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Algorithm Theoretical Basis Document (ATBD) for Along-Track Inland Surface Water Level Products as derived from Short-Repeat Satellite Radar Altimeters

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Abstract:
This document describes the theoretical basis of the algorithms employed in the processing of satellite data from short-repeat (revisit time is within approximately 1-month) satellite radar altimeter missions, and the subsequent approach to the formation of products associated with time-varying inland water surface water levels. These Level 3 products are derived from multiple missions, employ repeat-track methodology, and are output for select lake, reservoir, river reach, and wetland crossings. The ATBD includes descriptions of the Level 2 satellite data, the auxiliary datasets, the overall approach and assumptions, and the format and content of the final products. All final products are in the public domain and located at the NASA/GSFC Global Water Measurements (GWM) web portal,
https://blueice.gsfc.nasa.gov/gwm or https://earth.gsfc.nasa.gov/gwm/

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Funding sources
NASA ROSES Applied Sciences/Earth Science to Action - Water Resources
NASA ROSES Make Earth Science Data Records for Use in Research Environments (MEaSUReS)
NASA ROSES Ocean Surface Topography Science Team
NASA ROSES ICESat-2 Science Team
USDA Foreign Agricultural Service

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1.0 Introduction

Note: The terms "level", "elevation", and "height" are interchangeable in this Algorithm Theoretical Basis Document (ATBD) text.

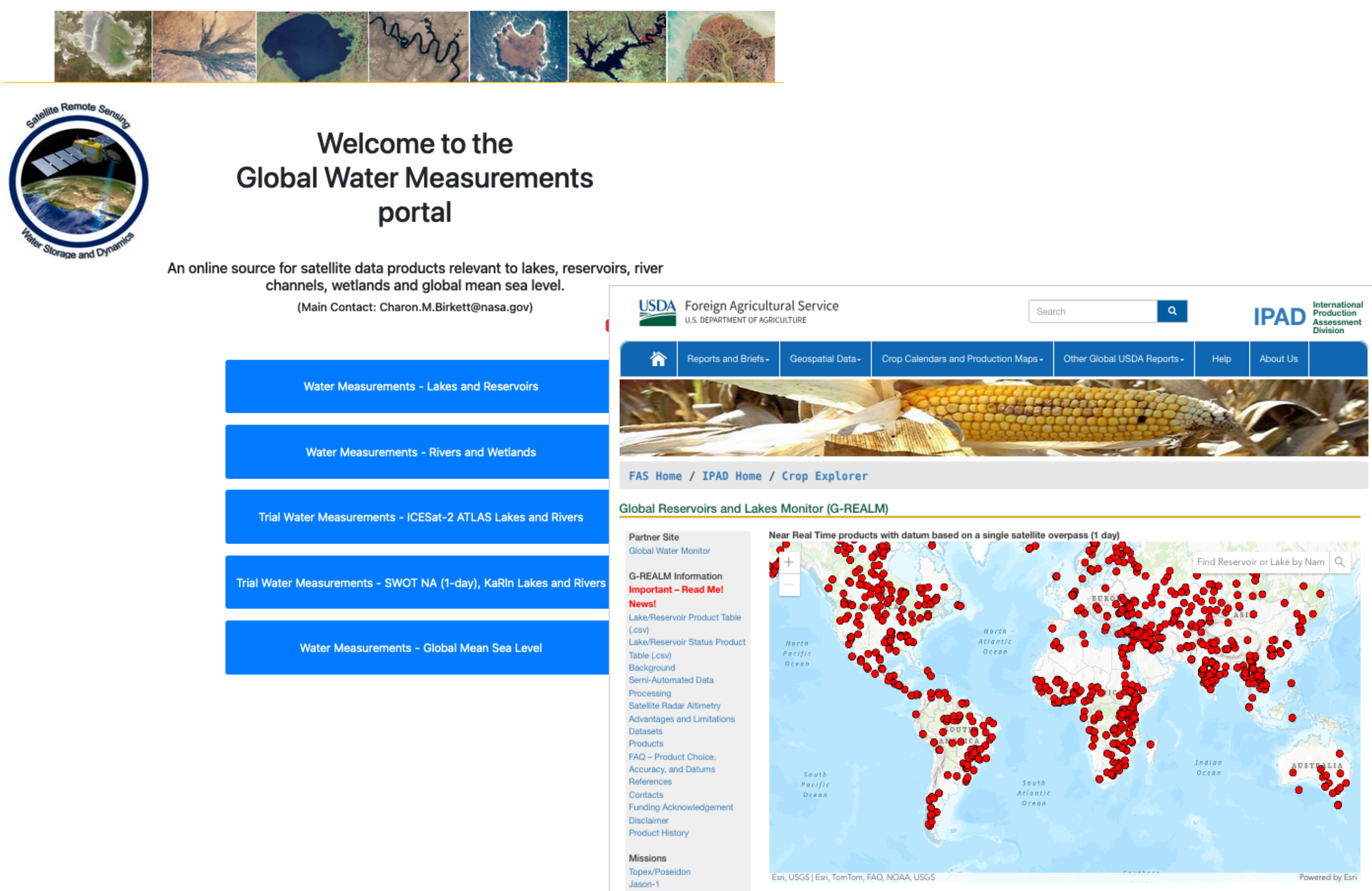
1.1 Purpose

This ATBD describes the Level 3 along-track inland surface water level products derived via satellite "repeat-track" methods and with reference to the short-repeat period (approximately 1month or better "target" re-visit time) satellite radar altimeters. These altimeters retrieve surface elevations over ocean, ice, land, and inland water surfaces during their mission lifetimes. The missions can be stand-alone, or part of a continuity suite that looks to the long-term collection of measurements at a set repeat period. This ATBD briefly describes satellite radar altimetry, its application to inland water, and the limitations and advantages. It also describes how the Level 3 near real time and archive-based height-variation products are formed, their format and content, and how the process undertakes quality assurance checks. Current water level products created via the system described below are freely available at two web-based portals (Fig. 1),

A) The Global Water Measurements (GWM) portal (for all inland water body types)
https://blueice.gsfc.nasa.gov/gwm or https://earth.gsfc.nasa.gov/gwm/

B) The Global Reservoir and Lake Monitor (G-REALM) portal (for lakes and reservoirs)
https://ipad.fas.usda.gov/cropexplorer/global_reservoir/

Figure 1. The GWM and G-REALM web-based portals. *The two web portals, GWM and G-REALM, offer GWM system-created inland water level variation products.*



1.2 Satellite Altimetry

Satellite-based radar altimetry has been utilized for inland water applications for several decades. Originally designed for sea surface mapping programs, scientific objectives expanded to include the mapping of ice sheets and sea ice, and to record water-level variations within inland water bodies which include lakes, reservoirs, river reaches and wetland zones. Techniques that were once exploratory are now well documented and validated, and Level 1 and Level 2 altimetric data sets are mature and promptly distributed by satellite data distribution centers. The Level 1&2 data sets are utilized by several organizations who create higher-level (Level 3), time series products of water level variations. These are distributed via the world-wide-web and underlying methodologies are described in peer-reviewed publications. While standard radar altimetry instruments (i.e., pulse limited, single nadir-beam profiling, operating at Ku- or Ka-band) have already provided a multi-decade set of water level observations, more enhanced delay doppler and swath radar altimeters are now operating with objectives to improve global coverage and spatial resolution. In addition, datasets related to several satellite lidar altimeters (laser-based) are also available that enable supplemental measurements for direct use or cross-validation.

1.3 Limitations and Advantages of Satellite Radar Altimetry

There are limitations and advantages to the application of satellite radar altimetry.

Limitations:

- Height measurements can only be retrieved along a narrow nadir swath, at pre-defined ground track locations, and the tracks are within designated latitude limits. A single mission therefore has limited global coverage. Use of designated instrument calibration zones may also disable routine science mode surface acquisitions, but these zones are typically chosen to be over desert regions.
- The re-visit period is fixed and maintained throughout the mission phase or lifetime. While trials have used 1-day or 3-day temporal resolutions, these have been short phases for ocean or ice-measurement requirements. The long-term continuity missions offer a choice of 10-day or monthly to the end user, though measurements from multiple water body overpasses (from a single mission) and from multiple platforms could be combined to achieve a finer resolution but there may be a loss in accuracy in this approach. Nevertheless, a daily or even hourly resolution is not feasible, and rapidly varying water levels, particularly at high latitudes, cannot be captured.
- Highly undulating or complex terrain may cause data loss or reduction in accuracy. Radar altimeters are primarily designed for relatively flat spans of ocean or ice sheet.
- Minimum water body size achievable is also determined by several factors that include water extent, the surrounding terrain, and the approach vector of the overpass.
- Height accuracy is dominated by many factors, including the size of the water body (in reality, the length of the water path presented to the instrument) and the surface roughness (how well the altimetric *Range* can be derived from the shape of the radar echo). Major wind events, heavy precipitation and ice formation will also affect height accuracy. It is also worthy to note that the Level 2 satellite data-derived heights are also an average and methodology requires they be averaged further, from bank-to-bank, to reduce noise. Resulting height variations rely on this averaging and thus deviate from a single spot height at a specific location.

Advantages:

- With global operation, measurements are potentially available at any location on a ground track, day or night, in all-weathers, over the mission lifetime.
- The repeat orbits enable systematic monitoring of any inland water body type (lake, reservoir, wetland, river reach) with measurements provided to one common reference datum.
- The nadir-pointing instruments are not hindered by vegetation or canopy cover.
- The ability to monitor monthly, seasonal and inter-annual variations and trends.
- The ability to supplement gauge networks, or the provision of a new satellite-based set of measurements where gauge data cannot be obtained.
- Near real time and multi-decadal archive measurements.

- Well-validated techniques with a large research-orientated science and instrument community who strive to maximize instrument and data potential.

1.4 Background

In situ (i.e., ground-based gauge data) is collected for many regions of the world. It can be recorded (and transmitted) in real time at set intervals, such as hourly or daily. While some *in situ* data is in the public domain, it can be deemed as sensitive information and thus its release is prohibited or delayed, and gauge deployment in remote locations can be prohibitive or costly. Satellite-based water-level measurements can thus supplement the existing gauge networks or lead to the creation of new measurement sets.

Altimeter-derived water levels are used to examine seasonal and inter-annual variations in hydrology- or climate-related projects (examples from this author team, Birkett 1995, 1998, Birkett et al., 2002, 2005, Mertes et al., 2004, Crétaux and Birkett, 2006, Bjerklie et al., 2018). For example, with additional knowledge on evaporation, precipitation, and runoff, and assumptions on ground seepage and morphology, lake and reservoir levels can also help solve the components of the lake water balance equation. In a more general sense, the water levels in lakes and reservoirs can be used as a proxy for precipitation, or be a proxy for water storage, or be a direct contributing parameter in the estimation of storage when lake extent and bathymetry are known. Many projects have been championing the use of multi-spectral imagery for the determination of lake extent variations. With approximate time-coincident lake level and extent observations, the lake hypsometry can be determined, and this provides a measure of the lake bathymetry above the water line. The integration of such level, extent, and bathymetry, enables satellite-based storage change estimates (e.g., Gao et al., 2012). Altimetric-derived river water levels can also reveal temporal and spatial variability (dynamics), be a contributing parameter to the estimation of reach slope and contribute to river discharge estimation when other parameters such as channel slope, reach width, and riverbed roughness, are known.

With multiple decades of satellite altimeter observations and validated technology, lake and reservoir water level variations were introduced in 2010 as a new climatic index (Birkett, 2010) highlighting available data sets with monthly (or finer) temporal resolution. This resolution is set for each altimetric mission or mission phase, where standard "repeat-cycle" operations ensure the position on the Earth's surface is re-visited within a set time-period (Tables 1&2). The instruments connected to the National Aeronautics and Space Administration (NASA) for example, operate their main science phases with a 10-day or 27-day exact repeat cycle. Such temporal resolutions enable observation of monthly, seasonal, and inter-annual variations associated with regional and global climate influences, enable long-term drought or recharge trends to be observed, and assist projects looking to identify variations induced by anthropogenic influences or controls.

Here, a "wetland" designation covers a broad range of sub-classifications such as mangrove, delta, peatland, paddy fields and swamp. "Reservoir" refers to a water body that is directly or indirectly affected by anthropogenic effects, e.g., the presence of a dam, barrage, or weir, the diversion of inflows, or a direct significant abstraction of water storage. "Lake" refers to a natural water body which can be "open" (with outflows) or "closed" (terminal or endorheic, with no outflows). An "ephemeral" lake is one that has intermittent water storage, and a "lagoon" refers to a coastal water body which may be protected or affected by tidal influences. A closed lake is often the more climatically sensitive and exists primarily in arid or semi-arid regions, though climate influences such as the El Niño Southern Oscillation (ENSO), can readily be discerned in the level variations of the largest open lakes and reservoirs (e.g., Birkett et al.,1999).

1.5 Applications

Satellite-derived water levels are utilized within both science and applied science projects and there is a need for both near real time and long-term observations. Archive datasets are ideal for studying the effects of climate change, noting changes in reservoir operating procedures, observing hydrological drought, and studying basin dynamics. Short-term observations are useful for checks on seasonal (agricultural) drought, and near real-time capability enables high (flood) water levels or low (reservoir "dead pool") water levels to be observed, thus assessing a go or no-go event and whether a fast response to a regional situation is required. Multi-decadal observations allow for daily, monthly, seasonal, and annual baselines to be formed, to which near real time levels can be compared and deviations from “normal” suitably flagged. Near real time observations can be constructed within 24hrs of satellite overpass, or within 2-3days after overpass, with the latter reporting to be marginally more accurate. The archive datasets, after altimetric-related parameter and model upgrades, are the most accurate, and available within 1-2months after satellite overpass, with several data version upgrades typically occurring over the mission lifetime. In general, validation exercises have revealed that time series of altimetric water level variations are accurate from a few centimeters root mean square (rms) to several decimeters rms (when compared with time series of *in situ* measurements) with a dependence on water body size (i.e., the amount water presented to the instrument along the satellite ground track), and surface roughness (i.e., waves). The multi-decadal altimetric water level products can be classed as Earth Science Data Records (ESDRs, Birkett 2010) and are an important standalone product. See also the References section for the NASA Make Earth Science Data Records for Use in Research Environments (MEaSUReS) web site link for inland water surface levels.

