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Algorithm Theoretical Basis Document (ATBD)

Stream Stage Measurements: V2.5.1 Water Level Products from Satellite Radar Altimetry

Charon Birkett, Martina Ricko and Xu (Hunter) Yang

January 2021

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1. Introduction

1.1 Overview

Satellite-based radar altimetry has been utilized for inland water applications for several decades. Originally designed for sea surface mapping, the scientific objectives developed to include the mapping of ice sheets and sea ice, and the recording of water-level variations within lakes, reservoirs, river channels and wetland zones. Techniques that were once exploratory are now well documented and validated, and altimetric datasets are mature and promptly distributed. The satellite datasets are utilized by several organizations who create higher-level, time series products of surface water level variations. These are distributed via the world-wide-web with accompanying technical notes on quality and application, with underlying methodologies described in peer-reviewed publications. While conventional radar altimetry instruments (i.e., pulse limited, single nadir-beam profiling, operating at Ku- or Ka-band) have provided the community with multi-decadal sets of water level observations, more enhanced delay doppler and swath radar altimeters, and multi-beam lidar altimeters, are set to improve spatial resolution and the minimum size of water body or reach width that can be observed.

1.2 Project Context and Applications

Knowledge of stage height (i.e., surface water level) and discharge at specific river locations is critical. These parameters assist a variety of science studies and applications. The latter includes elements such as flood preparation and response, the design of bridges, roads, and dams, the management of irrigation, municipal and industrial water supply systems, and the planning of land use and recreation. The potential effect of climate change on all applications is duly noted. Ground-based operational river monitoring relies on costly in-situ methods and currently does not take advantage of the technological advancements in remote sensing. While the objectives of the future Surface Water Ocean Topography (SWOT) mission include the estimation of variations in river discharge, there is no current plan to incorporate those data into operational decision support systems.

One step forward is to explore currently available satellite data with a focus on a remote region that has a sparse river gauge network, and to test operational river product development and applicability according to the requirements of a group of designated stakeholders. The State of Alaska makes for a prime study region with the Alaska Department of Transportation and Public Facilities (ADOT&PF) and the Alaska-Pacific River Forecast Center of the National Weather Service (NWS-APRFC), to name just two natural resource management agencies, requiring improved river monitoring services. ADOT&PF uses gauge data to design bridges and manage highway operations during floods while NWS-APRFC uses the data to calibrate and run models that continuously forecast river conditions and warn the public about impending floods. The integration of National Aeronautics and Space Administration (NASA) and other international satellite observations with hydraulic models would help build an operational system for stage and discharge estimation and dissemination, and thus improve the operations of agencies such as ADOT&PF and NWS-APRFC.

US Geological Survey (USGS) researchers (e.g., Bjerklie et al., 2018) have undertaken preliminary remote sensing river studies in Alaska and highlighted the merits of satellite data for those river and stream locations that are too hazardous or expensive to monitor with existing methods and resources. It was proposed that remotely sensed stage and discharge could be ingested into the USGS online National Water Information System (NWIS), for public dissemination. End-users, such as ADOT&PF and NWS-APRFC, could then integrate this new data into existing dataflows, decision-support systems, and operations that currently depend solely on NWIS ground-based stream gauge data.

1.3 Objectives of this Document

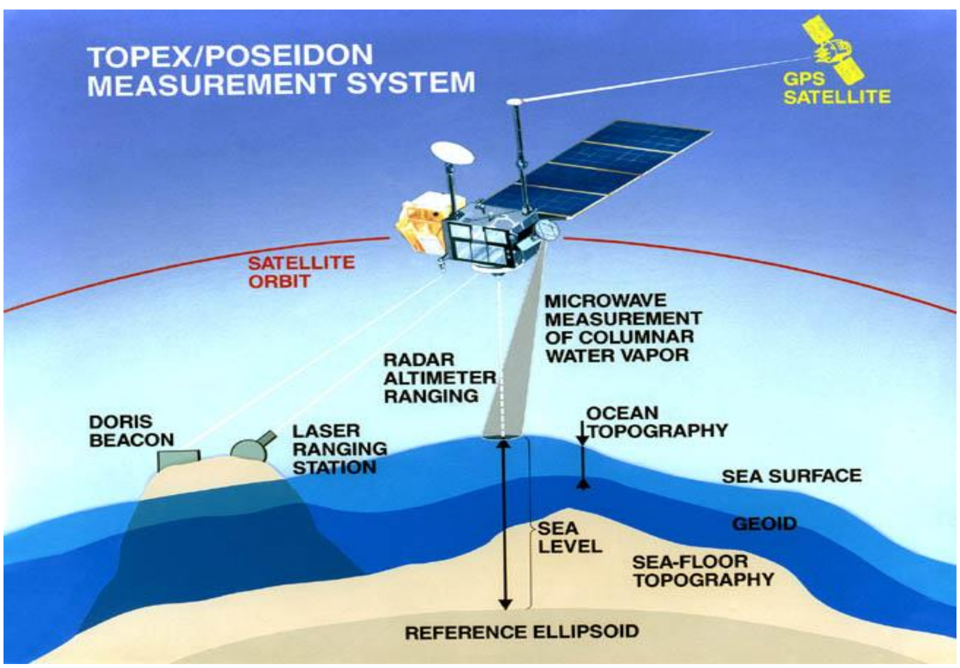
In response to the 2018 NASA ROSES Applied Sciences/Water Resources (NASA HQ Program Official: Dr. Brad Doorn) call for proposals, the “Integration of Remotely Sensed Streamflow Data into Alaska Water Resource Management Agency Operations” project with Principal Investigator (PI) Jack Eggleston USGS, was successful, and had the ultimate goal of creating a series of remotely sensed or derived Alaska river parameters for integration into NWIS. These parameters included surface water height and average reach surface water slope (from altimetry), average reach width (from Landsat imagery), and an associated river discharge derived via theoretical means. The surface water height products were required to have both archival and near real time components, noting the availability of ~25years of potential measurements, and accepting the temporal resolution (10-35days) of the suite of radar altimeters. Each surface water level product was expected to be a continuous time series of observation with a sufficient accuracy to highlight monthly, seasonal and interannual variation. The designated set of river reaches were chosen for their geographical distribution, their reach width, and the presence of a radar altimeter mission satellite overpass. ***This document describes the procedure associated with the creation of these altimetric surface water level products and is relevant to product Version 2.5.1 available from the Global Water Monitor (GWM) web portal.***

2. Theoretical Framework

2.1 Algorithm Details

Satellite radar altimeters operate by emitting a microwave pulse towards the surface (at nadir) and timing the return of the echo at the antenna. 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 (*Orbit*), the height of the surface is then derived (Fig.1). 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 datasets/models. The *Range* term (equation 1) must be corrected for the effects of atmospheric pressure (*drycorr*), and the presence of water vapor (*wetcorr*) and ions (*ionocorr*) in the atmosphere. The surface height (*Height*) is constructed (equation 2) with corrections for solid earth (*earthtide*), pole (*poletide*), and ocean loading (*loadingtide*) tidal effects. For the derivation of river 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 river reaches within (Birkett, 1998).

