From Research to Operations: The USDA Global Reservoir and Lake Monitor

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Abbreviations

ALT	NASA Radar Altimeter
AVISO	Archiving, Validation and Interpretation of Satellite Oceanographic data
CNES	Centre National d'Études Spatiales
CSR	Center for Space Research (University of Texas, Austin)
DDP	Defect Detection and Prevention
DESDynI	Deformation, Ecosystem Structure and Dynamics of Ice
DORIS	Doppler Orbit Determination Radiopositioning Integrated on Satellite
DSS	Decision Support System
Envisat	Environmental Satellite
ERS	European Remote Sensing Satellite
ESA	European Space Agency
ESRI	Environmental Systems Research Institute
EUMETSAT	European Org. for the Exploitation of Meteorological Satellites
FAS	Foreign Agricultural Service
FEWS	Famine Early Warning Systems
GDR	Geophysical Data Record
GEO	United States Group on Earth Observations
GEOSS	Global Earth Observation System of Systems
GFO	Geosat Follow-On Mission
GIM	Global Ionospheric Map
GLAM	Global Agricultural Monitoring Program
GLIN	Great Lakes Information Network
GPS	Global Positioning System
GRACE	Gravity Recovery and Climate Experiment
GRLM	Global Reservoir and Lake Monitor
GSFC	Goddard Space Flight Center
GUI	Graphical User Interface
ICESat	Ice, Cloud and Land Elevation Satellite
IGDR	Intermediate Geophysical Data Record
IPCC	Intergovernmental Panel on Climate Change
IRI	International Reference Ionosphere Model
ISRO	Indian Space Research Organization
ISS	Integrated Systems Solution
ITRF	International Terrestrial Reference Frame
ITSS	Information Technology and Scientific Services
JPL	Jet Propulsion Laboratory
LAD	Least Absolute Deviation
LakeNet	World Lakes Network
LEGOS	Laboratoire d'Études en Géophysique et Océanographie Spatiales
MODIS	MODerate resolution Imaging Spectroradiometer
MOE	Medium Precision Orbit Ephemerides
NASA	National Aeronautic and Space Administration
NCEP	National Centers for Environmental Prediction
NGA	National Geospatial Intelligence Agency

NOAA	National Oceanic and Atmospheric Administration
NOGAPS	Navy Operational Global Atmospheric Prediction System
NRC	National Research Council
NRL	Naval Research Lab
OGA	Office of Global Analysis
OMB	Office of Management and Budget
OSTM	Ocean Surface Topography Mission
POE	Precise Orbit Ephemerides
RMS	Root Mean Square
SARAL	Satellite with ARgos and ALtika
SDR	Sensor Data Record
SGT	Stinger Ghaffarian Technologies company
SLR	Satellite Laser Ranging
SSALT	Solid-State ALTimeter
SWOT	Surface Water and Ocean Topography
T/P	TOPEX/Poseidon
TRMM	Tropical Rainfall Measuring Mission
UMD	University of Maryland
USAID	United States Agency for International Development
USDA	United States Department of Agriculture
USGS	United States Geological Survey
WAOB	World Agriculture Outlook Board
WAP	World Agriculture Production
WASDE	World Agriculture Supply and Demand Estimate

2.1 The USDA/FAS Decision Support System

The USDA/FAS is responsible for providing crop production estimates for all international countries and benchmark data for commodity markets and the World Agriculture Outlook Board (WAOB). These values become an Office of Management and Budget (OMB) mandated "Principle Federal Economic Indicator" published monthly in the World Agriculture Supply and Demand Estimate (WASDE) report and the World Agriculture Production (WAP) circular. Such estimates drive price discovery, trade and trade policy, farm programs, and foreign policy. In addition, the FAS is also responsible for providing an "early warning of events" to the Farm Service Agency. This service output can have an effect on the agriculture production affecting both food programs and markets.

The monthly crop estimates are produced within the FAS/Office of Global Analysis (OGA) decision support system (DSS), the only operational unit of its type in the world and the primary source of global agricultural intelligence on crop production and conditions for USDA and the US Government. The OGA uses an "all sources" methodology that varies by region and commodity but, in general, integrates the US Government and commercial satellite imagery, agro-meteorology data and crop modeling output, to provide timely, unbiased information on crop condition and production. This information is used in the monthly "lockup" process to set global production numbers. The resulting information is shared with other USDA and US Government agencies as input to their various decision-support protocols. This permits the various agencies to meet national security requirements, assess global food security needs and agriculture policy, and provide the agriculture industry/producers with commodity price discovery and an early warning of global crop production anomalies.

A number of satellite datasets are currently used within the DSS to derive information on precipitation, land cover, and soil moisture (e.g., from the NASA/TRMM, NASA/Terra, NASA/Aqua missions), which enhance the distribution of crop information. Also of prime importance is the availability of water for irrigation purposes, that is, the volume of water stored in the region's lakes and reservoirs. For many locations around the world, such knowledge is lacking because of the absence of ground-based measurements, or is difficult to obtain because of economic or political reasons. Water-deficit regions, in particular, suffer from poor reporting. Initially the DSS had to rely on vegetation response products only, since precipitation has a less direct effect on conditions, but the availability of altimetric satellite data over inland water opened up new possibilities.

2.2
Satellite Radar Altimetry

Satellite radar altimeters are primarily designed to study variations in the surface elevation of the world's oceans and ice sheets (for general information, see Fu and Cazenave 2001). Innovative use of the data, however, has additionally enabled studies of the variations in surface water level of the world's largest lakes, rivers and wetlands (see reviews in Birkett et al. 2004; Mertes et al. 2004; Crétaux and Birkett 2006). The main advantages include day/night and all-weather operation with no loss of data because of cloud coverage. With continuous operation across all surfaces, the instrument behaves like a string of pseudo-gauges, sampling the elevation at discrete intervals along a narrow satellite ground track. The presence of vegetation or canopy cover is not a hindrance to this nadir-viewing instrument, the inundated surfaces being so bright at microwave frequencies that vegetation only interferes during periods of extremely low water level. The instruments can thus observe monthly, seasonal, and inter-annual variations over the lifetime of the mission, and unlike many gauge networks that operate using a local reference frame, all altimetric height measurements are given with respect to one reference datum to form a globally consistent, uniform data set. After several decades of validated research, the altimetry data sets are mature and generally freely available via DVD or ftp.

With respect to lake/reservoir monitoring, there are several limitations to utilizing radar altimetry. The altimetric satellites are placed in a fixed repeat-cycle orbit with instruments that only have nadir-pointing ability. These result in specific ground track locations that restrict viewing to a certain percentage of the world's lakes and reservoirs. A trade-off between the temporal and spatial sampling is also in play and can impose further restrictions on target numbers. Many altimetric missions also have ocean science objectives with instrument designs not optimized for studies in rapidly changing or complex (multiple target) terrain. In such cases, surface elevation data over inland water may be degraded or non-retrievable. In addition, a number of factors place limitations on lake size (generally ≥100 km^2), particularly, when program accuracy requirements are taken into consideration.

Table 2.1 Selection and continuity of satellite radar altimetry missions

Satellite mission		Operation period	Temporal resolution (days)	No. of Lakes, Reservoirs
10-day repeat orbit (A)				
NASA/CNES	T/P	1992–2002	10	122, 55
NASA/CNES	Jason-1	2002–current	10	122, 55
NASA/CNES/NOAA/ EUMETSAT	Jason-2	Launch 2008	10	122, 55
NOAA/CNES/EUM	Jason-3/GFO2	Launch 2012	10, 17	
35-day repeat orbit				
ESA	ERS-1	1992–1993, 1994–1995	35	446, 165
ESA	ERS-2	1995–current[a]	35	446, 165
ESA	Envisat	2002–current	35	446, 165
ISRO/CNES	SARAL/AltiKa	Launch 2010	35	446, 165
ESA	Sentinel-3	Launch 2012	35	446, 165
17-day repeat orbit				
US NRL	Geosat	1987–1989	17	~220, ~95
US NRL	GFO	2002–current[a]	17	~220, ~95
NOAA/CNES/EUM	Jason-3/GFO2	Launch 2012	10,17	
10-day repeat orbit (B)				
NASA/CNES	TOPEX-Tandem	2002–2005	10	145, 65

1. Lakes (≥100 km^2) and in the latitude range –40 South to 52 North are potential targets. Numbers shown are approximate and reflect those targets of most interest to the USDA/FAS. Instrument tracking and current data interpretation methods have limited the 10-day repeat orbit (A) targets to ~70 at the present time. Lake number statistics are taken from Birkett and Mason (1995).