1.6 The Global Water Measurements system

The Global Water Measurements (GWM) system at NASA Goddard Space Flight Center (GSFC) integrates satellite altimeter datasets and creates surface water level products for NASA-funded projects and a US Department of Agriculture (USDA) funded program. These products thus serve both the sciences and the applied sciences, and being in the public domain, they serve a much larger range of stakeholders and end users connected to various government, institute, educational, commercial and private entities. The GWM products are formed for select river reaches, wetland zones, lakes and reservoirs, according to the requirements of the NASA projects, the USDA program, or ad-hoc requests. The USDA program is based on a requirement to measure the varying water levels in low-to-mid latitude lakes and reservoirs in near real time with a baseline of archive measurements. Driven by the USDA’s Foreign Agricultural Service (FAS), this has a global outlook and draws on the connection between water levels, water storage, and the ability to irrigate crops (primary) and to produce Hydro Electric Power (HEP, secondary). Operational since 2003, the Global Reservoir and Lake Monitor (G-REALM) has been a successful element within the USDA “Crop Explorer” program,

https://ipad.fas.usda.gov/cropexplorer/
https://ipad.fas.usda.gov/cropexplorer/global_reservoir/

NASA also has a web portal where GWM-produced altimeter products for all water body types (including river reaches and wetlands) are available,

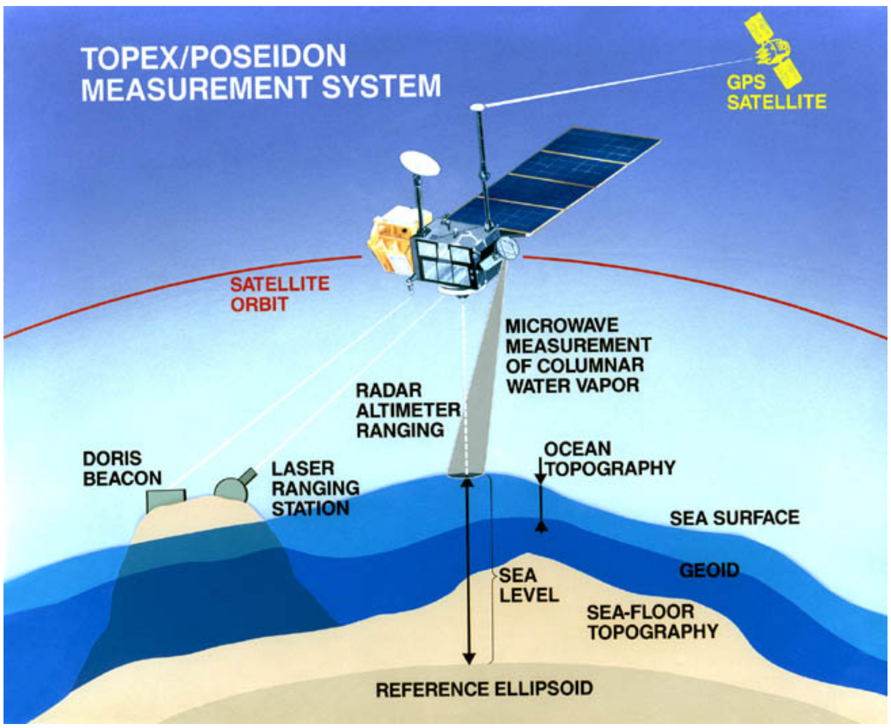
https://blueice.gsfc.nasa.gov/gwm or https://earth.gsfc.nasa.gov/gwm/

and this portal serves various NASA projects and acts as a backup system for G-REALM.

2.0 Theoretical Framework

The following sections describe the datasets, methodology, product format and content relating the current suite of altimeter products created within the GWM system.

Figure 2. Pulse-Limited Satellite Radar Altimetry. *Emitting microwave pulses the energy is reflected from the surface and the time of the returned energy is recorded and converted to a Range estimate. Being permanently switched on the surface could be ocean, ice, land or inland water. Use of Global Positioning System (GPS), Satellite Laser Ranging (SLR), and Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) beacons, help to record the exact location and orbital altitude of the satellite. Most altimeters record surface height within a geodetic (a reference ellipsoid) datum, translating to an orthometric datum (a mean sea level framework) via use of a geoid model. Figure courtesy of the NASA/California Institute of Technology's Jet Propulsion Laboratory (JPL).*



2.1 Pulse-limited Radar Altimetry

Satellite radar altimeters operate by emitting a microwave pulse towards the surface (at nadir) and timing the return of the echo at the antenna (Brown 1977, Fu and Cazenave 2001, Fig. 2). The two-way travel time allows the altimetric range (*Range*), i.e., the distance between the antenna and the surface, to be determined. Combined with knowledge of the satellite's altitude (*Altitude*), the height of the surface is then derived. The range and surface height need to be corrected for a variety of instrument corrections (*instrumentcorr*), as well as atmospheric and geophysical conditions, which are estimated via onboard instrumentation or ancillary data sets or models. The *Range* term (Equation 1) must be corrected for the effects of water vapor (*wetcorr*), atmospheric pressure (*drycorr*), and the presence of ions (*ionocorr*) in the atmosphere. The surface height (*Height*, Equation 2) is then constructed with corrections for tide effects, namely solid earth tide (*earthtide*), pole tide (*poletide*), and ocean-loading tide (*loadingtide*). For the derivation of inland water heights, other *Range* and *Height* corrections, such as the barometric height correction and the sea state bias correction, are not applied. A full account of the reconstruction of altimetric height can be found in Fu and Cazenave (2001), and notably for inland waters within Birkett (1995, 1998).

$$Range_{corr} = Range + instrumentcorr + wetcorr + drycorr + ionocorr \quad \textbf{(1)}$$
$$Height = (Altitude - Range_{corr}) - (earthtide + poletide + loadingtide) \quad \textbf{(2)}$$

The final altimetric surface height, *Height* (or elevation, or water level), is constructed with respect to a geodetic (mathematical, based on a reference ellipsoid) datum, typically the World Geodetic System or "WGS84" datum (equatorial radius 6378.1370km, flattening coefficient 1/298.257223563), or the one specifically defined for the early TOPEX/Poseidon mission (equatorial radius 6378.1363 km, flattening coefficient 1/298.257, additionally used by Jason-1 and Jason-2). Each *Height* is a mean derived from averaging the returned energy from the surface and analyzing the energy power spectrum. Essentially, a *Height* value is an average value related to the size of the instrument footprint and a set distance along the satellite ground track. Such *Height* values are provided in the Level 2 datasets at a pre-defined along-track resolution (Table 1), e.g., one value every 300m, and can be translated to an orthometric datum (based on mean sea level) via use of a geoid model. The footprint of a pulse-limited altimeter varies according to surface roughness, ranging from a few hundred meters in diameter for a very smooth specular surface, to several kilometers for a water surface under strong wind (high wave) conditions.

2.2 Altimeter Ground Tracks

The building of a time series of water levels specifically relies on gathering *Height* values along a single satellite overpass (or multiple overpasses) within a given repeat cycle and then monitoring this variation across all repeat cycles over the mission lifetime. Within the current GWM system, just one satellite overpass within the water body is utilized, and methodology employs standard "repeat-track" techniques where *Height* values along a section of ground-track are compared to their equivalent (in location) counterparts on all subsequent repeat tracks. The short repeat (within 1 month) altimetric missions are placed in orbits that are maintained such that the spacecraft re-visits the same location on the Earth's surface within a specified time-period. They thus trace out a set of ground tracks. These are decided upon prior to launch and once the mission commences are required to be constrained to ±1km, though in practice they can be kept to a much tighter ±250m. With nadir viewing, the instruments follow their mission-defined reference ground tracks, continuously emitting pulses and receiving echoes along a narrow swath (Fig. 3). The ground tracks correspond to ascending or descending satellite overpasses, and the resulting *Height* values are constructed with a 10-, 18-, 20-, or 40-Hz along-track spatial resolution (Table 1). From coast to coast or bank-to-bank, surface heights are therefore potentially obtainable every few hundred meters along each ground track.

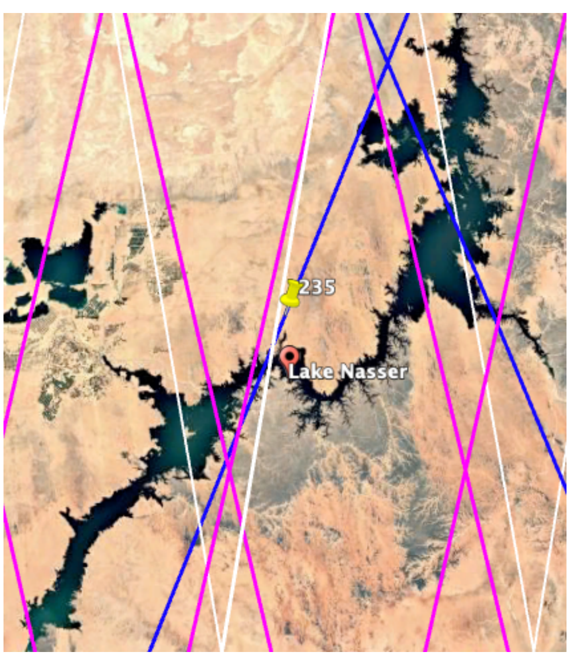
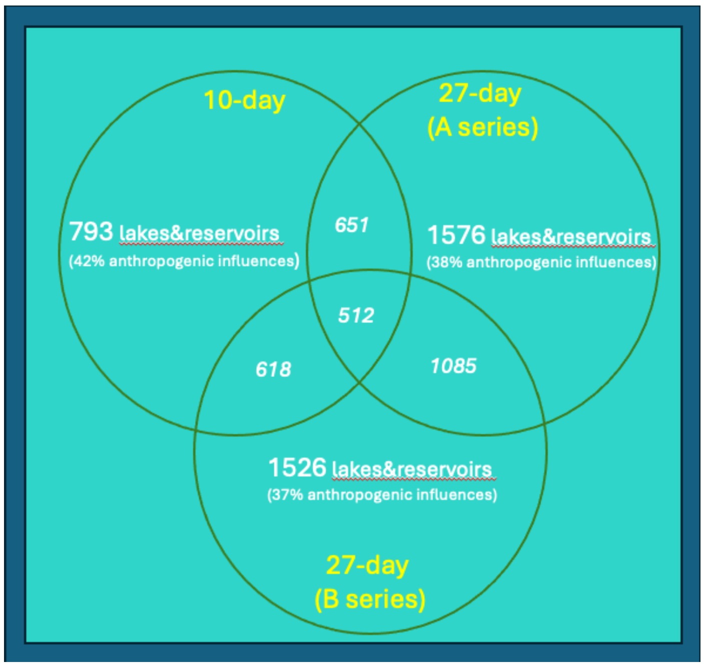


Figure 3. Ascending and descending satellite overpasses. *Relating to the nadir pointing radar altimeter instrument, each overpass has a corresponding ground track, and the spatial resolution of height data along each track is a few hundred meters. The image depicts the Sentinel-6A tracks (blue, 10-day resolution), the SWOT-NA tracks (white, 21-day resolution), and the Sentinel-3A tracks (pink, 27-day resolution) on Lake Nasser, Egypt. There is a trade-off between the density of ground tracks and the temporal resolution of the measurements. For example, there are many more ground tracks over the reservoir from the 27-day instruments than offered by the 10-day instrument suite. Here the reservoir has only 1 ascending 10-day overpass (pass235) and one descending 10-day overpass. (Image courtesy of Google Earth).*

Because the ground tracks are fixed, and each satellite has fixed geographical North/South coverage limits (Table 1), whether a lake or reservoir has an overpass, or where a specific river reach or wetland is sampled, is already set at the start of each mission. The density of ground tracks has a reciprocal relationship with the satellite repeat period, the finer the temporal resolution, the poorer the spatial coverage (Fig. 4). Larger lakes and reservoirs may have more than one ground track, smaller water bodies just one or none. It is important to note that a time series of *Height* variations derived for a lake or reservoir from different ground tracks may differ due to wind and wave effects or the distance from the dam.

Figure 4. The trade-off between spatial and temporal resolution. *The figure depicts the number of lakes and reservoirs (≥100km^2 in surface extent, Birkett et al, 2022) crossed over by the current 10-day and 27-day exact repeat cycle radar altimeter instruments.*



2.3 A Methodology-defined Reference Pass

Each mission has a defined set of Reference Ground Tracks (RGT). NASA defines these from theoretical approaches, while CNES creates average track-locations from actual overpass location variations. The employment of repeat-track methodology includes the creation or designation of a reference pass i.e., a single Reference Ground Track, which acts as the reference (or zero) datum and to which all other satellite overpasses associated with this track are compared to. The methodology also employs interpolation to shift all *Height* values to a common time/latitude/longitude grid to account for slight variability in the ground track locations. Often, the reference pass is an average formed over a specified time interval utilizing all available repeat passes, or it can be one specific overpass on a single date. In either approach, the reference datum is not a spot height, but a height profile across the water body. The advantage of using a reference datum derived over a long-time interval is that it may average out wind, tidal, and seasonal variations, creating essentially a datum that can be thought of as a "mean water surface". However, in practice, this datum can be noisy, especially for smaller water bodies, and a datum based on single ground track and a single date is often preferred.