Figure 1*. Satellite Radar Altimetry Technique. Figure courtesy of the NASA/California Institute of Technology Jet Propulsion Laboratory (JPL).*

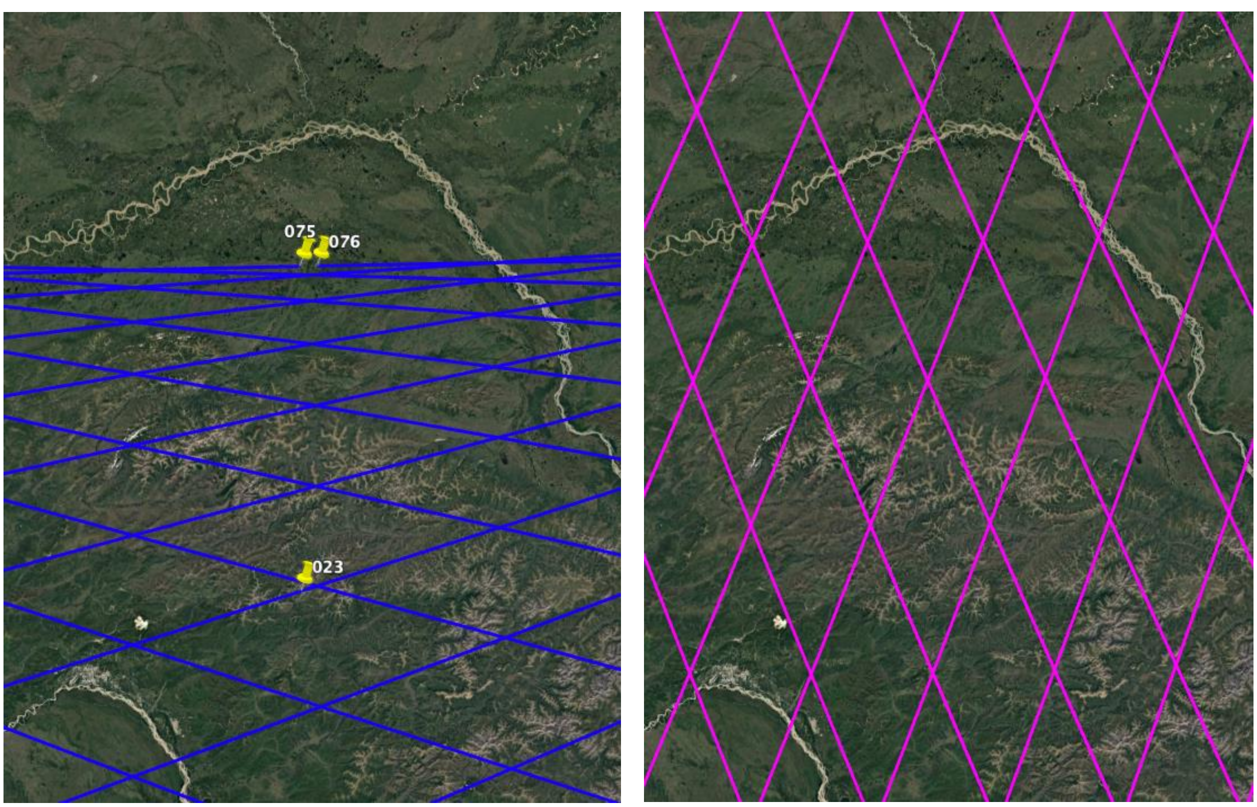


$$Range_{corr} = Range + instrumentcorr + wetcorr + drycorr + ionocorr \quad (1)$$

$$Height = (Orbit - Range_{corr}) - (earthtide + poletide + loadingtide) \quad (2)$$

The final altimetric surface height, *Height*, is constructed with respect to a reference ellipsoid datum, typically the datum specifically defined for the TOPEX/Poseidon mission which has an equatorial radius of 6378.1363km and a flattening coefficient 1/298.257. The building of a time series of water level variations relies on "repeat-track" techniques. This utilizes the fact that the altimetric missions are placed in repeat-cycle orbits, essentially re-visiting the same location on the earth's surface within a specified time period. The NASA-related missions must repeat their ground tracks to a required ±1km, though in practice a much tighter ±250m is often achieved. With nadir viewing, the instruments follow a reference ground track, continuously emitting and receiving pulse/echoes along a narrow swath (Figure 2). These ground tracks correspond to ascending or descending satellite passes, and the resulting *Height* values are constructed with a 10-, 18,- 20-, or 40-Hz along-track spatial resolution (Table 1). From bank to bank, reach surface heights are therefore potentially obtainable every few hundred meters along the ground track.

***Figure 2**. Ascending and descending satellite overpasses from the nadir pointing instruments. Each overpass has a corresponding ground track, and the spatial resolution of height data along each track is a few hundred meters. The density of ground tracks will depend on the repeat cycle of the mission, and each mission will have a latitude observation limit. The example is for a far North section of the Yukon River, (left) 10-day ground tracks (blue) from the TOPEX/Jason instrument series extending to only ~66˚North, and (right) 27-day ground tracks from the Sentinel-3A mission (pink) which extending to ~81˚North. (Image courtesy of Google Earth).*



The satellite ground track locations are fixed once the satellite repeat cycle is selected. Because the instruments are profiling only, a river basin will have multiple ground tracks depending on its size, but those reach crossing locations will be fixed. To additionally note is that each satellite mission has a geographical northern/southern observation band (Figure 2). For the 10-day resolution instruments this is ±66˚, and for the 27-day resolution instruments this is ±81˚. Each altimeter therefore crosses over specific reach locations (Figures 2 and 3) and each overpass will record the surface height of the water from bank to bank at set spatial resolutions along the ground track.
For a given satellite overpass or ground track, the creation of a time series of water level variations employs repeat track methods. These include the creation or designation of a reference overpass (which acts as zero datum) to which all other overpasses are compared to, and the use of interpolation to shift all dataset height values to a common time/latitude/longitude grid to account for slightly variability in the ground track locations. Often, the reference overpass or datum, is formed from an average of the all the height information on all ground tracks over a given time interval, or it can be formed from the height information along the overpass on one specific date. In any case, the reference datum is not a spot height, but a height profile across the reach. The advantage of using an average 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 the narrower reaches, and a datum based on a single date overpass is often preferred. In either case, the heights along a satellite overpass are compared to those along the reference pass, and a mean and standard deviation of the height differences is calculated. This is repeated for each overpass, until a time series of *relative* water height variations is created. For climatic or dynamic interpretations, relative water level variation products are acceptable, but they can be converted to an orthometric frame (approaching a mean sea level datum) via the introduction of a geoid model noting these models will have varying error at different reach locations.