2. Except for the TOPEX-Tandem mission, satellites with the same temporal repeat cross over the same set of lakes. A lake may be crossed over by more than one satellite. Larger lakes will have multiple same-satellite crossings increasing temporal resolution.

[a]ERS-2 (from 2002) continues to operate with reduced continental coverage. GFO (from 2006) continues to operate with reduced temporal coverage over inland basins.

Current altimetric satellites cross over a selection of the world's largest lakes and reservoirs, measuring variations in the lake level with a repeat frequency ranging from 10 to 35 days (Table 2.1). Comparing measurements from the NASA/CNES TOPEX/Poseidon (T/P) mission with ground-based gauge data, for example, has shown altimetric accuracies to be variable, ranging from ~3 to ~5 cm root mean square (RMS) for the largest open lakes with wind-roughened surfaces (such as the Great Lakes, USA), to several decimeters RMS for smaller lakes or those with more sheltered waters (Morris and Gill 1994; Birkett 1995; Shum et al. 2003). With validated data sets, a number of research projects have been undertaken with applications that include fisheries and water resources, sediment transport and navigation, natural hazards (floods/droughts), basin impacts via dam impoundments, and climate change (see Crétaux and Birkett 2006, and the chapter by Crétaux et al., this volume for examples).

2.3 The Creation and Implementation of the GRLM

Observing the lake/reservoir levels via the innovative use of satellite radar altimetry combined with satellite imagery for surface area estimates does offer the potential to monitor variations in total volume storage. However, the USDA/OGA noted that water levels alone do reflect irrigation potential and could singularly help practices better understand crop production characteristics. Satellite radar altimetry was thus considered as a potential new tool that could enhance the current USDA DSS in its monthly crop assessments. The USDA program strongly emphasized its need for archival information that could reveal the general status of the lake, and the availability of near-real-time data that could quickly assess drought or high water-level conditions. With such new information, the ultimate goal was to more effectively determine the effects on downstream irrigation potential and consequences on food trade and subsistence measures. Additional system requirements also included:

(i) The monitoring of all lakes and reservoirs in regions of agricultural significance.
(ii) The production of surface water-level variations with respect to a mean reference datum and accurate to better than 10 cm RMS.
(iii) The products to be updated on a weekly basis, with a latency of no more than 2 weeks after satellite overpass (defined as "near-real time" here).
(iv) All products (graphical and ascii text) to be incorporated within the OGA Crop Explorer web site database.

In 2002, the USDA/FAS funded the implementation and operation of the near-real-time altimetric monitoring program. It became a collaborative effort between the USDA, UMD, NASA/GSFC, Raytheon ITSS and SGT. By late 2003, the Global Reservoir and Lake Monitor (GRLM) went on-line and became an additional decision support tool within the cooperative USDA/NASA GLAM program and the first program to utilize near-real-time radar altimeter data over inland water bodies in an operational manner.

The well-documented and validated data from the NASA/CNES T/P satellite and its follow-on mission Jason-1 (Table 2.1) were chosen to initiate the program. With a 10-year T/P archive (1992–2002), a 10-day time interval between lake observations, and a near-real-time Jason-1 data delivery of 2–3 days after satellite overpass, a designated set of target lakes, reservoirs, and inland seas were selected by the OGA. Originally, lakes and reservoirs on the African continent were of interest (Phase I), but the program quickly became global in outlook (Phase II).

2.4 Satellite Data Sets

Table 2.1 outlines the historical, current and future radar altimeter missions that separate into three main data sets according to satellite repeat period i.e., the temporal resolution of the lake product, 10, 17, or 35 days. The trade-off between repeat period and the number of target hits can be clearly seen. While the NASA/CNES missions have the better temporal resolution, ideal for weekly updates of lake products, the ESA missions offer a far greater quantity of potential targets.

Phases 1 and II of the program focused on the NASA/CNES T/P and Jason-1 data sets. The T/P mission was the first to carry two radar altimeters; the NASA radar altimeter (ALT) operating at 13.6 and 5.3 GHz (Ku and C band, respectively) and the prototype solid-state altimeter (SSALT) operating at 13.65 GHz. The SSALT was allocated ~10% of the observing time and data gathered during these periods also included some of the larger lakes and inland seas. The Jason-1 radar altimeter (POSEIDON-2) also operated at Ku and C band. Both missions performed a total of 254 ascending and descending passes over the Earth's surface with a geographical coverage extending to ±66° latitude. Each repeat-pass crossed over, to within a few kilometers, the same location on the Earth's surface. The temporal resolution of the measurements are ~10 days, and the along-track resolution of the missions have the potential for one height measurement every ~580 m (the 10 Hz T/P GDR) and every ~290m (the 20 Hz Jason-1 IGDR).

For each mission, there is a choice of data set that can be utilized to construct lake-level variations. These data sets are offered to users in several formats including Fast Delivery (generated within a few hours after satellite overpass), Intermediate Geophysical Data Records (IGDR, available a few days after satellite overpass) and Geophysical Data Records (GDR, generally available 4–6 weeks after overpass). The Sensor Data Records (SDR) that include the original radar echoes are also available but have not, to date, been utilized within the program. Notably, the lake-level accuracy depends upon the knowledge of the satellite orbit that is deduced via Global Positioning System (GPS), doppler orbit determination, and radiopositioning integrated on satellite (DORIS), and satellite laser ranging (SLR) methods. Fast delivery data may contain mean global orbit errors of ~30–40 cm; IGDR errors are ~5–10 cm and GDR errors ~2–3 cm. Striking a balance between height accuracy and operational requirements, the Jason-1 IGDR data was selected for near-real-time observations and the archive product was constructed using the T/P GDR. Both IGDR and GDR data are in binary format with data structures that contain both altimetric and geophysical parameters.

2.5 Technique

The T/P and Jason-1 data processing procedures follow methods developed by the NASA Ocean Altimeter Pathfinder Projects (Koblinsky et al. 1998), although improved algorithms are utilized and there is some adjustment to the general procedures including an allowance for more automation of the process. The methodology (outlined in McKellip et al. 2004) includes height construction, application of a repeat track technique, the derivation of a mean reference datum, and the determination of height bias between differing missions. All of these steps are performed via the creation of a time-tagged geo-referenced altimeter database.

In general, the construction of ocean surface height assumes the following two equations,

$$\text{Altimetric Height} = (\text{Altitude} - \text{Range}_{\text{corr}}) - \text{Tides} - \text{Barometric Correction} \tag{2.1}$$

$$\text{Range}_{\text{corr}} = \text{Range} + \text{Atmospheric Corrections} + \text{SSBias} + \text{CGrav Correction} \tag{2.2}$$

Here, "altitude" is the satellite orbit above a reference ellipsoid, and "range" is the distance between the altimeter and the surface (estimated from the radar echo). Both range and the resulting height must be corrected for instrument and geophysical effects. For the GRLM system, earth tide is applied, but elastic-ocean and ocean-loading tides are only applicable to the Caspian Sea (for a detailed study on the Caspian Sea, see the chapter by Kouraev et al., this volume). The inverse barometric correction is not applied because the lakes/reservoirs are closed systems. Atmospheric corrections include the dry tropospheric correction, the radiometer-based wet tropospheric correction when valid (and the model-derived correction, when not valid) and the DORIS ionospheric range correction. The sea state bias (SSBias) correction is not applied because wind effects tend to be averaged out along-track, and CGrav is a correction to offset for variations in the satellite's center of gravity (see Birkett 1995 and Fu and Cazenave 2001 for full details on the reconstruction of altimetric height).

Dedicated ocean altimeter satellites have their orbit maintained to a near-exact repeat period to facilitate geoid-independent techniques to measure changes in the surface height based on the method of collinear differences. The term "collinear" indicates that heights for a particular exact repeat orbit mission have been geo-located to a specific reference ground track. During collinear analysis, the repeat tracks are assumed to have perfect alignment to facilitate separation of sea surface height variations from the geoid. However, orbit perturbations caused by atmospheric drag and solar radiation pressure cause departures from the nominal repeat path introducing errors from the slope of the local geoid. Over most of the ocean, a departure from the nominal repeat path is typically limited to ±1 km translating into an error of 1–2 cm. In areas of steep lake bottom topography (e.g., Lake Tanganyika), these geoid-related errors can be a few centimeters. For inland water applications, data users may elect to perform both along- and across-track corrections, or just along-track corrections (as in the GRLM system) to attempt to co-align elevation measurements on various ground tracks with the reference track. In some cases, perfect co-alignment is not required and instead a type of "finding the nearest neighbor" is performed. This is achieved by calculating the distance between elevation measurements on the ground tracks.