The heights along each satellite overpass are compared to those along the reference pass, and a mean and standard deviation of the height differences are calculated. This is repeated for each overpass, until a time series of relative water height variations is created. For climatic interpretations or storage change estimates, relative water level variation products are acceptable, but they can be converted back to a geodetic (reference ellipsoid) datum or shifted to an orthometric datum (mean sea level) with the introduction of a geoid model. These geoid models have unknown and varying errors across inland water surfaces, but if applied to smaller water bodies, the geoid height is often a constant height bias common throughout the time series.

2.4 LRM and SAR Data Processing

Historically, the altimeter data can only be processed to a “Low-Resolution Mode (LRM)” standard, meaning one mean elevation measurement along the ground track at a 10-, 18-, 20- or 40-Hz rate, and that measurement is derived from a narrow (cross-track) field of view. The more recent Sentinel instruments have Delay Doppler Synthetic Aperture Radar (DD-SAR) data processing capability which can result in a “High Resolution Mode (HRM)” set of measurements. These HRM elevations have the same along-track resolution as LRM, but they have a 1000m cross-track resolution cell size (Table 1). It has been reported that this SAR-style data processing can offer more accurate surface elevations for inland water, but the GWM system has not found this to be so on a global scale, and so only LRM measurements are currently utilized.

2.5 Instrument Surface Acquisition and Tracking Modes

Each altimeter instrument operates according to surface acquisition and surface tracking modes, and these choices are flagged in the Level 2 datasets. The most important are the a) surface acquisition modes, i.e., how quickly the instrument’s logic can acquire the correct elevation surface in a rapidly varying terrain, and b) the surface tracking modes i.e., how robust the instrument logic is at holding onto the correct surface when multiple radar-bright targets are within, or in the vicinity, of the instrument footprint. The GWM system records the acquisition and tracking operating modes in the GWM ascii text product (columns 12 and 13, see Section 7.2). These modes are set according to the last valid, high spatial resolution, elevation measurement over the target. The exception is the TOPEX/Poseidon dataset, which sets columns 12 and 13 based on the highest number of occurrences of a mode type. The TOPEX/Poseidon mission had two onboard altimeter instruments, TOPEX the primary instrument and Poseidon the secondary test instrument which operated alone during certain repeat cycles. The combined dataset has instrument operating flags that are either two values per second (TOPEX) or 1 value per second (Poseidon) and are based on “half-frames”, i.e., the 1st (relating to column 12) or 2nd (column 13) half of the 1-Hz measurement point.

The launch of Jason-2 saw a change in how the inland water bodies were acquired via use of a pseudo-Digital Elevation Model (DEM) employed within a new DIODE/DEM instrument operating mode combination (Birkett and Beckley, 2010). The DIODE (Détermination Immédiate d’Orbite par DORIS Embarqué) was an on-board real time function, part of the satellite’s DORIS system, to compute the satellite’s orbit ephemeris. The pseudo-DEM was a ground-track specific matrix of location and elevation that would give the instrument a priori elevation information, i.e. knowledge of the terrain before reaching the target arrival area, and so more quickly capture the returning radar each in the ~60m wide *Range* window. The DIODE/DEM mode was tested during a set number of cycles during the Jason-2 lifetime and showed some success in capturing inland water surfaces in highly varying terrain. A pseudo-DEM was therefore adopted on later missions, each one specific to the ground tracks associated with the temporal repeat frequency. The success of such a strategy though depends on assimilating many high-resolution valid elevation datasets (Le Gac et al., 2019) and the pseudo-DEM often undergoes upgrades during the mission lifetime as acquisition errors are reported to the space agencies (Table 3).

The instrument acquisition and tracking modes are currently not noted in columns 12 and 13 for ENVISAT and SWOT-NA, and column values are set to default. Noting the use of italics to denote available parameters and flags in the Level 2 datasets, the instrument acquisition and tracking modes for the other satellite missions are set as,

TOPEX: [checking of 1st (*current_mode1*) or 2nd (*current_mode2*) half of the 1-Hz dataset frame];
Column12=1 (Coarse Acquisition), 2 (Fine Acquisition), 3 (Coarse Tracking), 4 (Fine Tracking), (default=9, if Poseidon is operating)
Column13=0 (EML Tracking), 1 (Threshold Tracking), (default=9, if Poseidon is operating)

Poseidon: [checking of *current_mode2*]
Column12= 2 (Acquisition), 3 (Low-Rate Tracking), 4 (High-Rate Tracking)
Column13=9 (default)

Jason-1: [The *Alt_State_Flag_acq_mode_20hz* exists but was set to default]
Column12=9 (default)
Column13=9 (default)

Jason-2: [checking *Alt_State_Flag_Acq_Mode_20Hz and Alt_State_Flag_Tracking_Mode_20Hz*]
Column12=0 (autonomous acquisition), 1 (DIODE acquisition), 2 (DIODE/DEM)
Column13=0 (Split Gate Tracking), 1 (Median Tracking), 2 (DIODE/DEM)

Jason-3: [use of *alt_state_flag_acq_mode_20hz*]
Column12=0 (autonomous acquisition), 1 (DIODE acquisition), 2 (DIODE/DEM)
Column13=1 (Median "autonomous" tracking), 2 (DIODE/DEM)
Unlike Jason-2 there is no split-gate tracking mode for Jason-3. There were three Jason-3 operating modes, i) autonomous acquisition/autonomous tracking, ii) DIODE acquisition/autonomous tracking, iii) DIODE/DEM. The Jason-3 instrument was in DIODE acquisition/autonomous tracking mode for cycles 000 to 010 and cycle 020 and used DIODE/DEM mode during the rest of the mission. To note are these exceptions:

a) cycle 000 [passes 117-146], cycle 006 [passes 066-070, passes 113-116], cycle 008 [passes 144-148] in autonomous acquisition/autonomous tracking mode.
b) cycle 000 [passes 201-207], cycle 004 [pass 018], cycle 005 [passes 018, 070, 111], cycle 006 [passes 001-065, 070-113, 116-254], cycle 007 [pass 18], cycle 008 [passes 18,254], cycle 009 [pass 001-248], cycle 010 [pass 18] in DIODE/DEM mode.
c) cycle 020 [passes 018, 070, 111, 254] in DIODE acquisition/autonomous tracking mode.

Sentinel-6A: [use of *P4_mode_flag*]
Noting the following definitions,
OL=Open Loop (DEM used), CL=Closed Loop (DEM not used)
LRM=Low Resolution Mode, HRM = High Resolution (SAR)
RMC= Range Migration Function (A new function to reduce data volume for transmission, allows downloading of all three data sets at the same time, designed to validate the RMC processing).

Sentinel-6A has the following operating modes:
LRM_CL= LRM only
LRM_OL = LRM only but using DEM
LX_CL= Simultaneous LRM and HR data
LX_OL= Simultaneous LRM and HR but using DEM
LRMC_CL= Simultaneous LRM and HR data after RMC processing
LRMC_OL =Simultaneous LRM and HR after RMC processing, using DEM
LX2_CL = LRM and raw SAR plus SAR (entails a large volume of data)
CAL* = various calibration modes
TPX=Fully Open Loop Transponder commanding for calibration targets

ST=Self-Test mode

With GWM product columns set as,

	Column 12	**Column 13**
LRM_CL	0	0
LRM_OL	1	0
LX_CL	0	1
LX_OL	1	1
LRMC_CL	0	2
LRMC_OL	1	2
LX2_CL	0	3
TPX	2	9
ST	3	9
CAL1_INSTR	4	9
CAL1_LRM	5	9
CAL1_SAR	6	9
CAL1_RMC	7	9
CAL2	8	9

Sentinel-3A,: [Use of *instr_op_mode_20_ku(time_20_ku) and mode_id_20_ku(time_20_ku*]
The instrument can operate in either LRM or SAR mode according to a geographical mask but not both together. The intention was to eventually employ SAR mode over all land.
column 12 = 0 (closed loop), 1 (open loop), 2 (open loop fixed gain)
column 13 =0 (LRM), 1 (SAR), 2 (LRM+SAR)

Sentinel-3B,: [Use of *instr_op_mode_20_ku(time_20_ku) and mode_id_20_ku(time_20_ku*]
The instrument can operate in either LRM or SAR mode according to a geographical mask but not both together. The intention was to eventually employ SAR mode over all land.
column 12 = 0 (closed loop), 1 (open loop), 2 (open loop fixed gain)
column 13 =0 (LRM), 1 (SAR), 2 (LRM+SAR)

Table 1: *Short exact-repeat period (roughly within 1 month) profiling satellite radar altimeter missions. Instruments operate at either Ku- or Ka-band. DD-SAR reflects instruments with Delay Doppler (SAR) processing capability. Spatial resolutions below are the conventional altimeter along-track Level 2 data Range posting rates (e.g., 10-Hz TOPEX/Poseidon, 18-Hz ENVISAT, 20-Hz for the Jason series and Sentinel-3A,-3B,-6A, and 40-Hz SARAL) or the SAR resolution cells. Geographical coverage varies, e.g., from ±66˚ latitude (10-day resolution suite) to ±81˚ (35-day resolution instrument suite). The first instrument to test the use of an on-board pseudo-Digital Elevation Model (DEM) to aid surface height acquisitions over inland waters in complex or highly undulating terrain was Jason-2, with the later Jason-3 and Sentinel missions adopting its use.*

Mission	**Agency**	**Primary Instrument Radar Band**	**Time Period**	**Resolution Spatial(m)**	**Temp(days)**[Note 1]
SWOT-NA	Consortium	Ku	2023	300	1
ERS-1 phase A	ESA	Ku	1991	350	3
ERS-1 phases B&D	ESA	Ku	1992-1992, 1993-1994	350	3
TOPEX/Poseidon (T/P)	NASA/CNES	Ku	1992-2002	580	10
Jason-1	NASA/CNES	Ku	2002-2008	290	10
Jason-2/OSTM	NASA/CNES	Ku	2008-2016	290	10
Jason-3	Consortium	Ku	2016-2022	290	10
Sentinel-6A MF	Consortium	Ku/DD-SAR	launch2020	300x1000	10
T/P Interleaved	NASA/CNES	Ku	2002-2005	580	10
Jason-1 Interleaved	NASA/CNES	Ku	2009-2011	290	10
Jason-2 Interleaved	Consortium	Ku	2016-2017	290	10
Jason-3 Interleaved	Consortium	Ku	2022-2025	290	10
HY-2A	CNSA	Ku	2011-2016	290	14
HY-2B	CNSA	Ku	2018-	290	14
HY-2C	CNSA	Ku	2020-	290	10
HY-2D	CNSA	Ku	2021-	290	10
Seasat	NASA	Ku	1978	670	17
GEOSAT	NRL	Ku	1986-1990	670	17
GFO	NRL	Ku	2000-2008[note 2]	670	17
SWOT-NA	Consortium	Ku	2021-present	300	21
Sentinel-3A	ESA	Ku, DD-SAR	2016-present	300x1000	27
Sentinel-3B	ESA	Ku, DD-SAR	2018-present	300x1000	27
ERS-1 phases C&G	ESA	Ku	1992-1993,1995-1996	350	35
ERS-2	ESA	Ku	1996-2002[note 3]	350	35
ENVISAT	ESA	Ku	2002-2010, 2010-2012[note 4]	350	35
SARAL	ISRO/CNES	Ka	2013-2016	175	35

Mission Acronyms:
SWOT-NA=Surface Water and Ocean Topography Nadir Altimeter
ERS= European Remote Sensing Satellite
TOPEX= Ocean Topography Experiment
OSTM=Ocean Surface Topography Mission but denoted as just Jason-2 in this ATBD text
HY= Haiyang
Seasat=Sea Satellite, GEOSAT= Geodetic Satellite, GFO=GEOSAT Follow-On
ENVISAT= Environmental Satellite, SARAL= Satellite with Argos and Altika
MF = Michael Freilich but denoted as just Sentinel-6A in this ATBD text

Notes

1 There are a set number of ascending and descending passes per repeat cycle, e.g., 28 passes (within the 1day repeat), 254 (10day), 584 (21day) 770 (27day), 862 (30day), 1002 (35day).

2 From 2006 GFO operated with a reduced continental coverage.

3 From June 2003-July 2011 ERS-2 continued operating but with a reduced download of data.

4 Between May 2002-October 2010 ENVISAT operated from its nominal 35-day (501 passes) repeat orbit, but to ensure an extended lifespan the repeat orbit was changed. From November 2010 to May 2012, it operated in a modified 30-day (431 passes) repeat orbit with a less global data download.