Figure 3. *Comparison of a 'monitoring' versus 'mapping' altimetry mission with respect to ground track density. (Left) the monitoring mission ground tracks striking (white circles) the Tanana River near Fairfax at 10-day (blue), 27-day (pink, cerise), and 35-day (red) repeatability. (Right) the Cryosat-2 mapping mission ground tracks over the same region with a repeat period of approximately 1year.*

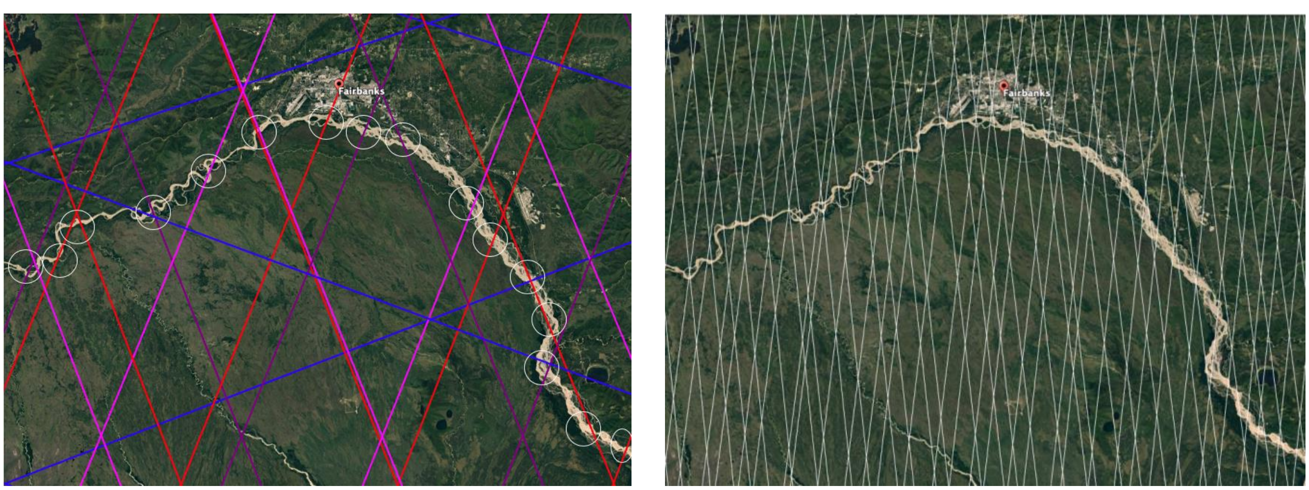


Table 1: Short-repeat Satellite Radar Altimeter Missions. These are 'monitoring' missions with low spatial ground track density but high (within a month) temporal resolution. They can be utilized for building time series of elevation variations at a given fixed reach location. Currently Global Water Monitor river reach products have a 10-day or 27-day temporal resolution utilizing the TOPEX/Jason instrument series and the Sentinel-3A mission data (highlighted in blue below).

Mission	Agency	Frequency	Time Period	Resolution	
				Spatial(m)	Temp(days)
ERS-1 phase A	ESA	Ku	1991	350	3
ERS-1 phases B&D	ESA	Ku	1992-1992, 1993-1994	350	3
TOPEX/Poseidon	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-present	290	10
Sentinel-6 Michael Freilich	Consortium	Ku/DD-SAR	2020-present	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-present	290	10
HY-2A	CNSA	Ku	2011-present	290	14
Seasat	NASA	Ku	1978	670	17
Geosat	NRL	Ku	1986-1990	670	17
GFO	NRL	Ku	2000-2008*	670	17
SWOT	NASA/CNES/CSA	Ka/Interferom	launch2021	<100#	<22
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**	350	35
ENVISAT	ESA	Ku	2002-2010, 2011-2012+	350	35
SARAL	ISRO/CNES	Ka	2013-2016	175	35

* *From 2006 GFO operated with a reduced continental coverage.*

\# *Spatial resolutions are a combination of conventional altimeter along-track data posting rates (e.g., 10-Hz TOPEX/Poseidon, 18-Hz ENVISAT, 20-Hz Jason-1, Jason-2, Jason-3, Sentinel-3, and 40-Hz SARAL), SAR resolution cells, and the distance over which a set of pixels are averaged.*

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

\+ *Between May 2002-Sept 2010 ENVISAT operated from its nominal 35-day repeat orbit but from Jan 2011-April 2012 it operated in a modified repeat orbit with less global data download.*

Table 2: Long-repeat Satellite Radar and Lidar Missions. These are 'mapping' missions with high spatial ground track density but low temporal resolution. They could be utilized for reach slope estimation.

Mission	Agency	Frequency	Time Period	Resolution	
				Spatial(m)	Temp(days)
ERS-1 phases E&F	ESA	Ku	1994-1995	350	168
ICESat-1	NASA	laser 1064nm	2003-2009	175	91+
CRYOSAT-2	ESA	Ku, DD-SAR&SARIn	2010-present	300x1000	369
SARAL drift phase	ISRO/CNES	Ka	2016-present	175	drift
ICESat-2	NASA	multi-beam laser 532nm	2019-present	0.7-3.0#	91&drift

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

\# *Icesat-2 operates with a 91-day repeat. At low-to-mid latitudes off-nadir pointing will allow 'fill-in' of spatial sampling, effectively resulting in a long-temporal repeat mapping mode. Icesat-2 along-track sampling is variable depending on the number of laser shot returns being averaged.*

2.2 Algorithm Description

This NASA-sponsored program provides altimeter-derived surface water level products for river reaches in an operational framework. The platform for product delivery is the Global Water Monitor (GWM) web site (Figure 4) which is a test platform for delivering lake, river and wetland satellite-derived products. The GWM is the sister-platform to the much earlier (2003) developed Global Reservoir and Lake Monitor (GREALM) which also delivers altimetric products and is sponsored by both NASA and the US Department of Agriculture/Foreign Agricultural Service (USDA/FAS, Birkett et al., 2010). The aim of the GWM is to provide both near real time and archive products, though time critical products (within 24hrs) is not currently its mandate. When an altimetric product is created and uploaded to the GWM it becomes operational with routine updates depending on the sponsorship and end user. A summary of the available GWM altimetric products (graphical and ascii text format) for river reaches is as follows,

i) 10-day resolution products. These are formed from the TOPEX/Jason suite of radar altimeters potentially spanning 1992 to the present day (Figure 5). To note is the ~6month mission follow-on (overlap or tandem) periods that assist the merger of products from each satellite (Table 1). These surface height variations are based on a single overpass (i.e. a single date) datum taken from the Ocean Surface Topography Mission (OSTM, commonly known as Jason-2) with 20-Hz along-track resolution. Internally the river products are currently designated as TPJOJ.2.5.1 where 2.5.1 is the current product version and the lettering denotes the various instruments used to form the product (T=TOPEX, P=Poseidon, J=Jason-1, O=Jason-2/OSTM, J=Jason-3). The height variations are relative to an arbitrary datum but the ascii text products also help convert to a mean sea level framework if this is required. The graphical product also displays an Interactive Data Language (IDL) filtered/smoothed version of the time series for visualization purposes only.

ii) 27-day resolution products. These are formed from the current Sentinel-3A mission. As the European Space Agency (ESA) switched from 35-day to 27-day resolution altimetric orbits that have different ground track locations, the Sentinel-3A products are not appended with an archive of measurements. As per the 10-day products, the Sentinel-3A products are both graphical and ascii text with internal designation Sen3A.2.0.

iii) Auxiliary information. For both 10- and 27-day products the GWM web site offers a view of the location of the satellite ground track. This guides the user to the exact location where the instrument is sampling the water surface. An additional graphical image reveals the elevation profile of the reference cycle which is acting as the single-date datum and displays how this datum can be transitioned from the satellite-based datum to the WGS84 geodetic datum, and then to various orthometric datums (i.e. approaching mean sea level) based on the availability of several gravity models. Current geoid models in use are the Earth Gravitational Models (EGM) EGM96 (15’x15’ resolution) and EGM2008 (1’x1’ resolution), and the European Improved Gravity model of the Earth by New techniques (EIGEN) model EIGEN-6C4 (1’x1’ resolution). The results from these transitions are also reported in the header block of the ascii files as “Datum Translation Factors”.