The T/P and Jason-1 ~10 day-repeat orbit had ground track positions that varied by up to ±1 km from the nominal reference ground track. Jason-1 IGDR data are provided at the 20 Hz rate (i.e., one altimetric range measurement every 0.05s along the ground track), while the T/P GDR data are given at 10 Hz (20 Hz averaged in pairs). The construction of the T/P and Jason-1 10 Hz geo-referenced database then is as follows:

(i) Nominal 1 Hz geo-referenced locations (lat, lon) along a reference track are computed using a Hermite tenth order interpolation algorithm.
(ii) The time-tag (number of seconds along the satellite pass) for each of these 1 Hz reference locations is then calculated using the actual (I)GDR track data. Alignment is achieved by constructing perpendiculars from the reference orbit track to the actual orbital track. Locations are then linearly interpolated.
(iii) Although no across-track corrections are performed within the GRLM system, the cross-track distance from the reference orbit to the actual observation location is also stored in the reference database. In addition, a 1 Hz collinear surface height is computed from a linear fit of the 10 Hz heights with the midpoint evaluated at the 1 Hz reference location. At this point in the process, the reference track is 1 Hz and the database contains lat, long, time, and height where lat/long are fixed for all repeat passes.

(iv) The 1 Hz reference ground track is then expanded to 10 Hz by associating a 10 Hz height value to each of the ten 0.1 s intervals from the 1 Hz reference time. The closest 10 Hz height point on the neighboring ground track, rather than interpolation of adjacent 10 Hz observations is then chosen. In this way, the 1 Hz reference ground track is expanded to 10 Hz, the 10 Hz heights are indexed, and the method preserves as many lake heights as possible. For the Jason-1 IGDR data, the nearest-neighbor approach searches for the closest 20 Hz data point along the actual ground track.

The resulting reference database has a structure that is based on direct access with three-dimensional directories for each mission based upon repeat cycle number, satellite pass (or "revolution" number), and the indexed along-track 1 Hz geo-referenced locations. Each lake that the satellite flies over will have an associated revolution number and a set of along-track time indices bounding the lake traverse. Each data record is a fixed length containing the 1 and 10 Hz geo-referenced heights, along with all geophysical and environmental range corrections. This random read–write approach permits (I)GDR data to be processed upon receipt regardless of repeat cycle order, and permits immediate revisions. The organization of the geo-referenced data directories and fixed record format enables the integration of a graphical user interface (GUI) to generate near-real-time data reports and performs as a quality assurance device.

To construct the T/P and Jason-1 time series of lake height variations, the elevation measurements along one satellite overpass, from coastline to coastline, have to be compared to measurements along a reference pass for each lake. The differences in height at the 10 Hz locations are then averaged and the result represents a mean height difference (with respect to the average pass) for that particular crossing date and time. In the GRLM system, the reference pass is based on an average pass which is deduced from the 10-year TOPEX (ALT) reference archive. The along-track alignment procedures result in a maximum 10 Hz along-track alignment error of 0.05 s (0.28 km) for TOPEX (ALT) and a maximum expected error of 0.025 s (0.14 km) for the 20 Hz Jason-1 data. The estimated error of the average TOPEX (ALT) height profile at each 10 Hz location though is further reduced by virtue of the 10-year averaging (cycles 1–364).

It is at the comparison of pass with average pass stage that the rejection of erroneous height values takes place. This is done by the removal of outliers with boundary limits set according to each lake. The filtering method rejects those height measurements that are contaminated by land (coastline or island) or by additional bright objects within the altimeter footprint. Coastline data for large lakes and inland seas (e.g. Lake Ontario) are readily rejected leaving many elevation measurements over which to form an accurate average measurement. With an along-track spacing of ~580 m, many smaller lakes or narrow crossing extents (e.g., Lake Powell) will have a notable reduction in height accuracy because of a smaller number of measurements. This is often coupled with a reduction in range precision because of determining the range from a narrower radar echo profile (Birkett 1995). In these cases, filtering is relaxed with the acceptance of greater inaccuracy. A resulting time series, though with large error bars, and an inability to reveal seasonal, inter-annual or long-term trends are rejected from the system until new methods can offer improvement.

In the compilation of the T/P time series, the team did not apply any additional range (or height) bias to the prototype SSALT measurements on the GDR; however, the merger of the

T/P and Jason-1 time series requires a check on the inter-mission height bias to maintain continuity of products on the single-product output graph. During the follow-on mission validation (or tandem) phase (Jason-1 cycles 1–21 and T/P cycles 344–364), both satellites flew in formation along the same ground track separated by approximately 72 s, the satellite observations being approximately spatially and temporally coincident (Ménard et al. 2003). The instrument-independent height corrections (Eqs. 2.1 and 2.2) that do not vary significantly over the 72 s essentially cancel at the geo-referenced locations. Analysis of the global ocean collinear sea surface height differences between the Jason-1 and TOPEX (ALT) data (Chambers et al. 2003; Vincent et al. 2003; Zanife et al. 2003) revealed that a relative bias of approximately 11 cm (Jason-1 higher than TOPEX (ALT) existed between the range measurement of the two missions. A similar analysis using the Jason-1 IGDR data over a suite of large lakes generated a relative bias of ~9 cm which was applied to the GRLM combined T/P and Jason-1 graph products and these were denoted as Version 1. For some lakes, this produced a smooth transition, but for many lakes an additional offset could be observed suggesting a regional effect.

2.6 Jason-1 Data Loss

There are many factors affecting the quantity and quality of elevation measurements over inland water targets and the later section on limitations provides a summary. Here, we present details of a data loss discovered within the Jason-1 IGDR data set.

For oceanography purposes, the low-rate, 1 Hz elevation measurement is adequate for most science objectives. For inland water applications, it is the 10 Hz (T/P GDR) or 20 Hz (Jason-1 IGDR) elevations that are demanded for the smaller targets. Within the T/P GDR the user has access to one 1 Hz altimetric range value and up to ten, "range difference" values. Adding the latter to the former gives the full 10 Hz range measurements which are combined with other parameters to form lake elevation (Eqs. 2.1 and 2.2). The ground processing teams average the 20 Hz rate data in pairs to form a 10 Hz data set. The 1 Hz value is then deduced by performing a least absolute deviation fit (LAD) of the 10 Hz values with up to 20 iterations. The 1 Hz value is the fit evaluated at the mid-point (the point between the 5th and 6th range values). Range values that deviate by more than 300 mm are marked as erroneous. There are contingencies though. If the LAD fit fails to converge, or if there are more than two erroneous range values, or if the slope of the fit is too high (3,000 mm/1 Hz), then the 1 Hz value is taken as the original median value (average of the 5th and 6th range values). In this latter case, it is assumed that the logic then checks the deviations of the 10 Hz values from this new 1 Hz value. Certainly from the observation of the T/P GDR data stream in these cases (over severe terrain or narrow river regions), as few as two 10 Hz range values can be accepted and pass unhindered into the data streams for the user to examine.

The Jason-1 data sets are also based on 20 Hz measurements with assumed similar deviation and iterative methods as per T/P. However, there are subtle differences in the processing. First, the 20 Hz measurements are not averaged into pairs to form 10 Hz values. Secondly, the criteria for the formation of the 1 Hz average appear to be based simply on having more than three valid 20 Hz values. If this is not the case, then the 1 Hz and the 20 Hz values are all defaulted in the IGDR. This condition was additionally tightened during cycle 46, when the minimum number of acceptable 20 Hz values was raised to six. This change in the formulation criteria of the 1 Hz values between T/P and Jason-1 had certainly resulted in data loss over some lake targets.

The program team expressed this data-loss concern to AVISO in the summer of 2003, and suggested that the full 20 Hz range values be included in the Jason-1 data stream whether deemed valid or not by the filtering algorithms. AVISO formally acknowledged the problem at the Jason-1 Science Working Team meeting in Arles, France in November 2003, and issued a "Request for Modification" on February 24, 2004. Ultimately though the problem could not be resolved as further discussion revealed that additional onboard filtering, which rejected data according to characteristics of the radar echo shape was also operating and could not be changed. Overall, there was a considerable loss of data over smaller lakes with calm-water surfaces that lacked significant wave height formation, and for those targets that had a greater standard deviation of range values along the ground track.