Table 2: *Long-repeat period profiling satellite radar and lidar missions. The instruments/phases below have mapping objectives thus trading a finer temporal resolution for a denser ground track coverage.*

Mission	Agency	Frequency	Time Period	Resolution	
				Spatial(m)	Temp(days)
ERS-1 phases E&F	ESA	Ku	1994-1995	350	168
CRYOSAT-2	ESA	Ku, DD-SAR&SARIn	2010-present	300x1000	369
Jason-1	NASA/CNES	Ku	2012-2013	290	406
SARAL drift phase	ISRO/CNES	Ka	2016-1019	175	drift
HY-2A	CNSA	Ku	2016-2021	290	368
Jason-2	NASA/CNES	Ku	2017-2019	290	371
ICESat-1	NASA	laser 1064nm	2003-2009	175	91 (note 1)
ICESat-2	NASA	multi-beam laser 532nm	2019-present	0.7-3.0 (note 2)	91&drift

Notes

1 *Icesat-1 operated for ~33days (of a 91-day cycle) during March, June, and November.*

2 *Icesat-2 operates with an exact 91day repeat at high latitudes. At low-to-mid latitudes off-nadir pointing allows a 'fill-in' of spatial sampling. The along-track sampling is variable depending on the number of laser photon returns being averaged.*

Table 3: *On-board pseudo-DEM versions for each mission's primary repeat phase period. The utilization of a DEM assists the acquisition of surface waters especially in complex or highly undulating terrain, essentially the DEM provide each instrument with an approximation elevation prior to overpass. The DEM have proved successful though they contain some inherent errors. Routine DEM upgrades are thus performed during the mission lifetime. During the SWOT-NA 1-day phase, a trial change to the DEM tracking procedure was implemented.*

Mission	DEM Version	Start or Upgrade Date
Jason-2/OSTM		*Launch 20th June 2008*
	2.0	since launch
	3.0	4th June 2009
	3.0	5th March 2014
	3.0	22nd June 2014
Jason-3		*Launch 17th January 2016*
	1.0	since launch
	2.0	2nd May 2016
	3.0	31st August 2017
	4.0	2nd September 2020
Sentinel-6A		*Launch 21st November 2020*
	1.1	18th December 2020
	1.3	10th May 2023
Sentinel-3A		*Launch 16th February 2016*
	4.1	18th April 2016
	4.2	24th May 2016
	5.0	9th March 2019
	6.0	27th August 2020
	6.1	26th August 2021
	6.2	8th September 2022
	6.3	25th September 2023
Sentinel-3B		*Launch 25th April 2018*
	2.0	27th November 2018 (interleaved orbit)
	3.0	18th June 2020
	3.1	20th August 2021
	3.2	15th September 2022
	4.0	24th August 2023
SWOT-NA 1day		*Launch 16th December 2022*
	1.0	13th February 2023
	2.0	20th March 2023
SWOT-NA 21day	3.0	9th October 2023

3.0 Data

The GWM system utilizes the following input data and auxiliary files,

i) Various Level 2 interim and final geophysical datasets provided by the altimeter mission ground-processing centers (Table 4). Interim datasets are provided in near real time (within 2-3 days after satellite overpass) and the more accurate non-time critical are provided within 1month. After mission launch interim data are utilized but replaced by the non-time critical data during GWM product upgrades. The Level 2 data include the *Range* and *Altitude* parameters at varying spatial resolutions (e.g., 1-Hz, 10-Hz, 18-Hz, 20-Hz, 40-Hz), but the atmospheric and tidal corrections are supplied at the lower 1-Hz resolution. The Level 1 data are the radar echoes (energy distribution with time) of the reflected microwave pulse. Table 4 lists the abbreviations for each mission name which are utilized in the following ATBD text.

Table 4. *Level 2 radar altimeter datasets currently employed by the GWM system. Changes to raw data processing code and Level 2 dataset upgrades are common during mission lifetime and post-mission period. Lidar data from ICESat-2 (Table 2) are additionally used for cross-validation purposes.*

Mission	Mission Abbreviation	Level 2 Range Posting Rate	GWM Employed Level 2 Dataset
TOPEX/Poseidon	T/P	10-Hz	MGDR-B
Jason-1	J-1	10-Hz	GDR-C
Jason-2/OSTM	J-2	20-Hz	GDR-D
Jason-3	J-3	20-Hz	GDR-D/IGDR-D/IGDR-F (note 1)
Sentinel-6A	S-6A	20-Hz	NTC, STC (note 2)
ENVISAT	ENV	18-Hz	RA2/MWR (note 3)
Sentinel-3A	S-3A	20-Hz	Baseline 5 NTC/STC (note 4)
Sentinel-3B	S-3B	20-Hz	Baseline 5 NTC/STC (note 4)
SWOT-NadirAltimeter	SWOT-NA	20-Hz	IGDR V1.0 (1-day), IGDR V2 (21-day) (note 5)

Acronyms

I//M/GDR=(Interim or Merged) Geophysical Data Records, STC/NTC= Short or Non Time Critical, RA=Radar Altimeter, MWR=Microwave Radiometer. In upper case, letters after hyphens denote dataset versions.

Notes

[1] Three Level 2 datasets are employed, each has its own internal parameter database; the version 5 database contains GDR-D records (cycles 1-160), version 6 IGDR-D (cycles 161-174), and version 7 IGDR-F (cycle 175-226).

[2] NTC Level 2 dataset processing versions are F06 (cycle 004 to cycle 065 pass 20), F07 (cycles 065 pass 21 to cycle 083 pass 8), F08 (cycle 083 pass32 to cycle 122 pass 15), F09 (cycle 122 pass 16 to cycle 160), and G01 (cycle 161 onwards). STC processing version is G01.

[3] Using dataset version 3.

[4] Utilizing the Hydrology and Land Ice Thematic datasets which start at cycle001 for S-3A and cycle 019 for S-3B. These are a mix of NTC and STC. Prior to cycle 019, S-3B was in a tandem orbit with S-3A before moving to its ground-track interleaved (with S3A) science orbit. The allocation of “019” to the first S-3B cycle in its interleaved orbit is somewhat misleading.

[5] IGDR (21day) are V2.0 (cycles 1 to 28) and V2.01 (cycle 29 onwards)

ii) The NASA/GSFC satellite orbit ephemerides for precise estimates of the *Altitude* parameter.

iii) RGT for each mission are obtained from NASA/GSFC (internal access), and from AVISO, http://www.aviso.altimetry.fr/en/data/tools/pass-locator.html

These are used within Google Earth for the satellite overpass selection and the noting of water crossing points. The NASA/GSFC versions are generated from the GSFC orbit determination and geodetic parameter estimation (GEODYN) orbital software and are based on orbital parameters and available satellite laser ranging (SLR) tracking. The AVISO version is generated from the actual satellite data (geographical locations) from which an average ground track location is formed.

iv) A NASA/GSFC subroutine ("MJDYMD", within GEODYN) which performs a conversion from Modified Julian Date to calendar date.

vi) Two NASA/GSFC algorithms (gd2gc and gc2gd) which convert between geodetic and geocentric co-ordinates. These assist with transferring *latitude* and *Altitude* between the WGS84 and TOPEX/Poseidon datums.

vii) A NASA/GSFC lake and reservoir database or catalog (initial Birkett and Mason, 1995, revised Birkett et al., 2022) which records location, water body type, water use, and potential mission overpasses.

viii) The Delft University of Technology Radar (TUDelft) Altimeter Database System (RADS) for potentially more precise *wetcorr*, *drycorr*, and *ionocorr* altimetric *Range* corrections (Fernandes et al. 2014). For single mission RADS downloads the following web portal can be accessed, http://rads.tudelft.nl/rads/rads.shtml. However, GWM utilizes the mirror image process to access the entire database for all missions which was achieved via the RADS rsync server at rads.tudelft.nl. Currently GWM products are based on Version 4 of the RADS software library.

ix) Meteorological model (climate reanalysis) output. Models include the Modern-Era Retrospective Analysis for Research and Applications (MERRA, courtesy of JPL) and the European Centre for Medium Range Weather Forecasting (ECMWF) Re-Analysis (ERA, courtesy of RADS). These are utilized for basic wet tropospheric *Range* correction (*wetcorr*) estimates. In addition, a revised *wetcorr* for the T/P and J-1 missions based on re-calibration and enhanced microwave radiometer measurements is also supplied from JPL (Brown et al., 2009) and can be found at,

https://podaac.jpl.nasa.gov/dataset/TOPEX_L2_OST_TMR_Replacement
https://podaac.jpl.nasa.gov/datasetlist?search=JASON1_JMR_ENH

4.0 System Process

The processing of the Level 2 radar altimeter data sets to form GWM products that are time series of water level variations for inland water has been discussed by several authors (including Birkett 1995, 1998) and more specifically for the GWM system within Birkett et al., (2010). The following sections briefly outline the methodology and task flow.

A) Level 2 satellite data ingestion and content storage

Input Data: The utilization of various altimetric data sets, auxiliary databases, and data files.

Creation of a Time-Tagged Reference Ground Track: These high-resolution mission-dependent time-tagged Reference Ground Tracks (time-tagged RGT) are a record of latitude (lat) and longitude (lon), with an associated time-tag (number of seconds along the satellite pass) relevant to the start of the mission repeat cycle. Their creation is based on the computation of a nominal 1-Hz geo-referenced reference track with datum-based locations (lat, lon) computed using a Hermite tenth order interpolation algorithm. The assignment of a 1-Hz time-tag is based on actual time values observed on a ground track within the GDR/NTC dataset. The 1-Hz time-tagged RGT is then expanded to the highest along-track resolution within the satellite dataset. For example, for a dataset containing 20-Hz elevations this results in 20 time-tags at 0.05s intervals. The higher-resolution time-tags are created at fractional second intervals centered about the 1-Hz mid-point reference time.

Creation of a mission-specific Geo-Referenced Parameter Database: The creation of a 1-Hz time-tagged geo-referenced radar altimeter parameter database is undertaken for each mission. The 1-Hz time tags are then expanded to 10-Hz or 20-Hz (T/P), 18-Hz (ENV), 20-Hz (J-1, J-2, J-3, S-3A, S-3B, S-6A, SWOT-NA), or 40-Hz (SARAL), such that the 1-Hz index represents the mid-point of the data record. The early parameter database structure was based on direct access with three-dimensional directories that were based on mission repeat cycle number, satellite pass number, and the indexed along-track 1-Hz geo-referenced locations (from the time-tagged RGT). The newly updated parameter databases are still organized via cycle/pass/indexed location, but they are now based on a series of mission HDF5 files (1 file per cycle), with data records being stored as "datasets" with the same HDF5 structure. To note is that each Level 2 dataset record is a fixed length containing a mix of low- and high-rate parameters at 1-Hz, 10-Hz, 18-Hz, 20-Hz, or 40-Hz. The time, location, *Orbit, Range*, and radar backscatter coefficient parameters are provided at the high-rate (except T/P and J1 radar backscatter coefficient which was only provided at 1-Hz), while tidal and atmospheric parameters are only provided at the low 1-Hz rate. When the mission parameter databases are created, all parameters remain separate i.e., fully reconstructed altimetric height values are not held at this point. Also to note is that because the GWM system was based originally on TOPEX/Poseidon data, the geo-referenced parameter databases store *latitude, longitude* and *Altitude* with respect to the T/P reference ellipsoid. Values of *latitude* and *Altitude* from missions using the WGS84 ellipsoid as a datum are thus converted to the T/P datum prior to storage in the internal parameter databases (*longitude* remain unchanged between the datums).

The Level 2 mission datasets use different epochs to record the *Range* measurement time which is the number of seconds passed since the epoch. Epoch shifts are performed to convert the number of seconds to the system's accepted Modified Julian Date (MJD) epoch (0hr Universal Time Coordinated or UTC on 17^{th} November 1858). Most of the GWM Level 2 datasets employ 0hrs UTC on 1^{st} January 2000 as the epoch. The exception is the TOPEX/Poseidon dataset which employed 0hr UTC on 1^{st} January 1958. Later in the GWM process this MJD is converted to a Year, Month and Day, plus UTC time, and is output to the GWM product text files.

The high-rate parameters are then entered into the database and time-aligned with the 10- or 20-Hz time tags by a "nearest neighbor" approach, rather than via time interpolation, to preserve as many height measurements as possible. The 1-Hz parameters though are linearly time-interpolated to the time tags via constructing perpendiculars from the RGT to the actual orbital track location and linearly interpolating from the surrounding along-track data. During this process the across-track distance between the RGT and the actual cycle track in the dataset is recorded. However, this distance value is never utilized, i.e., an across-track correction is never applied during any part of the co-alignment process. All database information is thus co-located to specific latitude/longitude points within the time-tagged RGT set. Note that co-locating the parameters as they are read in assists the repeat track methodology where heights along one satellite pass are compared to those on a repeat pass. However, as the co-locating does not correct for surface gradients in the across-track direction, this can introduce errors on the order of a few centimeters (Birkett, 1995) for water bodies such as the Rift Valley lakes in Africa.

The inland water target's reference pass (see Section C) below) becomes the datum for the water body in question and is a datum that is based on a specific overpass cycle and ground-track section. In terms of Level 2 along-track resolution, the reference pass can then be 18-Hz (ENVISAT 35-day products), 40-Hz (SARAL 35-day preliminary products), or 20-Hz (the Jason/Sentinl-6 10-day products). For the 10-day products there are additional procedures in place to store the 10-Hz TOPEX/Poseidon dataset records so that their height measurements can be compared to the reference pass at 20-Hz. Assuming the height measurements are 10-Hz(1) to 10-Hz(10), and 20-Hz(1) to 20-Hz(20), the system offers two choices, i) average the 20-Hz down to 10-Hz, or ii) extrapolate (linear interpolation) the 10-Hz out to 20-Hz to preserve as many TOPEX/Poseidon measurements as possible. The former (resulting in V.2.5 10-day products) is used for nearly all lakes and reservoirs, and is based on,

$$10\text{-Hz}(1) = 0.5*(20\text{-Hz}(1) + 20\text{-Hz}(2)) \ldots \; 10\text{-Hz}(10) = 0.5*(20\text{-Hz}(19) + 20\text{-Hz}(20))$$

while the latter (resulting in V.2.6.1 10-day products) has proved beneficial for narrower or smaller river reaches and wetland zones, and is based on the following three steps,

i) Preserve the end records, i.e. 10-Hz(1) => 20-Hz(1), 10-Hz(10) => 20-Hz(20)
ii) For the other records, copy over the 10-Hz values to the odd record elements in the 20-Hz, 10-Hz(2) => 20-Hz(3), 10-Hz(3) => 20h-Hz(5) ……. 10-Hz(9) => 20-Hz(17), 10-Hz(10)=>20-Hz(19) This implies that 10-Hz(10) is copied into both 20-Hz(19) and 20-Hz(20)
iii) Linearly interpolate to set the even elements in the 20hz, 20-Hz(2) = 0.5 * (20-Hz(1) + 20-Hz(3)) …………. 20-Hz(18) = 0.5*(20-Hz(17) + 20-Hz(19)

B) Inland water Target Selection

Inland water bodies are primarily selected according to NASA-funded projects and USA stakeholder requests. The USDA/FAS are primarily interested in mid- to low-latitude lakes and reservoirs that are situation in high agriculture production regions. Research projects look to high-latitude lakes in glacial regions or specific river basins (e.g., Congo). The United States Geological Survey (USGS) seek height measurements in remote locations (e.g., Alaska) to supplement meagre gauge records.