Figure 4. *The Global Water Monitor (GWM) web site home page (top), and the 10-day resolution river/wetland product access page (bottom) displaying reach locations with product availability. In early 2021, the new web site for GWM will likely be https://blueice.gsfc.nasa.gov/GWM.*

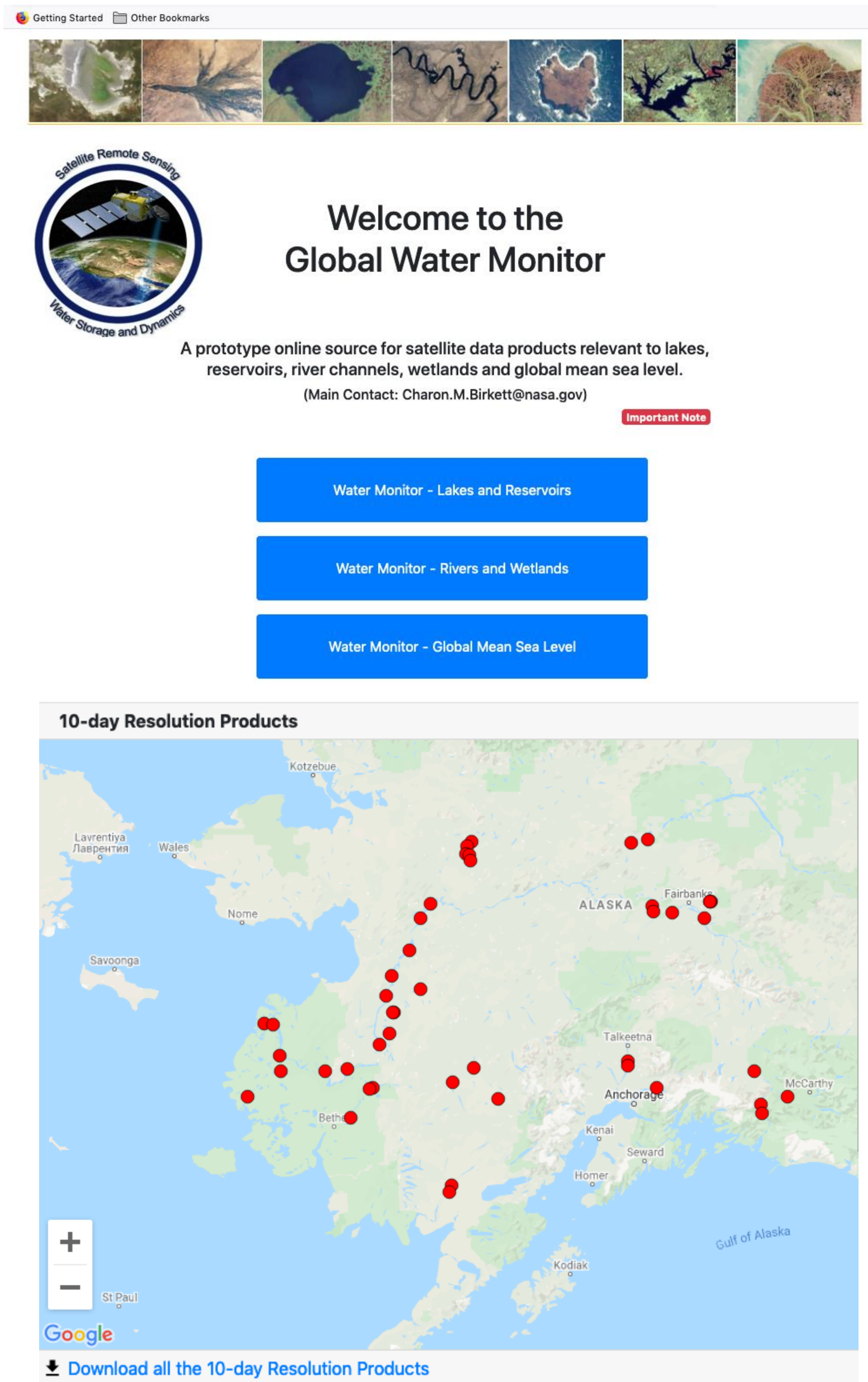
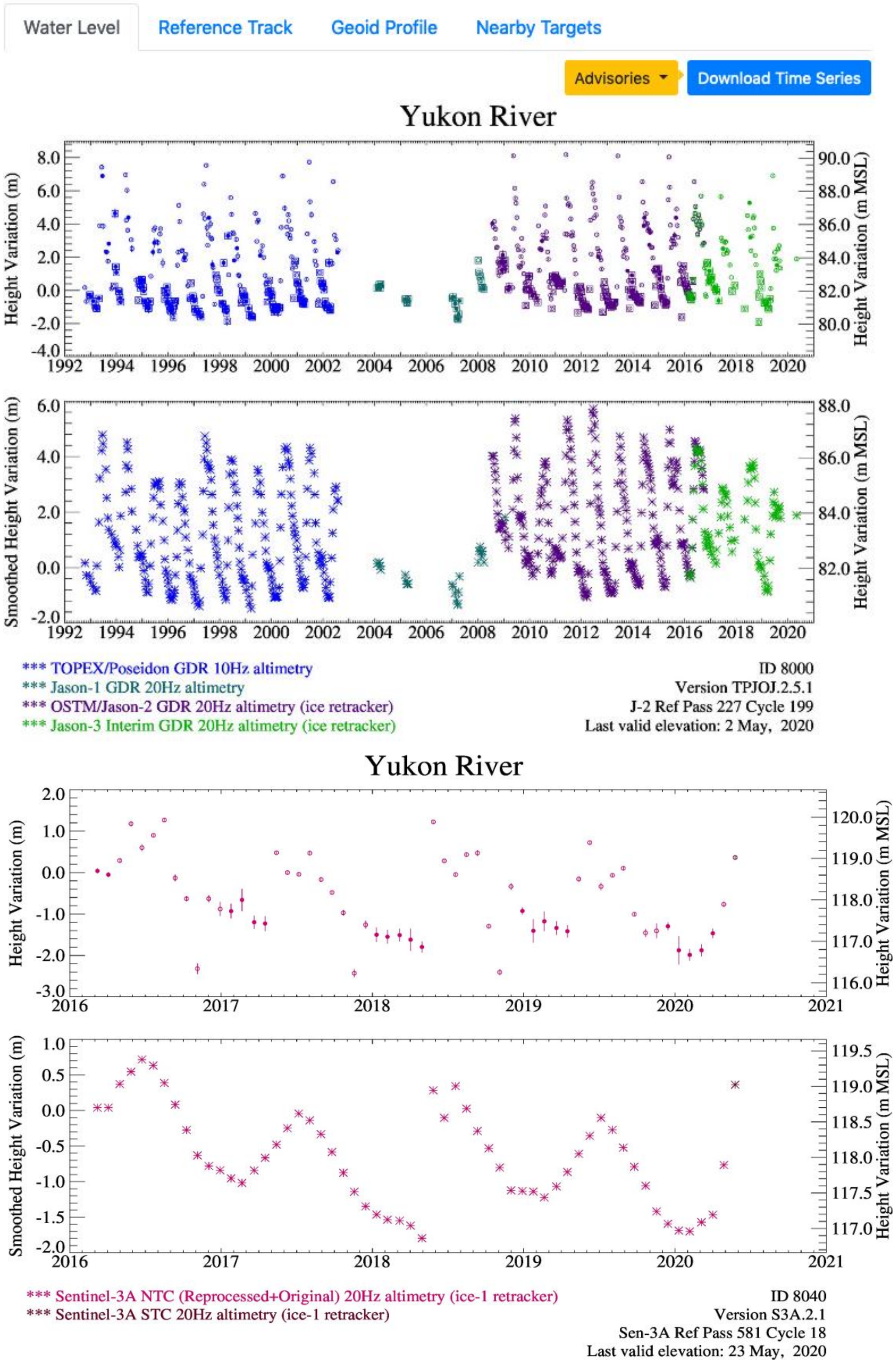