2.7 Preliminary Benchmarking and Product Validation

The GRLM was initiated as a USDA-funded project, but in 2004, NASA requested that an Applied Science Program Management Group document and observe the system, noting the use of products derived from NASA satellites. An "Integrated Product for Agriculture Efficiency Team" from NASA/Stennis Space Center led the study, outlining the USDA DSS, the role of the radar altimetry and the recording the program's successes and limitations. The output of the study became the basis of the first systems engineering report (McKellip et al. 2004) and later the validation and verification report (Ross and McKellip 2006). Both reports focused on the early T/P and Jason-1 lake products that were available at the time. The team compared the original system requirements with the final T/P and Jason-1 output and assessed the latency and spatial distribution of the products. They found that during the operational phase, the latency on the near-real-time product output varied from ~20 days in 2004 to ~10 days in 2005, and although the number of acquired lakes was only 70 of the original 178 potential lakes selected by the OGA, the products revealed lake-level status on every continent with the exception of Australia. The results also highlighted the known problems of acquiring the smaller targets (<300 km^2) and those situated within narrow valleys or in rugged terrain. Other factors that could cause or affect delay on data delivery were also discussed and the unexpected demise of the Jason-1 IGDR data was highlighted, the limitation affecting half of the lakes in the GRLM program.

Historical T/P validations showed accuracies ranging from ~3 to ~5 cm RMS (e.g., Fig. 2.1a for Lake Ontario) to several tens of centimeters depending on target size, location, and surface roughness. These studies used ground-based gauge data, selecting the gauge nearest to the satellite overpass (or averaging multiple gauge measurements) and interpolating the gauge measurements to the time of the satellite overpass. Such validation methods are considered "absolute" although the altimetric process is based on averaging

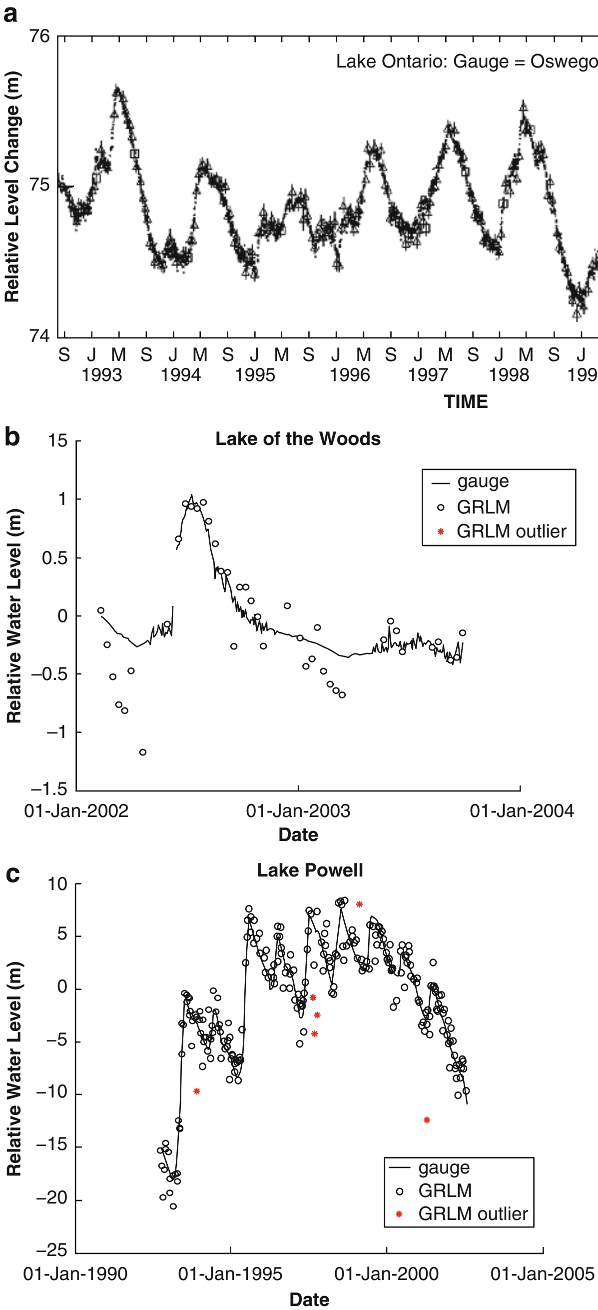
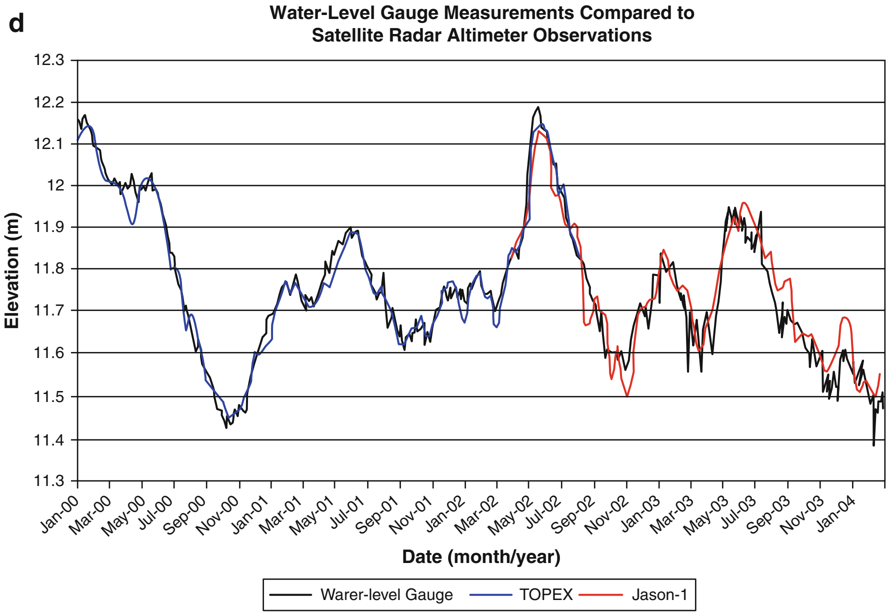


Fig. 2.1 Validation examples for (**a**) Lake Ontario (T/P), (**b**) Lake of the Woods (Jason-1), (**c**) Lake Powell (T/P), and (**d**) and (**e**) Lake Victoria (T/P and Jason-1). Note the reduction in accuracy for Jason-1 IGDR in comparison with T/P GDR for Lake Victoria (**d**) because of improved satellite orbit knowledge in the more delayed (30 days) GDR satellite data set. Lake Powell and Woods figures are courtesy of McKellip et al. (2004)



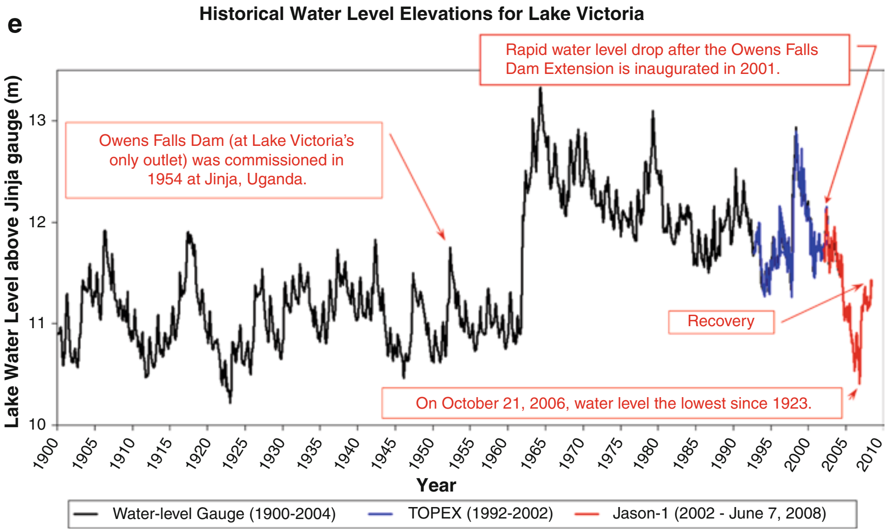


Fig. 2.1 (continued)

and there can be considerable separation distance between gauge site and ground track location. Relative validation checks can also be conducted testing one satellite product against synergistic measurements from another although errors will be introduced from comparisons of non-coincident satellite ground tracks. The GRLM benchmarking exercises revealed product errors of 5–7 cm RMS for the Great Lakes, increasing to 20–30 cm RMS for the smaller lakes (e.g., Lake of the Woods in Fig. 2.1b after removal of erroneous winter results due to the presence of lake ice). Surprisingly, the NASA/CNES instruments were able to acquire Lake Powell, and although the RMS error was ~1.6 m, seasonal and inter-annual trends could still be observed (Fig. 2.1c). The USDA/FAS also compared the T/P and Jason-1 products for Lake Victoria with gauge data from Jinja. Fig. 2.1d shows the difference in accuracy between the use of GDR (T/P) and IGDR (Jason-1) (e.g., 2.5 cm RMS compared to 5 cm RMS for the tandem phase in 2002) and Fig. 2.1e shows the merger of altimetry products onto the historical gauge data record.