C) Preliminary Assessment of Data Quality and Quantity

Height Reconstruction: This is the creation of high-rate height values along the ground track according to Equations (1) and (2), and the creation of the associated date and high-rate time, location, and radar backscatter coefficient. Note that corrections for tidal, ice, heavy precipitation, or vegetation cover effects are not included in the height estimate. The radar backscatter coefficient is the ratio of energy emitted to reflected. It is proportional to the surface roughness and is used to denote calm-surface or the presence of ice on the water surface.

Selection of a Satellite Overpass: For inland water targets with multiple overpasses or ground tracks, the best satellite overpass is chosen based on the quantity and quality of the height measurements on each ground track. This includes observation of the overpasses across the water body of interest within Google Earth noting coastline crossing points, potential interference from land (peninsulas, islands) and infrastructure, and the location of dams.

Selection of the Overpass Ground Track Limits: For a given overpass, a maximum of 4 sections (i.e., represented by 8 latitude start/stop values) on a ground track are identified. This assists with removing land contamination. This limit of 4 sections was set as it represents ~95% of the overpass situations when considering lakes or reservoirs. The system does not perform any along-track interpolation to close data gaps formed by the presence of islands, coastlines, or any sporadic instrument/data drop out periods.

Selection of a Reference Cycle: On the selected ground track, one overpass becomes the target's reference datum i.e., a height profile from coast to coast on a given date and within one repeat cycle. The reference cycle is selected based on the lowest height variability in the along track direction, and a maximum number of valid height measurements, For the 10-day products priority is given to a cycle within the J-2 dataset (primary), J-3 (secondary), or S-6A (tertiary) datasets. The selection of a cycle aims to avoid dates with i) potential winter (ice-on) conditions, ii) wind-set up effects, and iii) where the atmospheric range-correction parameters are not available. For the J-2 data set, the reference cycle also excludes repeat cycles where the instrument operated in the experimental DEM tracking mode (cycles 003, 005, 007, 034, 209, 220). During these cycles, the instrument used a look-up table based on a pseudo-DEM which potentially contained inherent errors of meters to tens of meters.

Derivation of Surface Height Variations: With a selected ground track, ground track latitude section/s, and the reference cycle, the system then employs standard "repeat track methodology". Near-exact repeat cycles facilitate a geoid-independent technique that estimate changes in surface height based on the method of collinear differences. "Collinear" indicates that the mission surface heights have been geo-located to a specific time-tagged RGT. During collinear analysis, the tracks of the repeat cycles are assumed to have perfect alignment to facilitate the separation of surface height variations from geoid undulations. However, the repeat track ±1km variability introduces errors, which can be several centimeters over large lake surfaces based on the slope of the local geoid. In the GWM process, the methodology employs along-track interpolations to co-align all height measurements to the mission time-tagged RGT. Comparing the 20-Hz heights on the reference pass with those on other repeat overpasses, produces a time series of surface height differences with respect to the reference pass. These relative height variations are central to the GWM products. Note that if a lake or reservoir has multiple satellite overpasses (at varying coastline crossing locations within a given repeat cycle), the methodology does not undertake multiple time series creation and mergers. It focusses only on a single ascending or descending overpass. The process also does not merge time series derived from the different instruments and different repeat-phases.

D) Multi-Mission Mergers

Where available, time series of relative height variations of the same temporal resolution are merged to form a single surface height variation product. *Inter-mission Range bias* estimates are applied to align the multi-platform results. In certain cases, a *Retracker Range bias* is additionally applied to account for differences between *Range* parameter selection.

E) Product Accuracy, Cross-Validation Checks, and Iterations

GWM product accuracy will depend on several factors. Regarding the GWM system, to consider are the selection choices of the Level 2 and/or RADS dataset parameters, the selection of overpass (e.g., proximity to the dam) and the specific location/s on the ground track to be used, and the processing ability to successfully reject interference from land (coastline, island, peninsula). When merging measurements from multiple platforms, there are assumptions concerning the estimation (or substitution for) the *Inter-mission Range bias*. There are also physical constraints such as the size of the stretch of water presented to the instrument and the water surface roughness (wind and waves). From a mission perspective, the accuracy of the on-board pseudo-DEM may be variable and there may be accuracy differences between the time critical and non-time critical dataset parameters. Between missions, accuracy differences may arise due to variations in dataset release version standards, and available parameter selection - particularly the choice of *Range* retracking algorithm output.

<u>*Filtering:*</u> This is both input data and water level product filtering to remove erroneous height values caused by land interference or poor surface tracking.

(a) Data Filtering. Visual observation of the satellite-based height values on multiple overpasses provides a guide to the target's seasonality. This seasonal height range and the height of the reference cycle are noted in the process and used as part of the filtering process. A minimum number (N=2) of valid along-track data points or height values along the reference cycle track is ideally required. Any other repeat pass having N<2 has its height difference value automatically set to a default value. On occasion, for very narrow crossings where data is sparse, N=1 can be accepted. In these cases, a mean height difference (between the reference cycle and cycle in question) is estimated, but the associated height error and radar backscatter coefficient are set to default values. The reference cycle though must have a minimum N=2.

(b) Product Filtering. Differences in height are computed between a particular repeat cycle and the reference cycle, and for each cycle a mean and standard deviation of the height differences are determined. The first series created in the process (internal version 0) then goes through a 2-step process. The first step estimates the mean of the height differences in the time series and then rejects any height difference that has an absolute value greater than or equal to a specified range. This initial height range can be varied, for example ±5m for open lakes, wetlands, and river reaches, or ±25m for reservoirs. The second step re-computes the mean and rejects any height difference if their absolute value is ≥ 1sigma (i.e., 1 standard deviation) larger than the mean. A 100% efficient filtering is not always achievable and in either step, manual intervention via user-defined cut-off ranges is allowed to override the system.

(c) Product Filtering to create a "smoothed" time series in graphical format only. This is a two-step process using the IDL "MEDIAN" and "SMOOTH" functions. The MEDIAN function uses a 30-day window and essentially rejects outliers. The SMOOTH function performs a 5-point (i.e., 5 cycles, or ~50days) smoothing. The smoothed products are a visualization aid only because the functions can introduce small phase shifts and amplitude changes.

F) The Global Mean Inter-Mission Range Bias

For the 10-day products, the ocean science community estimates the *Inter-mission Range bias* during the 6month tandem periods. For a given surface, the T/P, J-1, J-3 and S-6A *Range* estimates are greater than that of J-2 by 16.5cm (T/P), 7.8cm (J-1), 23.0cm (J-3), 22.1cm (S-6A). These values are global means based on fully corrected sea surface heights which have employed the "ocean" retracking algorithm. These bias values are added to the mission's elevations to bring those measurements into alignment with J-2 which is the primary datum used by the science teams and by the GWM system. So, these bias values are added to the height differences (J-2 reference cycle *Height* minus other mission cycle *Height*) in the computation of the time series. In rare instances when J-2 cannot be the datum, then J-3 or S-6A takes over that role, and bias values are first adjusted from J-2 to J-3 (or S-6A) and then the new adjusted value added to the height differences based on the J-3 or S-6A reference cycle.

G) Estimation of Inter-mission Range Bias

<u>*10day Products*</u>: These are based on a suite of follow-on missions employing multi-month tandem periods to allow for the determination of the *Inter-mission Range bias* between the instruments. During the tandem-operating phase in 2002, the J-1 satellite was placed in the same orbit as T/P and lagged only ~1minute behind in observations. During the tandem-operating phase in 2008, the J-2 satellite was placed in the same orbit as J-1 and recorded observations ~1minute ahead of J-1. To merge the 10-day resolution products, the system assumes the J-2 mission (2008-2016) as the reference mission and adjusts the J-3 time series (2016-2022) and the J-1 time series (2002-2008) to merge. The T/P (1992-2002) time series are then adjusted to merge with J-1, and the S-6A series adjusted to J-3. The adjustments are attempted by applying a vertical height shift calculated from finding the mean difference of the elevations of the tandem mission time series during the overlap periods. The process,

i) Assumes a set minimum number (N=2) of height comparisons.
ii) Rejects height pairs that have ≥1m height difference.
iii) Rejects height pairs which have a difference that is not in the 3-sigma range with respect to the mean of all height differences.

If N=1 or N=0, the process applies the *Global Mean Inter-Mission Range bias* values as estimated from ocean surface observations. If *in situ* data or other sources suggest that the applied tandem-period bias estimate or the global mean bias estimate are incorrect, then the *Inter-Mission Range bias* can have a manual override. A summary of the magnitude and type of applied *Inter-mission Range bias* are recorded in the GWM product header files.

<u>*Monthly Products*</u>: The GWM system began to integrate the S-3A and S-3B datasets (27-day repeat) during 2019. Currently, there are no plans to a) merge these with the GWM historical ENV (35-day) products or b) integrate the other historical ERS-1, ERS-2 (35-day) datasets, to create one overall 'monthly' resolution product. When the switch was made by ESA to switch from a 35-day to 27-day repeat orbit, the positioning of the ground tracks changed and so "exact repeat track" methodology could not be applied across the 35-day ESA instrument series. There is also a time gap between the ENVISAT and SARAL missions which would have to look to the application of a *Global Mean Inter-Mission Range bias* to merge their time series products. For now, the 27-day products are a standalone and the 35-day ENV products are only used as a cross-validation source. While the system is primed for creating preliminary SARAL products it has not released these. There is expectation that ESA will continue the relatively new 27-day series into the future.

H) Estimation of Retracker Range Bias

The application of different waveform retracking algorithms will result in variations in the *Range* estimate, for example a *Retracker Range bias* exists between the ocean- and ice-retracking algorithms of J-2. For products of the same temporal resolution, this bias is assumed to cancel out during the product merging procedure, which will compensate for both the *Inter-mission Range bias* and any *Retracker Range bias*. However, for product mergers devoid of an instrument tandem operating period or a tandem period with N<2 height values, a *Retracker Range bias* is estimated for and applied to a particular water body by determining the mean height difference between the various retracking algorithms. For the 10-day products, this mean is derived from the difference between the ocean and ice retracker output of J-2 for co-incident date/time records. For many lakes and reservoirs this ocean/ice retracker bias is ~20cm, but it can be variable and even negative. In some cases, time-coincident ocean and ice J-2 retracked ranges are not available, and so the *Retracker Range bias* cannot be computed and is set to 0cm.

5. Potential Issues and Limitations

With regards to the measurement of inland water elevation via satellite radar altimeters, a number of limitations apply.

i) Global Monitoring: Standard radar altimeters are nadir-profiling only, crossing over a given set of inland water targets at specific location according to their orbit path, which is unchanging over the lifetime of the mission or mission phase. A proportion of the world's lakes and reservoirs for example, are therefore not observed by the instruments.

ii) Surface Acquisition and Minimum Target Size: A variety of factors (including instrument acquisition and tracking logic, the instrument footprint size, the Level 2 dataset's along-track spatial resolution, the severity and complexity of the satellite approach path prior to the water body, and the water extent along the ground track) will affect the ability to acquire and maintain lock on a target's surface, and affect the minimum size of the retrievable target.

iii) Height Accuracy: A variety of factors will also influence the accuracy of the height variations. The *Range* parameter, which is determined from the radar echo, is of prime importance, with knowledge of the wet tropospheric correction being secondary. The precision of the *Range* value can be improved via averaging the elevation values along the ground track, from coast to coast or bank to bank. Due to penetration effects, height measurements over ice- or snow-covered surface may be erroneous. The GWM product output includes an estimate of the mean radar backscatter coefficient for a particular overpass cycle. Overpasses with a mean coefficient >18dB are highlighted (display as open circles in the graph products) to potentially denote calm water or surface ice conditions. Additional open square symbols plotted on top of the circle symbols denotes potential ice-on dates if known. No height correction can be made for wind set-up effects or the influence of tides without ancillary data sets. Heavy precipitation events will also affect height accuracy to a variable degree.

iv) Jason-1 Data Losses: The NASA/CNES J-1 mission employed an on-board algorithm that rejected all non-ocean like radar echoes prior to data download. In addition, any data that passed this algorithm and was downloaded, was further stringently filtered by the ground processing centers, such that a set number of 20-Hz measurements (in a 1-Hz data record block) had to be "valid" for the data to pass through to the IGDR/GDR. Both steps resulted in the loss of data over calmer water surfaces found on small or sheltered lakes, within vegetated-cover wetlands, and on calm-water river reaches. For a sub-set of inland water bodies, the J-1 data is therefore not available.

v) Multi-Platform Product Mergers: The merger of height variation products from multiple missions requires the use of an overlapping ("tandem") period to assist with determination of cross-platform *Range* bias. This bias has been found to be variable at the local scale and so is estimated on a target-by-target basis. The lack of an overlap period results in the application of a *Global Mean Inter-*

Mission Range bias (see Section 4.0 and item F)), which may introduce additional centimeter-scale errors into the merged product across a portion of the final time-period. For example, if J-1 data is absent, a *Global Mean Inter-Mission Range bias* will have to be applied to merge the T/P time series to the J-2 time series.

vi) Single-Platform Multi-Product Mergers: There are two Level 2 datasets associated with each of the S-3A and S-3B missions and these are merged to create a single product with near real time and archive components. The STC are the near real time data and the NTC are the archive data. At any given point in time, there is usually only 1 STC-derived elevation point in the product, because during product updates the last STC-derived height value is automatically replaced by the NTC-derived value, and the latest near real time STC-derived height is added.