Figure 5. *Examples of river reach surface water level products for the Yukon River, (top) site ID 8000 at 10-day resolution and (bottom) site ID 8040 at 27-day resolution. While the 27-day series is derived from 1 mission only (Sentinel-3A), the 10-day series is derived from 4 missions (TOPEX/Poseidon, Jason-1, Jason-2/OSTM, and Jason-3). In all product examples, the water level variations are relative, and the datum is based on a height profile from a single overpass date. Products show the water level variations as per output from the GWM system processing (the top sections), and after an additional application of an IDL-based median filter (the bottom sections).*



2.3 Input Datasets and Ancillary Data

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

i) Various interim and final geophysical datasets provided by the altimeter mission ground-processing centers (Table 3). For example, at 10-day resolution Interim Geophysical Data Records (IGDR) are provided in near real time (within 2-3 days after satellite overpass) and the more accurate Geophysical Data Records (GDR) provided within 1 month. At 27-day resolution there are the the Short Time Critical (STC) and Non Time Critical (NTC) data offered with similar delay times. In operational product generating systems, near real time datasets are routinely replaced by archive data at various product upgrade stages. Satellite ground-processing data centers provide *Range* and *Orbit* values at varying spatial resolutions (e.g., 1-Hz, 10-Hz, 20-Hz, 40-Hz), but the atmospheric/tidal corrections are supplied at the lower 1-Hz resolution.

ii) The NASA Goddard Space Flight Center (GSFC) satellite orbit ephemerides for more precise estimates of the satellite *Orbit* parameter.

iii) The Delft University of Technology (TU Delft) Radar Altimeter Database System (RADS) for potentially more precise *wetcorr*, *drycorr*, and *ionocorr* range corrections (Fernandes et al. 2014). Single mission RADS data downloads can be access via http://rads.tudelft.nl/rads/rads.shtml. However, GWM utilized the mirror image process to access the entire database (all missions) which was achieved via the RADS rsync server at rads.tudelft.nl. Current GWM 10-day (Version 2.5.1) products are based on Version 4 of the RADS software library.

iv) Meteorological models (climate reanalysis datasets) such as the Modern-Era Retrospective Analysis for Research and Applications (MERRA, courtesy of JPL) dataset and the European Centre for Medium Range Weather Forecasting (ECMWF) Re-Analysis (ERA, courtesy of RADS) dataset are utilized for the wet tropospheric range correction (*wetcorr*). In addition, a revised wet tropospheric range correction for the TOPEX/Poseidon and Jason-1 mission based on re-calibration and enhanced microwave radiometer measurements is also supplied from JPL (Brown et al., 2009). The latter 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

iv) Reference ground tracks for each mission from both the Centre National d'Etudes Spatiales/Archiving, Validation and Interpretation of Satellite Oceanographic Data (CNES/AVISO) and NASA/GSFC. The AVISO versions are used within Google Earth for the initial selection of satellite overpasses and ground track sections. The NASA 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. Geo-referenced locations along the nominal GSFC reference orbit are interpolated at 1-Hz using a Hermite 10th order interpolation algorithm. These 1-Hz locations are time-tagged based on the actual mission datasets. Higher resolution (e.g., 20-Hz) time tags, are created at fractional second intervals centered about the 1-Hz mid-point reference time. The AVISO ground tracks can be found at, http://www.aviso.altimetry.fr/en/data/tools/pass-locator.html

v) A NASA/GSFC subroutine (within GEODYN) which performs the conversion from Modified Julian Date (MJD, used within the satellite datasets) to calendar date.

Table 3. Radar altimeter missions and dataset versions currently employed by GWM to create the river reach products. Dataset upgrades are continuous within the altimetric communities as techniques improve. Currently, the historical TOPEX/Poseidon data is only available at Version B while the operational Jason-3 dataset is at the more refined D-version. The altimetric community is currently leaping to the much-enhanced Version F with continuity of standard 'F' across all mission data likely completed by early 2022.

Mission	***Abbreviation***	***Data Type and Version***
TOPEX/Poseidon	T/P	MGDR-B (M=Merged GDR)
Jason-1	J-1	GDR-C
Jason-2/OSTM	J-2	GDR-D
Jason-3	J-3	IGDR-D*
Sentinel-3A	Sen-3A	STC, NTC, NTC-R (R=reprocessed version3)

* River reach products based on internal v5 IGDR dbase for cycles c001-c160 and on v6 IGDR dbase for post cycle 161. During Jason-3 cycle 175 (mid-November, 2020), the J-3 data switched from version D to F in readiness to match the version F data from the recently launched Sentinel-6 mission.

2.4 Information Retrieval and Processing

Processing of the radar altimeter datasets to form time series of river reach water level variations has been discussed in general by many authors (e.g., from this team Birkett, 1998, Birkett et al., (2002, 2005), Mertes et al., 2004, Durand et al., 2015, Bjerklie et al., 2018) and there are slight variations in method and data processing between various groups. The GWM river product creation method is based on the following,

i) <u>Input Data</u>: The utilization of various altimetric datasets, auxiliary databases, and data files.

ii) <u>Creation of a Mission Reference Ground Track</u>: These high-resolution mission-dependent ground tracks 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. For GWM their creation is based on the computation of a nominal 1-Hz geo-referenced reference track with locations (lat, lon) computed using a Hermite tenth order interpolation algorithm. The assignment of a 1-Hz time-tag is based on an actual GDR track. The 1-Hz reference ground track is then expanded to (for example) 10-Hz or 20-Hz creating 10 or 20 time-tags at 0.1s or 0.05s intervals.

iii) <u>Creation of a Mission Specific Geo-Referenced Parameter Database</u>: 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 a high rate based on the highest rate of the *Orbit* and *Range* parameter rate in the mission dataset i.e., 10-Hz (T/P) or 20-Hz (J-1, J-2, J-3, Sen-3A). The original 1-Hz index point becomes the mid-point of the high-rate data record. The actual parameter database structure is based on direct access with three-dimensional directories that are based on mission repeat cycle number, satellite pass number, and the indexed along-track 1-Hz geo-referenced locations (from the mission reference ground track). While *Orbit*, *Range*, time, location and occasionally the radar backscatter coefficient are provided at the same high rate in the dataset, the tidal and atmospheric *Range/Height* corrections are usually provided at the 1-Hz rate. Each data record then is a fixed length containing a mix of 1-Hz and 10-Hz parameters, or 1-Hz and 20-Hz parameters.

