches discussed here, operations in closed-loop mode in the commissioning phase or during the first year of a mission could be an option instead of operating in open-loop without proper elevation. Another possibility is to make use of the data in the End-Of-Life phase. This geodetic phase will significantly increase the coverage of hydrology targets. However, the occurrence of tracking loss cannot be avoided in closed-loop mode. Last, but not least, frequent updates of the on-board a-priori elevation is also a good strategy to avoid delivering too much invalid data over the course of the mission lifetime.
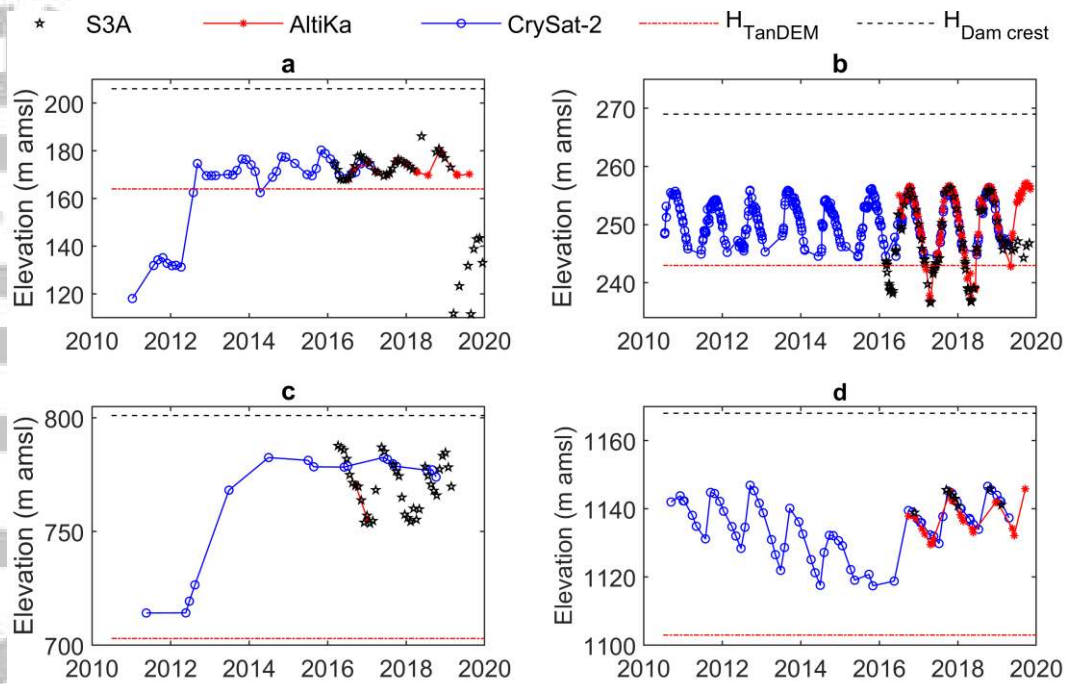
*Figure 4*. *Comparison of a-priori elevation derived from altimetry derived time series, TanDEM-X, and dam height for four representative reservoirs behind dams (a to d) Bui (Ghana), Bureya (Russia), Garzan (Turkey), and Tekeze (Ethiopia), corresponding to 8, 20, 32 and 7 as indicated in* **Figure 2**.

## 4 Summary and conclusions

To maximize the value of altimeters over inland water bodies, an open-loop tracking mode is adopted on Sentinel-3A/-3B. A determinant of the data acquisition in open-loop mode over inland water bodies is the a-priori on-board elevation. The definition of a-priori elevation for global inland water bodies is challenging, especially for newly built reservoirs. We assessed the suitability of the current on-board a-priori elevation data for 71 globally distributed reservoirs, mostly built after 2005.

By investigating waveforms and Level-2 heights, we found that the on-board a-priori elevation is appropriate for a minor portion (35%) of the studied reservoirs. In most cases, the elevation is too low due to the sharp increase of the water level after the dam construction. Moreover, for 14 reservoirs, no a-priori elevation is defined, probably because the reservoirs are not defined in water masks, which is used to define the targets. Moreover, we found that closed-loop tracking mode delivered useful data for some reservoirs, but did not perform consistently. In summary, the value of Sentinel-3A over these reservoirs is degraded due to the inappropriate a-priori elevation. To address this problem, we used four approaches to define/improve the a-priori information of the on-board elevation.

It is obvious that the determination of an a-priori elevation from the earlier and successful Sentinel-3A, CryoSat-2, and AltiKa acquisitions is the most appropriate solution, because the full dynamics of the reservoir water level is available and the range window can then be positioned to exactly match user needs. However, due to the limitation of the closed-loop

mode over rugged topography, reliable altimetry observations are not available for all reservoirs. Thus, we suggest that closed-loop should still be preferred over open-loop if no a-priori information is available. A few cycles in closed-loop at the very beginning of a new mission might be a reasonable compromise. The second approach based on dam height information from a global database is also effective. Given that the water surface elevation cannot be higher than the dam elevation, the range window can be positioned to ensure that high-level conditions can be observed. In cases where no dam height is available, we propose to use the TanDEM-X DEM elevations as an alternative source of information. A global DEM represents a transient state of the reservoir water levels; therefore, if this method is used, the most appropriate approach may be to reference the middle point of the range window to the TanDEM-X elevation.

In conclusion, the methods presented in this study can help define and improve the a-priori elevation. By ensuring that the elevation is correct and up-to-date, the data availability over reservoirs, as well as other inland water bodies, can potentially be greatly increased. Our suggested approaches are also applicable to other altimeters that are, or will be, operating in the open-loop mode, such as Jason-3, and future Sentinel-6 and Sentinel-3C/-3D.

## Acknowledgments

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