Overall, the benchmarking team concluded: "So far, the program has made great strides towards meeting the immediate needs of the OGA, and the requirements of other intra-governmental and public users. Product latency typically falls with the desired limits, products span the globe touching on many crop production and crop security regions, and product accuracy is sufficient for many lakes and reservoirs in the GRLM system". The team recommended though that (a) the original accuracy requirement be relaxed for lakes with very large seasonal amplitudes, (b) the Jason-1 data drop out should be further investigated and (c) the lake coverage be increased. They additionally noted the possibility of utilizing Moderate Resolution Imaging Spectroradiometer (MODIS) derived lake area measurement to enhance the products.

2.8 T/P and Jason-1 Product Revision

As emphasized in the early benchmarking reports, the rejection of non-ocean-like Jason-1 radar echoes, totally or intermittently, affected almost half of the on-line lake products in the post-2002 time frame. While Jason-1 data recovery efforts continued some enhancement of the existing T/P and Jason-1 products took place in the form of a re-computation of the relative height bias i.e., the shift in elevation required to bring the Jason-1 mission products in-line with the T/P products.

A mean bias of 9 cm had originally been applied to the Jason-1 IGDR (Version 1) products but further investigation of the atmospheric corrections within the T/P GDR and Jason-1 IGDR data sets pointed to differences in the models used to construct these parameters. This had the potential to introduce a regional bias with respect to the dry tropospheric correction that should be similar at the same location and time period during the validation phase. In addition, results from Beckley et al. (2004) indicated regional bias variability due to orbit differences arising from inconsistencies in the use of differing terrestrial reference frames. The T/P orbits are based on the Center for Space Research CSR95 terrestrial reference frame, whereas the Jason-1 orbits are based on the more recent international terrestrial reference frame ITRF2000. The largest translation velocity differences between the two reference frame realizations occur along the Z-axis (Morel and Willis 2005) resulting in a north–south asymmetry in the orbital radial height differences. By accommodating for the differences in the terrestrial frame, and the atmospheric models, the TOPEX (ALT) and Jason-1 inter-mission bias was recalculated once again, on a lake-by-lake basis, using the mean (single iteration 3.5 sigma edit) of the collinear height differences in the mission overlap period. The enhanced products were upgraded to version 2 and placed online.

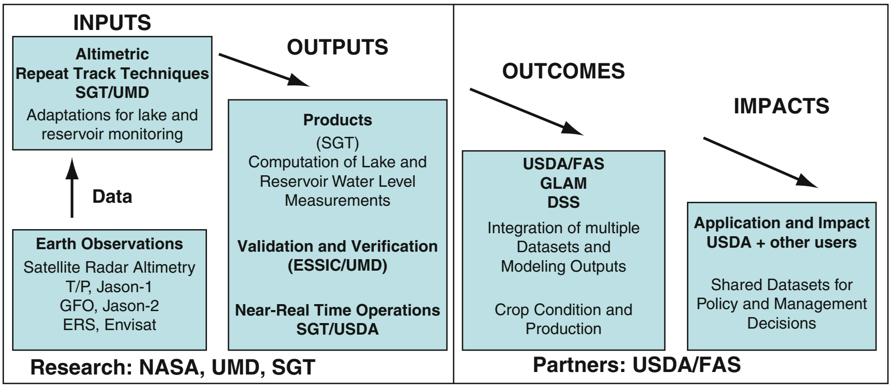


Fig. 2.2 The Integrated Systems Solutions (ISS) architecture of the GRLM

2.9 GFO Products and Further Validation

In 2006, NASA provided financial support allowing the NRL GFO mission data to be utilized and supplement the loss of data from the Jason-1 mission. Phase III of the program then came under the auspices of the NASA Applied Sciences Program where the team's collaborative effort, from data processing, product output, and utilization, were seen as an Integrated Systems Solution (ISS) (Fig. 2.2) to the USDA's DSS.

The Naval Research Lab's GFO mission was launched on February 10th, 1998 with a 17-day repeat cycle. Initial problems delayed data retrieval, and so valid operations did not commence until January 2000 (cycle 36). The mission was given a ~9 year life expectancy and by the fall of 2006 energy problems forced the instrument to be cycled off/on. The meant that the instrument was only operating during select periods of certain overpasses. As per the T/P and Jason-1 data sets, the GFO data set is freely available, but permission was sought for and granted by the National Oceanic and Atmospheric Administration (NOAA) to use the GFO data within the program. The GFO GDR data were thus ftp downloaded from NOAA (ftp://eagle.grdl.noaa.gov) for the post-2000 period and the number of on-line lake/reservoir targets crossed by this satellite was noted. Concentrating on those lakes that lacked Jason-1 data, the intersection of the GFO ground tracks with these 35 targets was estimated.

With ocean science objectives, the GFO data interpretation was assumed to be fairly straightforward following that of the T/P or Jason-1 processing chains. With minor modifications then to allow for changes in data structure between T/P, Jason-1 and GFO, the GFO data were then assembled into the time-tagged altimeter parameter database. The examination of the GDR data parameters, construction of lake water level and subsequent computation of GFO lake-level products followed the T/P, Jason-1 process with minor modifications and notes as follows:

(i) GFO Data: Two GFO products are currently available; (1) the operational data containing the Medium Precision Orbit Ephemerides (MOE) that are available 1–2 days after satellite overpass with radial orbit precision ~10–20 cm, and (2) a GDR product based on precise orbit ephemerides (POE) having a latency of ~3 weeks and a radial orbit precision ~3–5 cm. The GDR data was selected for the GRLM. It should be noted that the precise orbit for cycles 36 to 69, and for cycles 70 onward is derived by NOAA and NASA/GSFC, respectively, with more precise accuracy expected for the latter. However, there is an ongoing reprocessing of all the GFO orbits at NASA/GSFC based on (a) an improved gravity field from the NASA Gravity Recovery and Climate Experiment (GRACE) Satellite Mission, (b) an updated reference frame ITRF2005, and (c) other significant geophysical modeling improvements. In the future, this could provide high-class altimetry precision for the entire GFO mission (Lemoine et al. 2001).

(ii) GFO surface elevation: As per T/P and Jason-1, construction of the GFO surface elevation is conducted by differencing the GDR 10 Hz range parameter value from the satellite orbit parameter, and applying a number of geophysical, environmental and instrument-based corrections (Eqs. 2.1 and 2.2). Note here that the center of gravity range correction is already applied to the range parameter in the GDR (via net instrument correction). The GFO utilized a single frequency altimeter and thus the ionospheric path delay is not estimated directly as with the dual frequency altimeters onboard T/P and Jason-1. Instead, the ionosphere path delay is derived from GPS observations (from the Jet Propulsion Laboratory (JPL) Global Ionospheric Maps (GIM)), or from the international reference ionosphere model IRI95 (Bilitza et al. 1995). The dry and wet atmospheric delays are also derived differently. The dry correction stems from the Navy Operational Global Atmospheric Prediction System (NOGAPS) surface pressure data. The wet tropospheric delay is measured by a two-channel (22- and 37-GHz) microwave radiometer, or, when inoperable, the NOAA National Centers for Environmental Prediction (NCEP) model.

(iii) Geo-referencing: A 17-day reference orbit is generated from the GSFC orbit determination and geodetic parameter estimation (GEODYN) orbital software based on GFO orbital parameters and available satellite laser ranging (SLR) tracking. Geo-referenced locations along a nominal reference orbit are interpolated at 1 Hz using a Hermite 10th order interpolation algorithm. The GDR data are then aligned to these 1-s locations by constructing perpendiculars from the reference orbit to the actual orbital track location and linearly interpolating from the surrounding along-track data.

(iv) Collinear heights: The collinear surface height is computed from a linear fit of the 10 Hz GDR height values with the midpoint evaluated at the 1 Hz reference locations. The high rate 10 Hz heights are then geo-referenced with respect to time at exact 0.1 s intervals by indexing the closest 10 Hz height rather than interpolation of adjacent 10 Hz observations, to preserve as many lake heights as possible. The maximum 10 Hz along-track alignment error (at the equator) for GFO is less than 0.05 s translating to 0.28 km. The estimated error of the mean height profile at each 10 Hz location is further reduced by virtue of averaging over a period of 6 years (cycle 37–166, January 2000 to December 2005).