The 10-Hz or 20-Hz parameters are time-aligned with the high rate time tags by a "nearest neighbor" approach rather than via time interpolation, to preserve as many elevation measurements as possible. The 1-Hz parameters though are linearly time-interpolated to the time tags via constructing perpendiculars from the reference track to the actual orbital track location and linearly interpolating from the surrounding along-track data. During this process the across-track distance between the Reference ground track and the cycle track 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 on this mission reference ground track. Note that co-locating the parameters assists the repeat track methodology where heights along one satellite pass are compared to those on a repeat cycle pass. However, the co-locating does not correct for across-track surface gradients i.e., the surface slope between repeating ground tracks which are allowed to vary ±1km about a mission reference ground track. Also to note is that rather than averaging down the J-2 reference cycle's 20-Hz heights to 10-Hz for comparison with the 10-Hz T/P measurements (see section v) below), the version 2.5.1 product software extrapolates (linear interpolation) the T/P measurements out to 20-Hz in an effort to preserve as many T/P elevations as possible. The process takes the 10-Hz T/P *Orbit* and *Range* parameters from the T/P parameter database, extrapolates these out to 20-Hz, and then applies the 1-Hz T/P *Range/Height* corrections. These steps are done "on the fly" and so 20Hz T/P *Orbit/Range/Height* measurements are never held in the T/P parameter database.

iii) <u>Selection of Satellite Overpass and Ground Track Sections</u>: This is the observation of the satellite overpasses across the river reach of interest within Google Earth, the selection of the best overpass (with widest reach), and the latitude identification where the overpass enters and exits the channel. Up to a maximum of 4 sections (i.e., represented by 8 latitude values) on a ground track can be utilized to help avoid island or peninsular contamination. The system does not perform any along-track interpolation to close data gaps formed by the presence of islands, bank, or any sporadic instrument/data drop out periods.

iv) <u>Height Reconstruction</u>: This is the creation of height values along the ground track according to Equations (1) and (2) and also the creation of the associated date, and high-rate time, location and radar backscatter coefficient values. 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.

v) <u>Selection of Reference Datum</u>: For each reach a satellite overpass has a ground track which crosses from bank to bank and this is repeated at a certain frequency (denoted as repeat cycles, e.g. c001, c002 etc.) during the mission lifetime. An overpass on a given date (i.e., a given cycle number) is chosen to be the reference overpass based on the quantity and quality of the height measurements. This "best" overpass becomes the site reference datum and is a height profile from bank to bank. The reference selection avoids 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 dataset, the reference overpass also excludes repeat cycles where the instrument operated in the experimental DIODE/DEM tracking mode (cycles 003, 005, 007, 034, 209, 220). During these cycles the instrument used a look-up table based on a preliminary Digital Elevation Model (DEM) which potentially contained errors of meters to tens of meters.

vi) <u>Derivation of Surface Height Variations</u>: Based on the selected satellite overpass, the ground track section/s, and the reference overpass, 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 reference ground track. 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 some surfaces depending on the slope of the local geoid. For the GWM process, the repeat track methodology employs along-track interpolations in an attempt to co-align the height measurements on the chosen river reference overpass with the mission reference ground track. 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 overpass. These relative height variations are central to the GWM products.

vii) Filtering: This applies to both raw input data and water level product filtering to remove erroneous height values caused by land interference or poor surface tracking.

a) Data Filtering: Observation of Google Earth height profiles, and the satellite-based height values for multiple overpasses across a reach provide a guide to the mean river height and expected seasonal range. This mean height and seasonal range are input as a filter to the initial processing. A time series product currently cannot be created from a reference cycle that is based on one initial high-rate height measurement ($N_{initial}$=1). In addition, the process requires $N_{initial} \geq 2$ non-default height measurements on the comparison repeat cycle at the pre-filtering stage. If this condition is not met the height difference is automatically set to a default value. On occasion, if the $N_{initial} \geq 2$ condition is met, but only one valid point passes through the filtering, this is allowed to form a height difference value, but the associated standard deviation, radar backscatter coefficient, and height error are all set to default values.

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. The default range is ±5m but can be modified to be target dependent. The second step re-computes the mean and rejects any height difference if their absolute value is ≥ 1sigma different than the mean. A 100% efficient filtering is not always achievable and in either step, manual intervention via user-defined cut-off ranges are allowed to override the system.

viii) 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, an inter-mission *Retracker Range bias* is additionally applied.

2.5 Selection of Altimetric Parameters

Based on the height reconstruction equation (2), the following parameters are currently employed or derived by GWM in the creation of the 10-day and 27-day products.

Orbit:

T/P	GSFC std 1007 orbit with the International Reference Frame (ITRF) ITRF2008
J-1	GSFC std 1007 orbit (ITRF 2008)
J-2	GSFC std 1007 orbit (ITRF 2008)
J-3	IGDR-D orbit standard
Sen-3A	STC/NTC GDR orbit standard

Range:

Assumes *instrumentcorr is* already applied.

T/P, J-1	GDR Ocean retracking algorithm
J-2	GDR Ice retracking algorithm
J-3	IGDR Ice retracking algorithm
Sen-3A	STC/NTC Ice-1 retracking algorithm (based on earlier ESA mission algorithm)

wetcorr:

For river reaches the model-derived correction values (below) are utilized. The instrument-based (radiometer) correction is not applicable over land when water target width/extent is small.

T/P	Primary choice is RADS/ERA, Secondary choice the JPL/MERRA
J-1	Primary choice is RADS/ERA, Secondary choice the GDR ECMWF
J-2	GDR ECMWF
J-3	IGDR ECMWF
Sen-3A	STC/NTC ECMWF

drycorr:

Set to zero if all correction options re unavailable

T/P, J-1, J-2	Primary choice is the RADS/ERA, Secondary choice is the GDR ECMWF
J-3	IGDR ECMWF
Sen-3A	STC/NTC ECMWF

ionocorr:

Set to zero if all correction options are unavailable

T/P, J-1, J-2	Primary choice is the RADS NOAA Ionosphere Climatology (NIC) 2009 model (nic09) for pre1998 data records and the RADS Global Ionosphere Model (GIM) for post 1998 data records. Secondary choice is the RADS International Reference Ionosphere (IRI) 2007 model (IRI2007).
J-3	IGDR GIM
Sen-3A	STC/NTC/NTC-R GIM

earth/pole/loading tides:

All missions	Earth, Pole, and Loading tide corrections as per the IGDR, GDR, NTC or STC with the Pole tide additionally corrected for Love numbers for T/P and Sen-3A. These corrections are set to zero if unavailable.