6.0 Level 2 Parameter Selection

Based on the height reconstruction equation (2), the outline below summarizes the selection of Level 2 data parameters that are currently employed in the creation of the 1-day, 10-day, 21-day, 27-day, and 35-day inland water GWM products. See Table 4 for mission abbreviations, and the Acronyms section at the end of this document for definitions.

Satellite Altitude and altimetric Range

Acronyms: std=standard, ITRF=International Terrestrial Reference Frame, MLE=Maximum Likelihood Estimator retracking algorithm (for ocean-like waveforms, suited best to large lakes with significant wave presence), OCOG=Offset Center of Gravity (an empirical threshold retracker, a robust algorithm for tracking various surface types, suited to all inland water body types).

Altitude:

T/P: GSFC std1007 orbit (ITRF 2008)
J-1: GSFC std1007 orbit (ITRF 2008)
J-2: GSFC std1007 orbit (ITRF 2008)
J-3: IGDR/GDR orbit standard
S-6A: STC/NTC orbit standard
ENV: GDR orbit standard
S-3A: STC/NTC orbit standard
S-3B: STC/NTC orbit standard
SWOT-NA: IGDR orbit standard

Range (the waveform retracking algorithm):

T/P: "Ocean" based on MLE3
J-1: "Ocean" based on MLE4
J-2: "Ice"
J-3: "Ice"
S-6A: "OCOG" (similar to ice and ice-1)
ENV: "Ice-1" based on OCOG
S-3A: "Ice-1"
S-3B: "Ice-1"
SWOT-NA: "Ice-1"

Altimetric Range Corrections (assumes *instrumentcorr* is already applied to *Range*)

wetcorr:

For lakes and reservoirs, the radiometer-based correction takes priority over any model-based correction value excepting the SWOT-NA for which the model is priority due to observed model versus radiometer correction differences. Across the various missions, the onboard radiometers may be different (e.g., T/P carried the NASA/JPL Topex Microwave Radiometer (TMR), J-2 the NASA/JPL Advanced Microwave Radiometer (AMR), and ENV carried the ESA Microwave radiometer (MWR)). For rivers and wetlands, the model-based correction is utilized. Terrain elevation is taken into consideration in all model-based corrections. If all wet tropospheric *Range* corrections are not available or invalid, *wetcorr* is set to zero but the process continues its reconstruction of the *Height* measurement. Correction choices below are found in the appropriate IGDR/GDR/STC/NTC unless RADS is the option.

T/P:

(i) Primary choice JPL/Re-calibrated Radiometer
(ii) Secondary RADS/ERA
(iii) Tertiary JPL/MERRA

J-1:

(i) Primary choice JPL/Re-calibrated Radiometer
(ii) Secondary RADS/ERA
(iii) Tertiary ECMWF

J-2, J-3, S-6A, ENV:

(i) Primary choice radiometer
(ii) Secondary ECMWF

S-3A, S-3B, SWOT-NA: ECMWF

***drycorr*:**

All 10-,18-,20-Hz height measurements associated with a Level2 1-Hz data point entry become invalid if all *drycorr* options are unavailable. The process moves on to the reconstruction of heights associated with the next Level2 1-Hz point in the Level2 dataset. Terrain elevation is taken into consideration in these model-based corrections. The choices below are found within the appropriate IGDR/GDR/STC/NTC Level 2 datasets unless RADS is the option.

T/P, J-1, J-2:

(i) Primary choice RADS/ERA
(ii) Secondary ECMWF

ENV: ECMWF ERA-interim

J-3, S-6A, S-3A, S-3B, SWOT-NA: ECMWF

ionocorr:

This is set to zero if all options are unavailable, but the process continues its reconstruction of the *Height* measurement. The choices below are found within the appropriate IGDR/GDR/STC/NTC Level 2 datasets unless RADS is the option.

T/P:

For repeat cycles ≤ 135 (prior to 23rd May 1996) the priority is,

(1) DORIS
(2) GIM from RADS
(3) NIC09 from RADS
(4) IRI2007 from RADS
(5) BENT

For repeat cycles > 135

(1) GIM from RADS
(2) NIC09 from RADS
(3) DORIS
(4) IRI2007 from RADS
(5) BENT

J-1:

(1) GIM
(2) NIC09 from RADS

(3) IRI2007 from RADS
J-2, J-3, S-6A, ENV, S-3A, S-3B, SWOT-NA: GIM

Altimetric Height Corrections

earthtide, poletide, loadingtide:
T/P, J-1, J-2, J-3, S-6A, ENV, S-3A, S-3B, SWOT-NA:
Tidal corrections are as per the IGDR/GDR/STC/NTC with the pole tide additionally corrected for Love numbers (a 0.46 scaling factor) for T/P, J-1, J-2, J-3 GDR-D, and ENV. If the *poletide* or *loadingtide* is unavailable in the Level 2 dataset, then its value is set to zero and the *Height* parameter continues to be constructed. However, if the much larger *earthtide* is not available, then a *Height* value is not constructed.

Altimetric Height and Range Correction Validity Ranges

Noting acronyms, U/A=unavailable i.e., when the *Range* and *Height* correction terms are set to defaults, and N/A=not applicable (when *Altitude* or *Range* are set to default and so *Height* is also set to default)

wetcorr	-600mm<value<0mm, set to zero if all options are N/A or U/A
drycorr	value<0mm, the *Height* parameter is rejected if all options are U/A or N/A
ionocorr	-400mm<value<10mm, set to zero if all options are N/A or U/A
earthtide	the *Height* parameter is rejected if this correction is N/A or U/A
loadingtide	set to zero if N/A or U/A
poletide	set to zero if N/A or U/A

7.0 Level 3 GWM Inland Water Products

Currently there are two altimetric product portals that offer water level products created under USDA/FAS or NASA sponsorship,

i) The NASA and US Department of Agriculture (USDA) funded Global Reservoir and Lake Monitor (G-REALM) program (Birkett et al., 2010)
http://www.pecad.fas.usda.gov/cropexplorer/global_reservoir/

ii) The NASA funded Global Water Measurements (GWM) program,
https://blueice.gsfc.nasa.gov/gwm
or
https://earth.gsfc.nasa.gov/gwm/

7.1 Overview

The lake and reservoir water level products are identical on both G-REALM and GWM, though the GWM includes additional very high-latitude and glacial lakes and ultimately aims to provide satellite-derived lake extent, lake storage change estimates, and lake Status Indicators. The G-REALM system was initiated by USDA in 2003 and provides near real time (operational) and archive water level products for global lakes and reservoirs, generally in low-mid latitude regions. The GWM was initiated in 2019 to serve other stakeholders and additionally offers water level products for wetland zones, river reaches, and high-latitude glacial lakes.

Product format is identical within both G-REALM and GWM. Summaries of the graphical and ascii text products are as follows with details provided in Section 7.2. Note that the product versions are included in the product ascii text file header which also contains conversion factors to help translate the relative height variations into geodetic or orthometric (mean sea level) datums.

The 1-day (Figs. 5 and 7) and 21-day resolution products (Fig. 5) are derived from the SWOT-NA and the 27-day resolution products (Figs. 5 and 7) either from Sentinel-3A or Sentinel-3B. The 10-day resolution products (Figs. 5 to 7) are formed from the TOPEX/Poseidon/Jason/Sentinel-6 suite of radar altimeters

spanning 1992 to the present day. To note is the multi-month mission follow-on (or tandem) periods that help determine the *Range* bias between the old and new instruments. This assists with measurement merger when creating a time series (Table 1). These products are based on a single overpass (i.e. a single date) datum taken from the J-2 (primary), J-3 (secondary) or S-6A (tertiary) missions. Currently TPJOJS Version 2.5 (lakes and reservoirs) and Version 2.6.1 (rivers, wetlands and a small number of lakes and reservoirs) products are available (see section 7.2). On both G-REALM and GWM a zoomed-in graph of the last 3years of height variations is additionally displayed to help end users better view the current situation. On the GWM site, an IDL filtered and smoothed version of the product is also available as a visualization aid only. Like the original 10-day products, these smoothed graphs retain height information from both instruments during a tandem overlap period but for the smoothed products there is no interpolation between measurements for missing time periods.
The 35-day resolution products (Fig. 5) are formed from the historical ENVISAT radar altimeter. To note here is that there was no continuity of the 35-day observations after the SARAL mission (Table 1), though the Sentinel-3 instruments offer some measure of a follow-on at 27-day resolution for a subset of lakes and reservoirs flown over by the 35-day repeat orbit. To note also, there is an ~11month time gap in the 35-day series between the demise of the original ENVISAT orbit and the launch of SARAL (Table 1). G-REALM/GWM focus thus remains on the 10-day and 27-day resolution products with 35-day products currently acting as cross-validation sources, though a sub-set have been released to the portals. The current 35-day products on GWM ad G-REALM are an upgraded version (ENV2.1) based on the availability of a revised Level 2 dataset.

<u>Auxiliary Information</u>

i) Both G-REALM and GWM offer a view of the satellite ground track location across the target. This is crucial as it guides the user as to the exact location of where the instrument is sampling the surface water. For example, satellite overpasses far from dam locations, or at the outer limits of a lake, may not record the full seasonal variation. Height variations within river reaches and wetlands will certainly be location dependent.
ii) Both G-REALM and GWM offer a view of the target's reference cycle height profile with respect to the T/P and WGS84 geodetic datums and the orthometric (mean sea level) datums. The geoid model profiles are also displayed. The reference cycle profile is converted to an orthometric datum after translation to WGS84 and the application of a geoid model. Current geoid models in use are EGM96 (15'x15' resolution) and EGM2008 and EIGEN6C4 (1'x1' resolution). The datum translations are reported in the header block of the product ascii text files as "Conversion Factors".
iii) GWM offers background information on the reservoir water use, the reservoir formation year, the approximate winter ice-on period, and a range of Status Indicators to help identify short- and long-term drought or re-charge conditions. It also offers "Product Advisories" which single out and highlight potential issues which may have to be taken into consideration when time series analysis is being performed for research investigations.
iv) Both G-REALM and GWM allow viewing and downloading of all graphical and ascii text products, for both a single water body, or the global data product set.

Figure 5. Examples of surface water level products for lakes and reservoirs*. Examples include high-latitude Lake Aropuk (USA) and a selection of lakes in Africa. The graphs depict, Lake Aropuk (at 1-day resolution), Lake Kariba (at 10-day resolution), Lake Nzilo (at 21-day resolution), Lakes Albert_1 and Wamala (at 27-day resolution), and Lake Chilwa (at 35-day resolution). The 10- and 27-day measurements are part of a continuity series, while additional radar and lidar measurements serve as validation checks. The GWM products offer relative height variations and absolute (orthometric) height values and include the actual variations (shown here) and a smoothed version.*