(v) Inter-mission bias: As previously noted, revised height bias estimates between T/P and Jason-1 were computed for each lake to minimize regional variability due to geographically correlated orbit error and path delay estimates. Since the GFO is not spatially coincident with T/P and Jason-1, a more "ad hoc" bias adjustment was performed by minimizing cycle-to-cycle mean height differences between the GFO and Jason-1 height differences with increased weight given to observed differences during the T/P, Jason-1 verification phase. The result was an arbitrary (but constant) height-shift to the GFO results to bring them visually in line.

(vi) GFO data filtering: GFO data filtering was performed by comparison of individual 10 Hz height observations with respect to the 6-year mean reference that is constructed at each 10 Hz along-track geo-location. Individual along-track height profiles were interrogated for each cycle in an effort to identify land/island contamination to construct a representative mean profile. Note that no GDR "erroneous elevation" flag parameters were utilized.

GFO lake products, each with respect to its own 6-year reference datum, were easily calculated, but the USDA requirement to place all mission results onto one graph revealed both amplitude and phase-lag differences despite attempts to correct for inter-mission height bias. The effects were more marked for some lakes than others. One explanation centers on the fact that the satellite ground track locations differ between the instruments that are thus sampling water variations at differing locations within the lake. Without resources to explore this further, the team decided to select only the best T/P, Jason-1, GFO-merged products (15 out of the original 35) which were assigned version number 1, and uploaded to the Crop Explorer GRLM web site as a separate clickable graph and text file. Some of these targets (e.g., Lake Nasser, Fig. 2.3) benefited

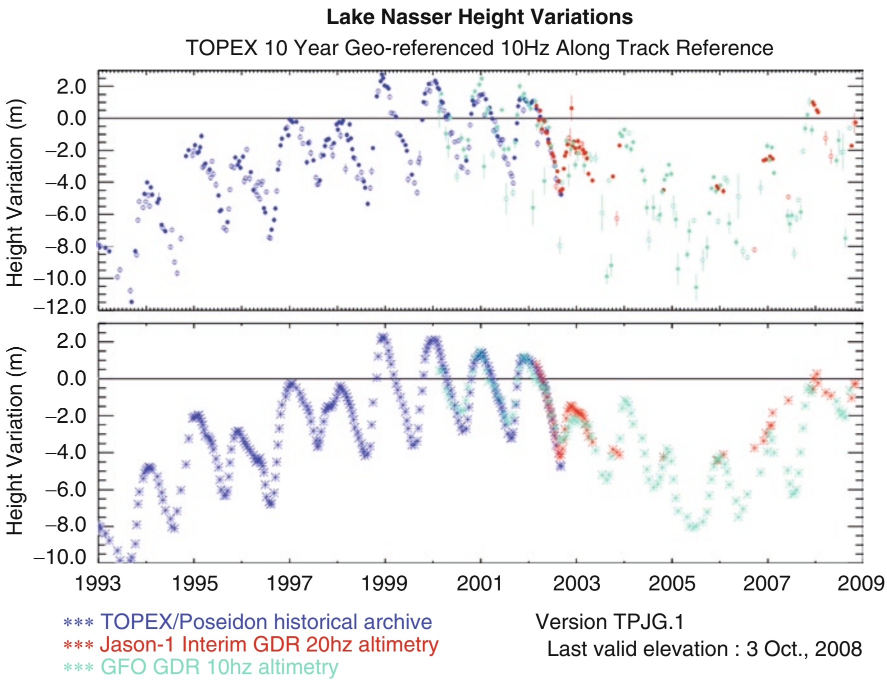


Fig. 2.3 Surface elevation product for Lake Nasser/Aswan High Dam (T/P blue, Jason-1 red, GFO green). Raw results (top), smoothed result (below)

Table 2.2 Validation of GFO Great Lakes Products

Lake	Pass	Gauge site	RMS[1]	RMS[2]	RMS[3]
Erie	069	Cleveland 9063063	14.66	14.53	14.04
Ontario	155	Rochester 9052058	23.96	23.68	13.69
Michigan	141	Calmut Harbor 9087044	12.12	12.36	12.36
Huron	227	Harbor Beach 9075014	14.01	13.88	11.40
Superior	055	Marquette 9099018	27.33	27.33	13.41

Gauge data are courtesy of NOAA and are verified 6 min or hourly products. Altimetric results are paired with one nearest gauge site. Gauge versus altimeter RMS values are for 6 min (1), hourly (2), or hourly with removal of major altimetric outliers (3). Outliers are cycles 065, 102, 131, 171 (Lake Ontario), cycle 148 (Lake Erie); cycles 104 and 105 (Lake Erie), and cycles 104 and 107 (Lake Superior)

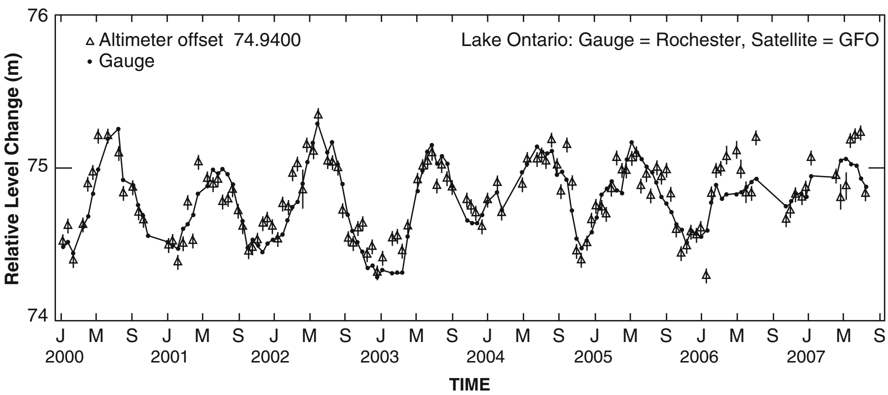


Fig. 2.4 Validating the GFO altimetric time series of height variations for the Great Lakes with ground-based hourly NOAA gauge data, example Lake Ontario

greatly from the additional GFO data, but GFO validation exercises over the Great Lakes (the results of which can be translated to other similar large bodies of water) showed accuracies ~15 cm RMS (Table 2.2, Fig. 2.4). In comparison with T/P and Jason-1, these are poorer and are themselves a cause for further investigation. Relative validation exercises between GFO and T/P, and GFO and Jason-1, were not deemed feasible because of the differences in satellite pass location, overpass time, and the computation of mean reference datum.

As per the NASA/CNES missions, other GFO target data losses are attributed to the poor acquisition of water levels for smaller targets or failure in complex terrain. Discussion with NOAA (J. Lillibridge, 2007, personal communication) also suggested that the data filtering procedures between the GFO SDR and GDR (in particular the use of the high bandwith/low variability RA Status Mode I flag) could also be placing restrictions on the amount of lake data being initially stored on the GDR. The possibility of reprocessing the

SDR/GDR and additionally updating the GFO satellite orbit to a higher precision has been suggested and noted as a future possibility.

2.10 Program Limitations

With nadir-pointing technology not dedicated to inland water monitoring, a number of data limitations were inherent at the start of the program. In addition, several other factors are important to note. At the top level, the program depends on the continuity of funding, both at the space agency level for ensuring follow-on missions, and also at the NASA/USDA program level, which maintains manpower support for product creation and delivery. The continuation of lake products is also obviously dependent on the lifetime of the satellite mission and during flight time it is not improbable to expect both satellite and instrument anomalies that result in data loss. The onboard and ground processing of the raw altimeter data prior to the formation of the IGDR/GDR may also be affected by data filtering and quality control that does not have inland water priorities. The instrument-tracking logic is also crucial to acquiring the lake surface. It determines how quickly the lake can be detected and how fast it can recover if lock is lost over the nearby terrain (Sect. 2.14). Because there can be several hundred meters separation between repeat passes, the same approach topography is not always sampled and subtleties can cause data loss if the instrument follows other smaller water bodies or surrounding topography.

As an operational program with a semi-automated system, the program team needs to ensure man-power backup to maintain continuity of the weekly updates and be readily accessible to answer queries from USDA/FAS and a wide variety of other users. Although technical information is on the GRLM web site, questions on reference datum, height accuracy, target size, and product accuracy do continue to demand further explanation. Users also make requests for additional lake targets to be included when they are not included in the USDA targets of interest list. Requests have also been made for similar products for wetlands and rivers, but as per the non-agriculture lakes, these are outside the objectives of the program. With the products in the public domain, the team has also had to consider liability and the placing of a limitation clause on the world-wide-web site. This was particularly in consideration that the products continue to be subject to further investigation and revision.