Inter-mission Range Bias:

10-day Products: A suite of follow-on missions with ~6month tandem periods allows for the determination of the *Inter-mission Range bias* between the instruments. For example, 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) is the reference and adjusts the J-3 time series (2016 to present) and the J-1 time series (2002-2008) to merge all three. The T/P (1992-2002) time series is then adjusted to merge with J-1. 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 comparisons
ii) rejects pairs that have ≥1m height difference
iii) rejects pairs which have a height difference that is not in the 3sigma range with respect to the mean of all height differences
iv) does not make any allowance between the quality of the two datasets to be merged (which could both be archive, or a mix of archive and near real time)

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 is recorded in the product header files.*

27-day Products: There are no current plans to merge the 27-day products with archive 35-day products derived from other ESA or Indian Space Research Organization (ISRO) missions such as

ERS, ENVISAT, SARAL (to create an overall 'monthly' resolution product) due to varying locations of the mission ground tracks. The 27-day products thus standalone as individual time series.

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 also compensate for the *Inter-mission Range bias*. However, for product mergers devoid of an instrument tandem operating period or a tandem period with N<2 height values i.e., where the *Global Mean Inter-Mission Range bias* has to be utilized, a *Retracker Range bias* is also estimated and applied to a particular reach 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 the majority of the river reaches 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.

Validity Ranges and Checks:

All dataset default values (U/A=Unavailable) are additionally checked for.

Wetcorr	-600mm<x<0mm, set to zero if all options are Not Available (N/A) or U/A
Drycorr	x<0mm, rejected if U/A or N/A
Ionocorr	-400mm<x<10mm, set to zero if all options are N/A or U/A
Earthtide	rejected if 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

Global Mean Inter-Mission Range Bias Estimates:

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, and J-3 Range estimates are greater than that of J-2 by 16.5cm (T/P), 7.8cm (J-1), and 23.0cm (J-3). These values are global means based on fully corrected sea surface heights (ocean range retracker algorithm employed). Where tandem periods offer no co-incident measurements, these global bias estimates are applied.

2.6 Potential Issues and Limitations

With regards to the measurement of surface water level, a number of limitations apply to the utilization of satellite radar altimetry.

i) <u>Global Monitoring</u>: Standard radar altimeters are nadir-profiling only, crossing over specific reach locations according to their orbit path, which is usually unchanging over the lifetime of the mission. Not all reaches are observed by the suite of current instruments.

ii) <u>Surface Acquisition</u>: The severity and complexity of approach path prior to the reach will affect the ability to acquire a river surface. Most radar altimeters continue to be designed to only cope with the relatively unvarying 'flat' surfaces of the ocean and ice sheets. Historical instruments used on-board tracking logic to help acquire and maintain lock on a surface. The use of an on-board version of a DEM was introduced at set time periods during the J-2 mission as a test acquisition mode over continental surfaces. The results were mixed but sufficient for the space agencies to decide to employ DEM mode on later missions (J-3, Sen-3A) according to a geographical mask. The employed DEMs are not 100% accurate leading to full or partial surface acquisition failures, but there is a mechanism for reporting and correcting such failures though DEM upgrades can only be made infrequently during the mission lifetime.

iii) <u>Minimum Width</u>: A variety of factors (including instrument footprint size, along-track spatial resolution, severity and complexity of approach path prior to the reach, the water extent along the ground track) will affect the minimum size of retrievable reach. Noting technical/instrument limitations, it is unlikely that individual braids within a river reach can be isolated and separated.

iv) Height Accuracy: A variety of factors will influence the accuracy of the height measurements. The "Range" parameter is determined from the radar echo and is of prime importance, knowledge of the wet tropospheric correction is a secondary consideration. The precision of the Range value can be improved via averaging the elevation values along the ground track, from bank to bank. Due to penetration effects, height measurements over snow/ice covered river surfaces may be erroneous. The GWM product output includes an estimate of the mean radar backscatter coefficient over the reach for a particular overpass cycle. Repeat cycles where the mean backscatter coefficient is >18dB are highlighted as open (not solid) circles on the graph products to potentially denote calm water or ice surface conditions. In addition, potential ice-on dates (from general observation) are also reflected in the graph products by an additional square symbol being plotted around the open/solid circle symbol. No height correction can be made for wind set-up effects or the influence of tides without ancillary datasets. Heavy precipitation events will also affect height accuracy to a variable degree.

v) Jason-1 Data Rejection: 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 of these steps resulted in the loss of data over calmer water surfaces such as typically found on river reaches. For many rivers the J-1 data is therefore not available.

vi) Multi-Platform Product Mergers: The merger of height variation products from multiple missions requires the use of an overlapping ("tandem") period to assist with cross-platform Range bias. This period can vary in length but is ~6months for the TOPEX/Jason series. The inter-mission Range bias is variable at the local scale and has to be deduced on a target-by-target basis, the process requiring a minimum of 2 tandem height points. For the TOPEX/Jason series the tandem periods are undertaken during Northern hemisphere winters which does present the additional problem of variable instrument penetrations if snow/ice is on the water surface. The lack of an overlap period or any tandem height points results in the application of a *Global Mean Inter-mission Range Bias*, which may introduce additional centimeter-scale errors into the merged product across a portion of the final product time period. For example, if J-1 data is absent, a *Global Inter-mission Range Bias* will have to be applied to merge the T/P time series to the J-2/J-3 time series.

vii) Single-Platform Multi-Product Mergers: There are three ESA datasets associated with the Sentinel-3A mission and these are merged to create a river product that has both near real time and archive components. The STC are the near real time data and the NTC are the archive data. In addition, the NTC are offered at their original or (more accurate) reprocessed (NTC-R) versions. Within this project, cycle030 is the cross-over time between use of NTC-R (cycles001 to 029) and NTC (cycle 030 onwards) so there is no NTC/NTC-R overlap period in the product time series. At any given point in time there is typically only 1 STC-derived elevation in the product because at the next product update the last STC-derived height value is automatically replaced by the NTC-derived value, while the latest STC-derived height is added. In merging results from both NTC and NTC-R care has to be taken to check for any height bias that might exist. In this respect an NTC/NTC-R height bias is computed for all reach locations using Sen-3A cycles 011 to 029. This period is a total of 486 days where both NTC and NTC-R data sets are both fully available. To date the NTC/NTC-R bias has been observed to be <10cm and it is applied to both NTC and STC. Because this bias is between datasets and not an inter-mission bias, the value is not recorded in the Sen-3A ascii text product header.

3. Product Quality Indicators

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 that are interpolated to the same date and time. In general, validation exercises show that a time series of altimetric water level variations for river reaches can be accurate from ten to tens of cm rms depending on a number of factors based on reach width, the water surface roughness, and other effects such as wind and heavy precipitation events, and tidal effects. The GWM web site and reach products contain a number of indicators to help end-users highlight potential erroneous measurements,

a) For each reach site, the relevant GWM web page does provide a list of general "Advisories" that might highlight a braided reach, a narrow reach, the potential for winter (ice-on) conditions, tidal affects, whether the merger of altimetric datasets could be compromised, and whether the time series has been affected by poor onboard DEM setting for that location.
b) The *.txt product files contain a header block that advises on the multi-instrument data merger. The presence of "Global Mean Bias" is a potential red flag but need not signify 100% error.
c) The *.txt and *.jpg product files both highlight potential winter (ice-on or calm) conditions
d) The *.txt file records whether the height for that particular cycle has been derived using the more accurate archive (GDR, NTC-R) datasets, or the less accurate near real time (IGDR, STC) datasets. For example, the entire J-3 portion of the 10-day water level time series are created with the J-3 IGDR data.
e) The *.txt file provides a height error (column 7) which is statistically correlated with the number of elevation measurements available across the reach. Note that this height error is only 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.
f) The *.txt files provides a mean radar backscatter value (column 8). A defaulted value (999.99) may be indicative of an erroneous height measurement.
g) Column 15 of the *.txt product file 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 inaccuracy with errors that are geographically variable. It is difficult to quantify such errors.
h) In general, the more recent satellite missions (J-2, J-3, Sen-3A) have a combination of improved onboard tracking software, data processing, and high spatial resolution, that enable them to better capture water level variations in river reaches than their historical predecessors, T/P and J-1. While this can't be quantified, this should be noted.