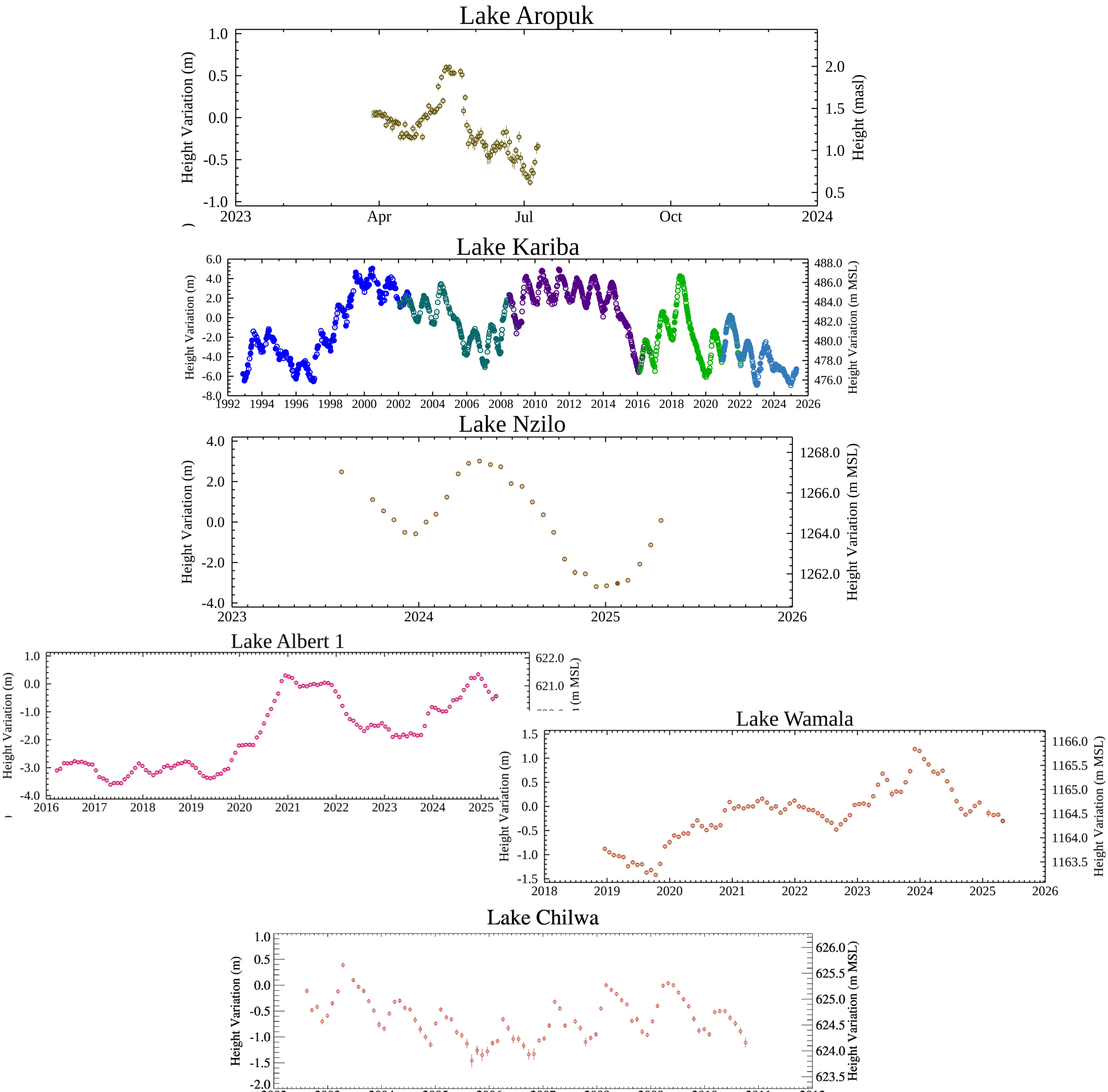


Figure 6. Example of a reservoir surface water level product at 10-day resolution. *The GWM graphical product for the Cahora Bassa reservoir, Mozambique, as shown on the GWM portal. The 10-day products are appended results from 5 different missions. In addition to the actual variations (top) and a smoothed version (bottom), there is a zoomed in plot representing the last 3years (center). The legend defines the processing version, mission datasets, water body ID, satellite overpass number, the repeat cycle used as the reference cycle (datum) and the last valid elevation date. At the top of the page, clickable tabs and options allow end users to view additional water body and product-related information. The color of the tear-shaped symbol represents current water level status in comparison to a historical mean, and this is provided for lakes and reservoirs only.*

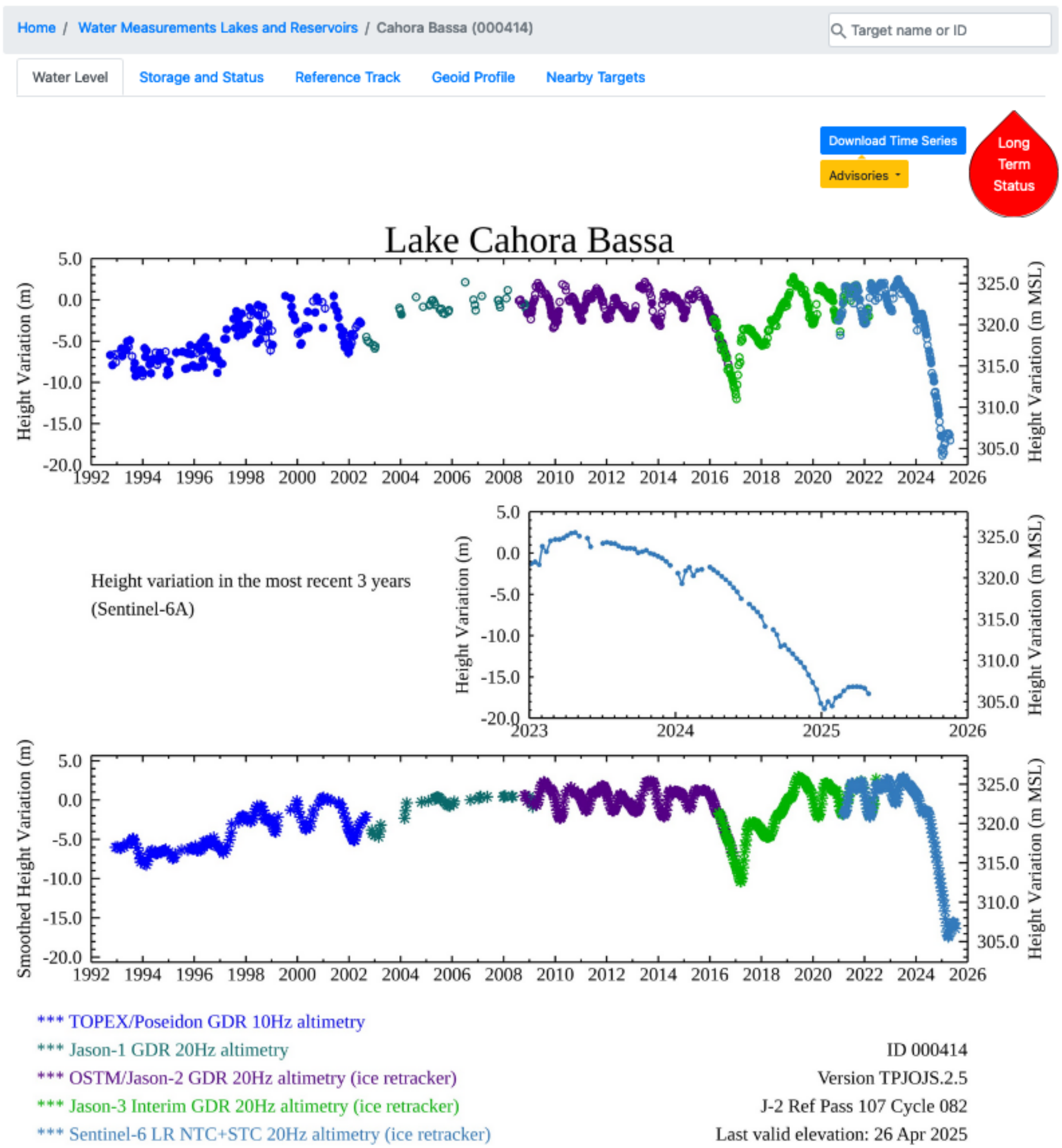
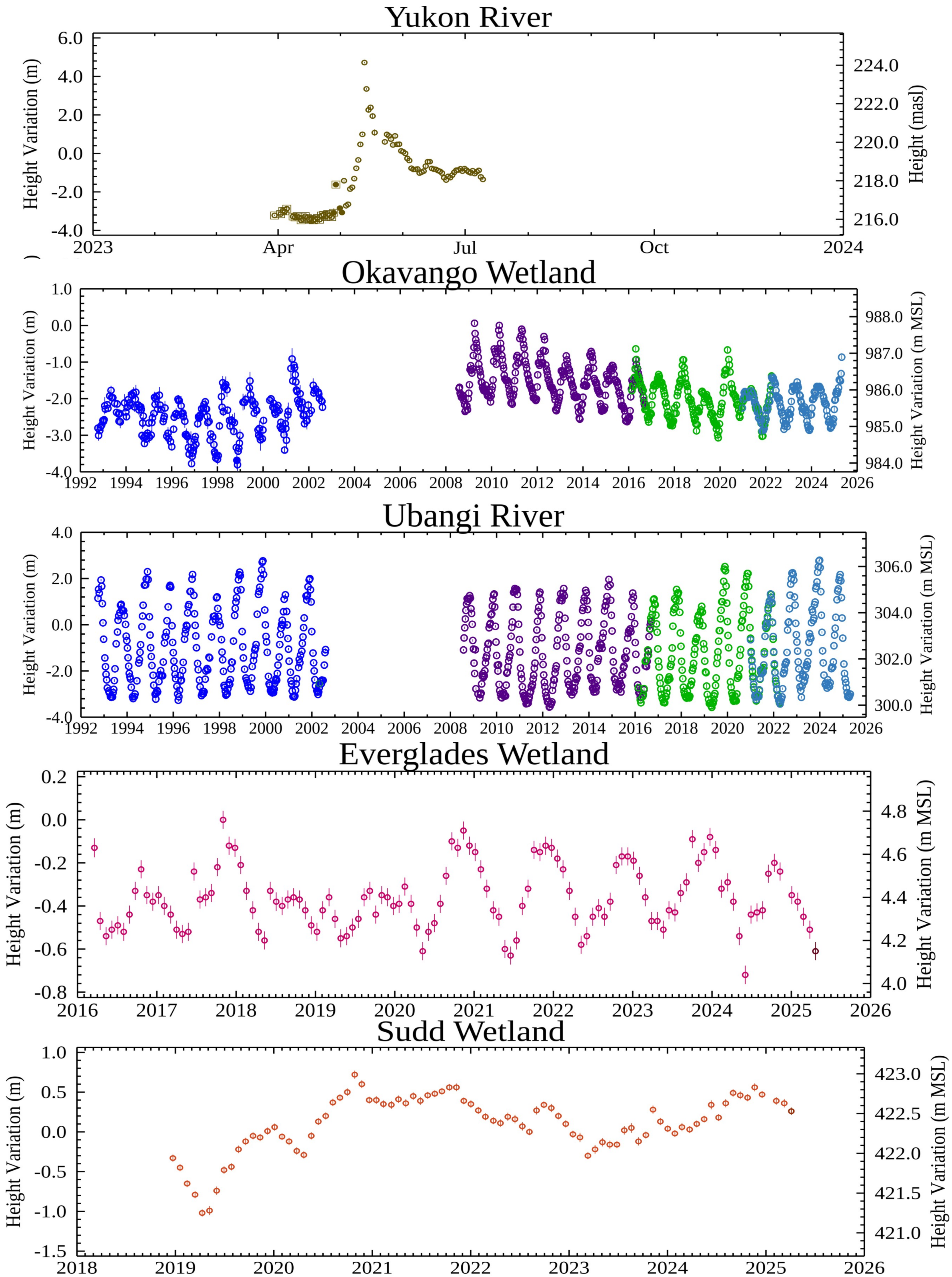


Figure 7. Example of surface water level products for rivers and wetlands. *Examples include the Yukon River, Alaska, USA (1-day resolution), the Okavango Delta, Botswana (10-day resolution), the Ubangi River, Democratic Republic of Congo (10-day resolution), the Everglades, USA (27-day resolution) and the Sudd wetlands, South Sudan (27-day resolution). The lack of measurements during 2002-2008 for the Okavango and Ubangi River is due to an on-board Jason-1 technical fault that resulted in loss of data when surface conditions were very calm and highly reflective.*



7.2 Name Conventions

These are graphical and ascii text file formats and conform to the following convention.

- A four-digit ID number is assigned to each water body, e.g. 0314 is the large Lake Victoria in Africa. The first digit of the four is set to 0 to 7 for lakes/reservoirs, 8 for river reaches and 9 for wetlands. This 4-digit is then right-embedded into a 6-digit product ID number. The first digit of the 6 represents the number of altimeter products available for the water body. The 2nd digit of the 6 is currently not utilized and is set to zero. The first digit of the 6 is always set to =0 for the first water level product attempt, it can then take values =1 to 9 for additional attempts provided by other satellite passes (of a single instrument) or other instruments, if time series products are found to be poor or the overpasses not in the most ideal location.
- Lakes and reservoirs around the globe may have the same name so we distinguish their names by appending additional numbers, so Lake Victoria in Africa becomes "Victoria_1". If a reservoir is named after the dam which is one in a series or cascade, then the reservoir takes the dam's name with an appended dam/gate/lock/weir number in Roman numerals, e.g., "Grand_Riviere III". However, these nuances only affect the water body name that is embedded within the products.
- Actual product names (Table 5) distinguish between water bodies via designation of a water body "type" (lake, river or wetland) and a six-digit ID number. The six digits are two additional digits added to the left of the four-digit water body ID. So, for example, the 10-day products for Lake Victoria_1 in Tanzania take the names lake000314.10d.2.gif and lake000314.10d.2.txt where 10d denotes the 10-day repeat frequency of the measurements. The first digit of the six is set to =0 to 9, allowing up to 10 time series to be assigned to a single water body derived from multiple locations and/or instrument platforms. This is a useful tool in the process if the first time series attempt is found to be poor or highly location dependent. Note that the graphical products are gif (G-REALM) and jpg (GWM), and the associated ascii text files (*.txt) are the same filename format. Current graphical product name format examples are,

Table 5. *GWM product name, type and version number*

Product Name	**Product Version (April 30th, 2025)**
01-day (short-term archive plus near real time)	
lake201878.01d.2.jpg	SWOT-NA.01d.1.0
river008048.01d.2.jpg	SWOT-NA.01d.1.0
10-day (long-term archive plus near real time)	
lake000314.10d.2.gif	TPJOJS.2.5
river08000.10d.2.jpg	TPJOJS.2.6.1
wetland009021.10d.2.jpg	TPJOJS.2.6.1
21-day (short-term archive plus near real time)	
lake401296.21d.2.jpg	SWOT-NA.21d.1.0
27-day (short-term archive plus near real time)	
lake001854.27a.2.jpg	S3A.3.1
river008233.27a.2.jpg	S3A.3.1
wetland009901.27a.2.jpg	S3A.3.1
lake000705.27b.2.jpg	S3B.3.1
river008366.27b.2.jpg	S3B.3.1
wetland009511.27b.2.jpg	S3B.3.1
35-day (ENVISAT, archive only)	
lake001547.35d.2.gif	ENV.2.1

1-day and 21-day products are derived from SWOT-NA, 10-day from the TOPEX/Poseidon, Jason and Sentinel-6 suite, 27-day from either Sentinel-3A or Sentinel-3B, and 35-day from ENVISAT. The 10-day products are version 2.5 (lakes and reservoirs) or version 2.6.1 (river reaches, wetlands, and some small lakes). The *.2.gif (or *.2.jpg) and *.2.txt products are created utilizing a datum based on a single satellite overpass on one given date. The GWM portal also uses the Jason-2 operating period as a long-term datum for its additional Status Indicators information (not discussed in this ATBD).