The USDA and other users are disappointed at the number of targets observable by the T/P and Jason-1 missions and at the lack of smaller targets on-line. This will improve in Phase IV (see next sections), as additional mission data sets are utilized. However, the exercise with the GFO data and consideration of the ERS/Envisat data sets does pose an interesting technical question as to how to combine results from differing missions. For those missions in the same orbit, where the follow-on mission operates synergistically with its predecessor during a "tandem-phase", the height bias between the two instruments can be deduced and the products merged. With different mission orbits the instruments are sampling lake surfaces at different locations where wind, ice, and other surface characteristics differ. In complex regions suffering from the effects of excessive abstraction of water or drought (like the Aral Sea and Lake Chad), phase and amplitude differences between observed variations found across the basin will also be common. We have no answer to this problem at the present time other than to attempt mergers based on crude “eye-balling” , that is, simply shifting vertically one deduced time series to another for visualization only (as per GFO) or to deliver products on separate graphs.

Another technical issue of importance relates to the calculation of the lake mean reference datum. The T/P and Jason-1 products are based on a lake datum that is calculated from 10 years of T/P measurements. In the case of GFO, each mean reference datum is based on only 6 years of archival data. Although the GFO mean datum could be revised now that ~8 years of GDR data have been acquired, this averaging could also introduce a height bias and/or an offset that affects the match when aligning GFO with the T/P and Jason-1 results. The product accuracy can also be affected by the presence of lake ice, which we do not reject or correct for but attempt to flag on the product graph via the use of the radar backscatter coefficient. For many targets, the wet tropospheric range correction must also rely on model-derived values rather than instrument-derived. Although we assume a height error for the model-correction application, this is really a mean global value, and there is no attempt to place a magnitude on the error when the model value is absent from the IGDR or GDR data streams. Lastly, it must be stressed that there will be differences in product errors between the use of the IGDR (near real time) and GDR (archival). IGDR and GDR data sets use medium- and high-precision orbits, respectively (Fig. 2.1d), so there is loss in accuracy at the near-real-time level. Although recent science working team discussions are suggesting that with streamlined orbit-calculating processes the precision of the IGDR orbits will improve, a future phase of the program could include the revision of the IGDR-derived products with those from the GDR when available.

2.11 Products and Applications

The web–based portal, Crop Explorer, is a crucial part of the OGA operational decision support system with both an internal FAS analysis and public access functionality (http://www.pecad.fas.usda.gov/cropexplorer). On multiple occasions, it has been cited by the Office of the Secretary as a flagship example of USDA’s effort to assist food-deficit countries and recently won the Environmental Systems Research Institute (ESRI) “Special Achievement in GIS” award in April 2007. Statistics show that Crop Explorer receives approximately 40,000 hits and 2000 visits per day, with 85% of the visits from the US and 15% of the visits from international visitors.

A link within Crop Explorer allows users to enter the GRLM, the front-end global map depicting target locations and the overall lake-level status (red/low water, blue/high water) with respect to a 1992–2002 mean. Each lake or reservoir target can then be selected via a series of clickable maps. The first displayed products are the combined T/P and Jason-1 in graphical form, depicting 15 years of monthly, seasonal, and inter-annual variations as well as revealing overall trends (Fig. 2.3 and 2.5). Each graph displays the raw (top) and

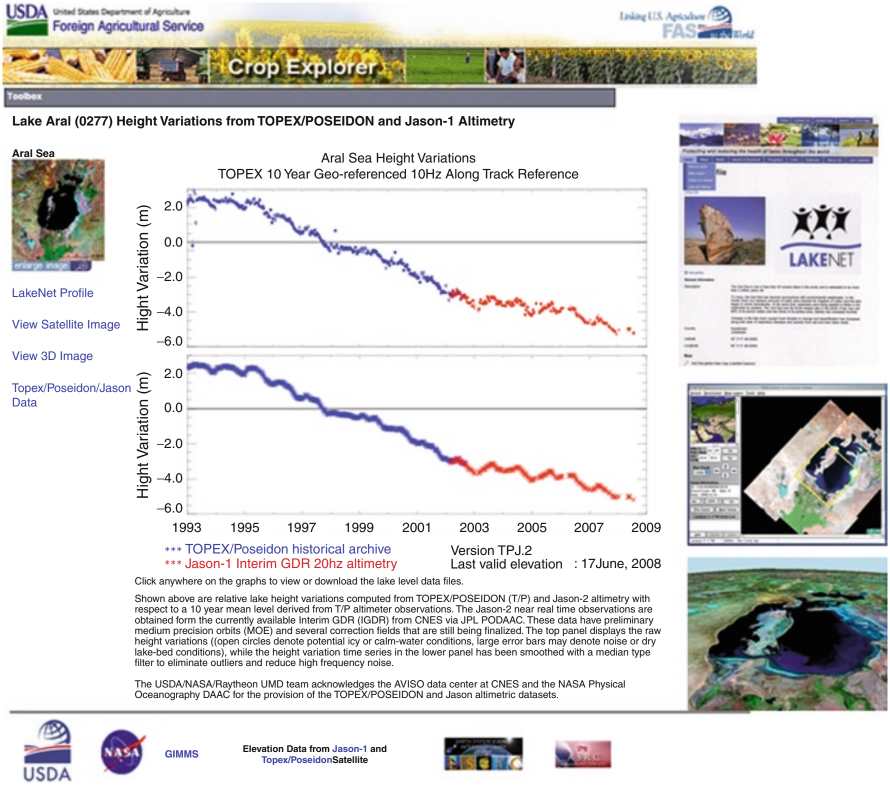


Fig. 2.5 An example of the information given in the Global Reservoir and Lake Monitor (GRLM) with focus on the Aral Sea. Through collaborative efforts, visitors to the web site can access Landsat and MODIS satellite imagery through a USGS visualization tool and connect to the LakeNet database to retrieve characteristics and biodiversity information

smoothed results (bottom), the smoothing performed with a median-type filter to eliminate outliers and reduce high-frequency noise. Error bars are given on the raw height values and estimated as per the method outlined in Birkett (1995). Clicking on a graph enables the download of the associated ASCII text file. Clicking on an additional link to the side of the page enables the display of the combined T/P, Jason-1, and GFO product. For visualization of the lake and satellite overpass location, Landsat imagery and MODIS Land Cover Classification are provided and additional imaging sources provided via a United States Geological Survey (USGS) Global Vizualization Viewer tool. An additional web link also provides access to the World Lakes Network (LakeNet) information database.

Within a short time period, the USDA DSS transitioned from a state of no direct water storage information to having access to T/P, Jason-1, and GFO water-level products for ~70 of the worlds largest lakes, reservoirs, and inland seas. In particular, the Middle Eastern and African (Lake Victoria, Nasser, Volta and Kariba) lake products have proved most useful. For example, FAS regional analysts used the GRLM products for Lakes

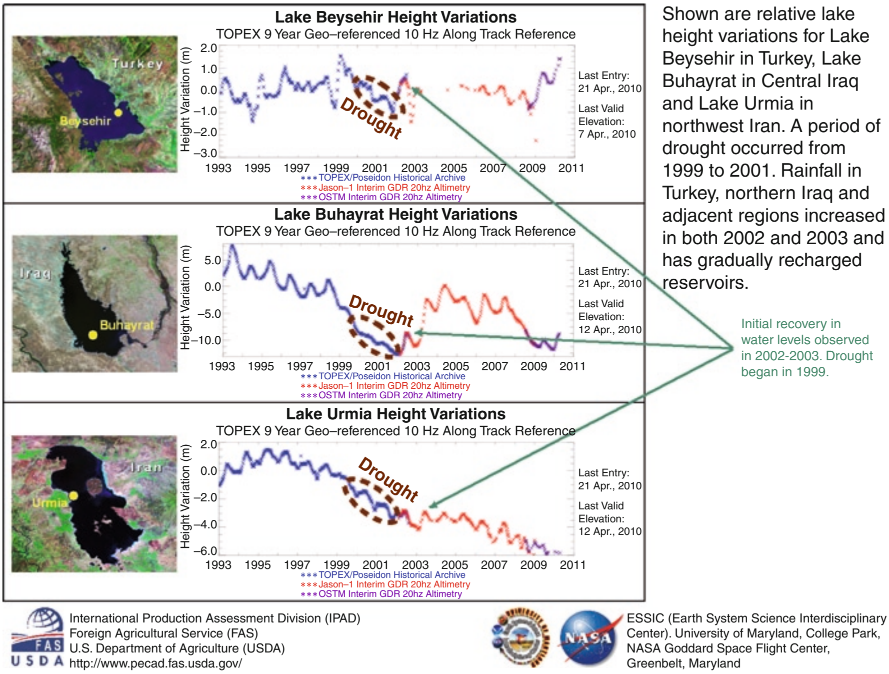


Fig. 2.6 GRLM products used to support an OGA regional analyst's discussion regarding a recovery from drought in the Middle East (Anulacion 2003). The analysts linked regional wheat production and the general state of the reservoirs to regional weather trends. (Example taken from McKellip et al. 2004)

Beysehir, Buhayrat, and Urmia (Fig. 2.6), to examine the recovery from 1999–2001 drought conditions in the regions. In these cases, it was the recharging of the reservoirs with respect to ground water reserves for winter wheat and barley production that was of concern (Anulacion 2003).