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Appendix A Product Naming Convention and Specifications

These are graphical and ascii text in format and conform to the following convention.
A four-digit site identification (ID) number is assigned to the satellite overpass location on a certain reach, e.g. ID=8000 is where the 10-day ascending ground track (A/227) crosses the Yukon River upstream of the Steven Village gauge site. Both 10-day and 27-day resolution products are currently available,

river8000.10d.2.jpg	graphical file
river8000.10d.2.txt	associated ascii text file
river8040.27d.2.jpg	graphical file
river8040.27d.2.txt	associated ascii text file

The *.10d.* products are 10-day resolution with jpg/txt files denoting that these are “TPJOJ” products at version 2.5.1 where TPJOJ signifies that they are derived from the merger of the Topex/Poseidon/Jason-1/Jason-2(OSTM)/Jason-3 datasets. The *.27d.* products are 27-day resolution derived from the Sentinel-3A dataset, denoted as “S3A.2.0” with the end number signifying that these are version 2.0 products.

Appendix B Product Components

For the *.10d.2.txt and *.27d.2.txt products,
Header:

Data Product and System Processing Version
Reach ID and name
Lat/Long values for the reach mid-point
Start/End Latitudes where elevation data is accepted[1]
Satellite Pass (and Revolution) numbers
Cycle number of the Reference Pass
Retracking algorithm used for Range determination
Range bias to merge multiple data sets:

For the 10-day products:

Range bias (meters) applied to merge the J-3 time series to J-2
Range bias (meters) applied to merge the J-1 time series to J-2
Range bias (meters) applied to merge T/P time series to J-2

For the 27-day products:

Currently not in use (set to default)

A text block providing Datum Conversion Factors

Multi-line text block describing data columns and their default values

Data:

Column 1+2: Satellite Mission and Repeat Cycle

Column 3: Year/Month/Day (at overpass mid-point)

Column 4+5: Time (UTC) in hour/minutes which is static for the 27day (and 35day) products these missions being sun-synchronous, but there is an ~2hr difference in Time between repeat cycles for the 10day products due to the repeat cycle length actually being 2hrs shorter than the full 10days, the TOPEX/Jason mission series being in non-sun synchronous orbits.

Column 6: Mean Relative Surface Height (meters) for the repeat cycle [2]

Column 7: Height error (meters)[3]

Column 8: Mean radar backscatter coefficient for the track section (dB)[4]

Column 9+10+11: The type of wet troposphere/ionosphere/dry troposphere atmospheric corrections utilized in the height construction. If the type varies across a reach, then these columns represent the most frequent correction. If there is an equal number of two types, then the column will state 'MIX'.

For the 10-day products

Column 12+13 The instrument operating modes *(set to default for 27-day products)*
Column 14: Flag for potential ice-on conditions
Column 15: Surface height converted to the EGM2008 datum (meters)
Column 16: Data source, archive (GDR) or near real time (IGDR)

For the 27-day products

Column 12: Flag for potential ice-on conditions
Column 13: Surface height converted to the EGM2008 datum (meters)
Column 14: Data source, archive (NTC-R, NTC), or near real time (STC)

[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 dataset parameters (e.g., Date&Time, Range, Orbit) are defaulted. This can occur due to a number of 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 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&10).
Note that the 10-day product may have overlapping tandem phase observations resulting from the two instruments flying over the reach within 1 minute of each other). If both height measurements are valid, this will result in two sets of height estimates for a given date in the product.

[3] The data sections within the product text files attempt 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 resolution product types this constant is 4.2cm (when radiometer-based *wetcorr* utilized) or 5cm (when the model-based *wetcorr* is utilized or selected but either unavailable or not applicable). If the i*oncorr* correction is available or not applicable the 5cm constant is similarly not modified to reflect this omission.

[4] The mean radar backscatter coefficient will be based on values associated with the ice retracker (J-2, J-3(, the ice-1 retracker (Sen-3A) or ocean retracker algorithms (T/P, J-1), and are available at 20-Hz (J-2, J-3, Sen-3A) or 1-Hz (T/P, J-1). The mean backscatter value is computed across the target excluding default values and those outside specified backscatter validity ranges (5-42dB T/P, 0-50dB J-1, 0-60dB J-2, J-3). For version 2.5.1 river products no validity range is currently in use for Sen-3A.

Appendix C Abbreviations and Acronyms

ADOT&PF	Alaska Department of Transportation and Public Facilities
ATBD	Algorithm Theoretical Basis Document
AVISO	Archiving, Validation and Interpretation of Satellite Oceanographic Data
CNES	Centre National d'Etudes Spatiales
DEM	Digital Elevation Model
ECMWF	European Centre for Medium Range Weather Forecasting
EGM	Earth Gravitational Model
EIGEN	European Improved Gravity model of the Earth by New techniques
ENVISAT	Environmental Satellite
ERS	European Remote Sensing Satellite
ESA	European Space Agency
GDR	Geophysical Data Record
GEODYN	GSFC orbit determination and geodetic parameter estimation orbital software
GIM	Global Ionosphere Model
GREALM	The Global REservoir and Lake Monitor
GSFC	Goddard Space Flight Center
GWM	The Global Water Monitor
ID	Identification (Lake ID number)
IDL	Interactive Data Language
IGDR	Interim Geophysical Data Record
IRI	International Reference Ionosphere
ISRO	Indian Space Research Organization
ITRF	The International Reference Frame
J-1/J-2/J-3	Jason-1, Jason-2 or Jason-3 missions
JPL	Jet Propulsion Laboratory
KBR	Kellogg Brown & Root (company)
MGDR	Merged Geophysical Data Record
MJD	Modified Julian Date
N/A	Not applicable
NASA	National Aeronautics and Space Administration
NIC	NOAA Ionosphere Climatology
NWIS	National Water Information System
NWS-APRFC	Alaska-Pacific River Forecast Center of the National Weather Service
NTC	Non Time Critical
NTC-R	Non Time Critical Reprocessed
OSTM	Ocean Surface Topography Mission (i.e., Jason-2)
PI	Principal Investigator

RADS	Radar Altimeter Database System
SARAL	Satellite with ARgos and ALtiKa
Sen-3A	Sentinel-3A mission
SLR	Satellite Laser Ranging
STC	Short Time Critical
SWOT	Surface Water and Ocean Topography satellite mission
TOPEX	Ocean TOPography EXPeriment
T/P	TOPEX/Poseidon mission
TPJOJ	TOPEXPoseidonJason1OSTMJason3 (The current 10-day GWM product type)
TU Delft	Delft University of Technology
U/A	Unavailable
USDA/FAS	US Dept of Agriculture/Foreign Agricultural Service
USGS	US Geological Survey