7.3 Ascii Text Layout

The G-REALM and GWM product text files contain a header block and measurements table. For the 10-day products, measurements will be provided from both operating instruments during the overlapping tandem phases i.e., there may be 2 height measurements on a single day spaced only 1 minute apart.

<u>Header Block Line Content</u>

Line1: Data product and system processing version
Line 2: Target ID and name
Line 3: Latitude/Longitude for the target mid-point
Line 4: Start/End latitude where elevation data is accepted on the ground track (Note 1)
Line 5: Satellite pass and revolution number
Line 6: Reference Pass cycle number
Line 7: Radar echo retracking algorithm used for *Range* determination (see Section 6)
Lines 8-11: *Range bias* values. This is specific to the 10-day products and is defaulted in all other resolution products. For the majority of targets the *Range* bias is with respect to Jason-2 but can be with respect to Jason-3 or Sentinel-6A. Lines 8 to 11 below are assuming Jason-2 is the datum but are modified when either of the other two datum are being utilized.

- Line 8: Range bias (meters) applied to append the Sentinel-6A time series
- Line 9: Range bias (meters) applied to merge the Jason-3 time series
- Line 10: Range bias (meters) applied to merge the Jason-1 time series
- Line 11: Range bias (meters) applied to merge TOPEX/Poseidon time series

Lines 12-34: Datum Conversion Factors
Lines 35-50: Measurement Table column descriptions and default values

<u>Measurements Table</u>

Columns 1+2	Satellite mission and repeat cycle
Column 3	Year/Month/Day (at overpass mid-point)
Columns 4+5	(UTC) Time in hour/minutes
Column 6	Mean relative surface height (meters) with respect to reference cycle (Note 2)
Column 7	Height error estimate (meters) (Note 3)
Column 8	Mean radar backscatter coefficient (dB) (Note 4)
Columns 9+10+11	The choice of wet troposphere/ionosphere/dry troposphere atmospheric corrections utilized in the height construction. If the choice varies across a target, then the most frequent correction is reported. If frequency is equal, then the column will state 'MIX'.
Columns 12+13	Instrument acquisition (12) and operating (13) modes (See Section 2.5)
Column 14	Flag to highlight potential winter ice-on conditions
Column 15	Surface height converted to the EGM2008 datum (meters)
Column 16	Original dataset source, archive (=0) or near real time (=1)

Notes

[1] If multiple sections of a ground track are used, these are the first latitude of the first section, and the last latitude of the last section.

[2] The relative surface height values may be set to a default 999.99 if the original satellite data set primary

parameters (e.g., Date and Time, Range, Orbit) are defaulted. This condition can be set due to mission or instrument factors. In addition, a default height value is also set if the *drycorr* or *earthtide* parameters are either unavailable (U/A) or outside their validity range (not applicable or N/A) for the entire cycle. If the *wetcorr*, *ioncorr*, *poletide*, and *loadingtide* are U/A or N/A, then these parameters are set to zero, and the surface height field is still constructed with notable warning flags in the product ascii text file columns for *wetcorr* and *ionocorr* (columns 9 and 10).

[3] An attempt is made to provide an estimate of the error on the height value. This error is a combination of a) the standard deviation value determined when estimating the mean of the height differences (between the reference overpass and another overpass) for a given cycle, and b) a constant value specific to the instrument series and type of wet tropospheric range correction applied. For all products this constant is 4.2cm when the radiometer-based *wetcorr* utilized, or it is set to 5cm when the model-based *wetcorr* is utilized. It is also set to 5cm if both radiometer and model-derived *wetcorr* are U/A or N/A. If the i*oncorr* is U/A or N/A the constant is not increased to reflect this omission.

[4] The backscatter coefficient values are related to the chosen *Range* parameter and thus the employed radar echo waveform retracking algorithm. For T/P and J-1, the backscatter coefficient is based on the ocean retracker. For J-2, J-3, S-3A, S-3B, ENV, S-6A, and the SWOT-NA, it is based on the ice (or ice-1 or OCOG) retracker. The mean backscatter coefficient value is computed across the target excluding default values and those outside specified backscatter validity ranges.

Table 6. *Radar backscatter coefficient validity ranges*

Satellite Mission	**Radar Backscatter Coefficient Validity Range (dB)**
TOPEX/Poseidon	5-42
Jason-1	5-50
Jason-2	5-60
Jason-3	5-60
Sentinel-6A	5-60
ENVISAT	5-60
Sentinel-3A	5-70
Sentinel-3B	5-70
SWOT-NA	5-70

7.4 Quality Indicators

a) The quality of the altimetric height variations can be validated via two methods,
   i) via comparison with *in situ* gauge-based data (absolute validation).
   ii) via comparison with results from a synergistic altimetric mission (relative validation).

Validations can be performed via comparisons between height measurements on the same day, sometimes additionally interpolated to the same time. The 1-day/21-day, and 10-day resolution missions are not sun-synchronous, so the local satellite overpass times vary. The 27-day and 35-day resolution missions are sun-synchronous, so the local overpass times for each repeat cycle remain constant. Validation exercises show that a time series of altimetric water level variations can be accurate to 3-5cm rms for the very largest of lakes (e.g., Lake Victoria_1 in Tanzania, the Great Lakes in the USA), reducing to 10 to 30cm rms for smaller lakes, river reaches and wetlands (Birkett 1995, 1998, Ricko et al., 2012).

b) The products contain indicators to help end-users consider elevation accuracy across a time series and to highlight potential erroneous measurements. In general though, the more recent satellite missions (J-2, J-3, S-3A, S-3B, S-6A, SWOT-NA) have a combination of improved onboard tracking software, data processing, and high spatial resolution, that enable an improved capture of water level surface in smaller lakes and river reaches than their historical predecessors, T/P and J-1. While this can't be quantified, this should be noted.

c) Both graph and text product files aim to highlight potential winter ice-on conditions. Because microwaves can penetrate ice-cover to unknown depths, freeze periods must be noted.

d) Within the product text files,

- For the 10-day products the ascii text product files contain a header block that advises on the merger validity of the measurements from the available instrument suite. The presence of "Global Mean Bias" in this block is a potential red flag but need not signify a 100% error.
- Column 7 provides a height error which is statistically correlated with the number of elevation measurements available across the reach. It is a first order estimate, and in cases where N=1 (i.e., 1 available height across the reach width) this error estimate is set to a default value.
- Column 8 provides a mean radar backscatter value. Typical values are ≥10dB (lakes), ≥18dB (rivers, wetlands, small calm lakes) though some variations can arise. Values <10dB could be indicative of radar echo returns from land and a defaulted value (999.99) may suggest an erroneous height measurement.
- Columns 9 and 11 indicate what type of *wetcorr* and *ionocorr* have been applied. If either value has a default value but a non-default *Height* exists in column 6, this indicates that *Height* has been constructed without a valid *wetcorr or ionocorr*. The consequence on the accuracy of the time series depends on the atmospheric variation of the region. For example, a tropical region may have constant humidity and so the absence of *wetcorr* is negligible on a <u>relative</u> height change series. However, *wetcorr* can be seasonally variable with values up to 0.5m, and this will reflect heavily on the accuracy of the time series if absent.
- Column 15 provides the reach height within a mean sea level frame. In this case, this datum conversion is based on the EGM2008 global geoid. Like all geoid models, this will contain errors that are geographically variable. It is difficult to quantify such errors.
- Column 16 indicates whether the height measurement has been derived from the archive (potentially more accurate) or near real time dataset.

e) The GWM portal provides a list of general "Advisories" including,

- *Series mission-merger compromised*
  For time series created from multiple instrument platforms. This is a warning that the appending of one set of measurements to another may have an elevation bias.
- *Regulated water levels or Anthropogenic effects*
  Presence of a dam or known human interference on water storage.
- *Mid-series reservoir formation*
  Dam completed at a date that is within the time series period.
- *Overpass skims coastline/riverbank or Overpass is far from dam*
  The satellite reference ground track skims the target or the ground track is a significant distance from the dam. The time series may not reflect the full seasonal amplitude.
- *Data Capture compromised*
  The instrument is "toggling" between two or more surfaces. The surface acquisition is compromised for a considerable number of cycles. The correct water surface is not always observed.
- *Data capture DEM compromised*
  Incorrect on-board pseudo-DEM settings have partially compromised the time series.
- *Ramping*
  The instrument may not have 100% successfully gained lock onto the water surface.
- *Narrow water crossing*
  Set if widths are <1km for rivers and <3km extent width for lakes and wetlands.
- *Winter ice or High Latitude/High Altitude*
  The water body is known to freeze and over what general period. If the time-period is unknown,

then this advisory is set if the water body is situated at high latitude/altitude.

- *Potential seiche/wind effects*
  The water body has sufficient fetch to cause elevation oscillations (a shift in surface gradient).
- *Shallow waters or Ephemeral*
  Set if mean depths are typically only a few meters or the lake contains water only sporadically.
- *Desiccated*
  The water body appears to be in drought or disaster mode, i.e., land is partially or fully exposed over the satellite observation period.
- *Complex region*
  The water body is situated within or near a wetland or a multi-pool zone.
- *Braided reach*
  The river is divided into many braids.
- *Channel islands*
  One or more major islands are near the satellite overpass ground track position.

8.0 References

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The USDA/FAS Global Reservoir and Lake Monitor portal,
https://ipad.fas.usda.gov/cropexplorer/global_reservoir/

The PODAAC lake level products as derived for the NASA MEaSUReS project,
https://podaac.jpl.nasa.gov/dataset/PRESWOT_HYDRO_L2_GREALM_LAKE_HEIGHT_V2

The Delft University of Technology RADS database of satellite radar altimeter parameters,
http://rads.tudelft.nl/rads/rads.shtml

AVISO Satellite Pass Locator,
https://www.aviso.altimetry.fr/en/data/tools/pass-locator.html

9.0 Acronyms

ATBD	Algorithm Theoretical Basis Document
AVISO	Archiving, Validation and Interpretation of Satellite Oceanographic Data
CL	closed loop
CNES	Centre National d'Etudes Spatiales
dB	decibels
DD-SAR	Delay Doppler Synthetic Aperture Radar
DEM	Digital Elevation Model
DIODE	Détermination Immédiate d'Orbite par DORIS Embarqué
DORIS	Doppler Orbitography and Radiopositioning Integrated by Satellite
ECMWF	European Centre for Medium Range Weather Forecasting
EGM	Earth Gravitational Model
EIGEN	European Improved Gravity model of the Earth by New techniques
EML	Echo Masking Loop
ENSO	El Niño Southern Oscillation
ENVISAT	Environmental Satellite
ERA	ECMWF Reanalysis (atmospheric, land, and ocean, climate variable dataset)
ERS	European Remote Sensing Satellite
ESA	European Space Agency
ESDRs	Earth Science Data Records
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
GDR	(I=Interim) (M=Merged) Geophysical Data Record
GEODYN	NASA/GSFC orbit determination and geodetic parameter estimation software
GEOSAT	Geodetic Satellite
GIM	Global Ionosphere Model
GPS	Global Positioning System
G-REALM	The Global Reservoir and Lake Monitor
GSFC	Goddard Space Flight Center
GWM	Global Water Measurements (NASA system and web portal)
HEP	Hydro Electric Power
HRM	High Resolution Mode (SAR processed)
HY	Haiyang (ocean satellite series)
ID	Identification (water body number)
IDL	Interactive Data Language
IRI	International Reference Ionosphere
ISRO	Indian Space Research Organization
ITRF	International Terrestrial Reference Frame
JPL	Jet Propulsion Laboratory
KBR	Kellogg Brown and Root
lat	latitude
lon	longitude
LRM	Low Resolution Mode (not SAR processed)
MEaSUReS	Make Earth Science Data Records for Use in Research Environments
MERRA	Modern-Era Retrospective Analysis for Research and Applications
MF	Michael Freilich
MJD	Modified Julian Date
MLE	Maximum Likelihood Estimator
(A)(T)MR	(A=Advanced) (T=TOPEX) Microwave Radiometer
MWR	Microwave Radiometer

N/A	Not applicable
NASA	National Aeronautics and Space Administration
NIC09	NOAA Ionosphere Climatology 2009 model
NOAA	National Oceanic and Atmospheric Administration
OCOG	Offset Center of Gravity
OL	Open Loop
OSTM	Ocean Surface Topography Mission
PI	Principal Investigator
PODAAC	Physical Oceanography Distributed Active Archive Center
RADS	Radar Altimeter Database System
RGT	Reference Ground Track
RMC	Range Migration Correction
Rms	Root mean square
ROSES	Research Opportunities in Space and Earth Science
SAR	synthetic aperture radar
SARAL	Satellite with Argos and Altika
Seasat	Sea Satellite
SLR	Satellite Laser Ranging
Std	Standard
SWOT-NA	Surface Water and Ocean Topography Nadir Altimeter
TBD	To Be Done
TBR	To Be Reviewed
(N)(S)TC	(N=Non) or (S=Short) Time Critical
TOPEX	Ocean Topography Experiment
TUDelft	Delft University of Technology
U/A	Unavailable
USDA/FAS	US Dept. of Agriculture/Foreign Agricultural Service
USGS	United States Geological Survey
UTC	Universal Time Coordinated
WGS84	World Geodetic System (gravity model released in 1984)