In the case of Lake Victoria, current low-level water reports led to discussions of regional drought and the Owen Falls Extension (the Kiira Dam) as potential causes. The Owen Falls dam was completed in 1954 just below the Ripon Falls, but under an agreement it was to be operated so that its outflows through both turbines and sluices were to be controlled to conform to a relation known as the “Agreed Curve”. With water levels rivaling the lows of 1923, excessive withdrawals for power generation in Uganda from April 2002–October 2006 were discussed by Reynolds (2005) and Reynolds et al. (2007), with the GRLM products providing accessible and up-to-date records (Riebeck 2006). Mangeni Bennie (2006) later suggested that the Agreed Rule curve had been ignored and reservoir operation during this time had been in violation of the 1954 Nile Treaty. Sutcliffe and Petersen (2007) agreed with this result and announced that as much as 0.6 m of water level (~50%) decline was attributed to excess abstractions. The dramatic water-level drop has caused extensive environmental and economic losses and the effect on rapid population growth in the region has been highlighted (UNEP 2006).

To summarize, since implementation the GRLM has become the 9th most popular Crop Explorer page with (a relatively long) average viewing time of over two minutes. Since integration, it has received much publicity (Reynolds 2005; Riebeck 2006) with its content attracting the attention of FAS foreign resource analysts, international governments, humanitarian organizations, and conservation groups. A number of commercial, military, organization, government, and educational departments have also expressed interest along with network groups such as the Great Lakes Information Network (GLIN) and LakeNet. Other users include the World Bank, the United Nations, the USGS (both in general and through the Famine Early Warning Systems/United States Agency for International Development (FEWS/USAID)), the National Geospatial Intelligence Agency (NGA), and international organizations such as Genesys International Corporation Ltd. (India), the Lake Balaton Development Coordination Agency (Hungary), and the Research Hydraulic Institute in South Brazil. Applications cover many aspects relating to water quantity and quality. In addition to irrigation potential/agriculture impacts, users have been concerned with fish productivity, water security, vegetation ecology, and information theory metrics relating to ecological surveillance monitoring decisions.

It is interesting to note that several research groups have also utilized the lake products as a means to validate results from the GRACE mission (e.g., The Caspian Sea and Lakes Malawi, Swenson et al. 2006; Lake Victoria Malawi and Tanganyika: Swenson S.C. and Wahr J. 1997, personal communication) while other users are focused on basin or continental-scale hydrological modeling. With a continuous product series that spans more than 15 years, the data products are also attracting attention from the Intergovernmental Panel on Climate Change as a potential set of proxy climate data records.

The importance of monitoring surface water for a variety of applications is also recognized by the fact that since its inception in 2003, the GRLM has been joined by two other web-based databases containing altimeter-derived surface water levels. The ESA/De-Montfort University (UK) River and Lake web site (viewed at http://tethys.eaprs.cse.dmu.ac.uk/RiverLake/shared/main) offers near-real-time water-level products derived from the ESA Envisat mission via point and click target selection methods and product access via registration. Here, the time resolution of the product is 35 days and lake/reservoir and river channel variations are included. The Laboratoire d'Études en Géophysique et Océanographie Spatiales (LEGOS) also display lake, reservoir, river, and wetland elevations within their web-based database at http://www.legos.obs-mip.fr/soa/hydrologie/hydroweb/. Currently, there is a few months lag on product output but here the user can visualize the ERS, Envisat, T/P, Jason-1, and GFO satellite tracks across Landsat imagery and access additional location and hydrological data for each target. Point and click access to graphs and text files gives surface water variations for the 1992–2009 time period for ~100 lakes (dominated by the T/P and Jason-1 data sets) and ~250 river locations (using several altimetric data sets). There is thus similarity between the programs, although the GRLM remains primarily as a monitoring tool within a much larger decision support system. Nevertheless, multiple sites offer scope for additional checks on output, serving to verify product accuracy via cross-validation, and leads the way to future discussions on methodologies, formats, and standards.

2.12 Current Status

From mid-2008 the operational program received new funding from the NASA Applied Sciences Program and additional funding from USDA/FAS to take the program into phase IV with product expansion and enhancement objectives using both NASA/CNES and ESA satellite data sets. Because the GRLM had been on-line for several years, the USDA/FAS could examine past performance and revise the original system requirements. The objectives though remain the same with agriculture efficiency as the national (and international) priority topic of interest and maintaining relevance to the NASA Earth Science Division goals.

Past performance of the GRLM in the DSS were based on (i) findings within the McKellip et al. (2004) and Ross and McKellip (2006) reports, (ii) the compilation of verbal and written feedback from the FAS resource analysts and general users, and (iii) web statistics that were monitoring public access to Crop Explorer/GRLM. A review of these sources led to the revised 2008 DSS requirements:

(i) To observe the maximum number of lakes possible, with particular focus on acquiring the smaller (100–300 km^2) reservoirs in all terrain types.
(ii) To focus on water bodies in agriculture-sensitive regions such as Thailand, Iran, Iraq, Turkey, Argentina, India, Africa, Brazil, and Australia.
(iii) The weekly near-time product updates are to continue, with time since last satellite overpass set at no more than ~1 month.
(iv) To have products accurate to better than 20 cm RMS, or better than 10% of the expected total seasonal amplitude. The accepted accuracies must allow for monthly, inter-annual, and long-term trends to be readily discernible.
(v) To regain lake-level information that was missing from the Jason-1 data stream or Jason-1 observation period.
(vi) To assemble all the mission lake products onto one timeline graph, if permissible, within the scope of the repeat track techniques.

In general, the new FAS requirements satisfy other web user demands noting that complete global coverage of all lakes is not within the scope of the current radar altimetry capabilities (see Sect. 2.15). Overall feedback showed that a product temporal resolution of 10 or even 30 days is not being rejected, particularly for those regions where any form of current or historical gauge data cannot be acquired. Users have requested though the ability to download all lake products as one data set and have requested additional information on the construction and interpretation of the reference datum for each lake. Users, in general, also had interests in seeing additional lake basin parameters (areal extent, lake temperature and salinity, surrounding soil moisture, land cover, local precipitation etc.) being made available via a one-click map tool.

The new requirements demanded the use of additional radar altimeter mission data sets to expand lake numbers. The enhancing of existing products also focused attention on the possible merits of the SDR, the replacing of IGDR-derived products with those that were GDR-based, and on data filtering algorithms in general. Although the ISS remains the same, the GRLM system has to be modified in terms of (i) making additions to the system software to account for new data structures, (ii) expanding the on-line altimetric parameter database, and (iii) modifying the lake-level product determination software to accept multiple iterations to the altimetric range parameter based on new verification and validation exercises. There are thus several objectives within Phase IV. First, it allows the current Jason-1 and GFO products to be improved in terms of quality and quantity. It also extends the current 15-year timeline with near-real-time products derived from the follow-on Jason-2 mission (also called the Ocean Surface Topography Mission or OSTM, which was launched in June 2008 and is a joint collaboration between NASA, CNES, NOAA, and the European organization for the exploitation of meteorological satellites (EUMETSAT). With Jason-2, there are no foreseen "missing lake data" problems as per Jason-1. Also, via the inclusion of ESA ERS-1 and ERS-2 (archive 1994–2002) and Envisat (post 2002 and near-real-time) data, the number of targets in the current system will increase by at least a factor of 5. This step greatly enhances the DSS by the inclusion of a large number of smaller reservoirs (100–300 km^2), and additionally provides a means to validate the current T/P and Jason-1 products in regions where ground-based gauge data cannot be acquired.

The operational tasks of the system will of course continue with near-real-time products derived from the Jason-2 and Envisat missions and evaluation studies will run in parallel. These studies are a strong component of Phase IV under the guidance of the NASA Applied Sciences Division who request at all times that the project, the products, and the program team adhere to benchmarking and continuous evaluations that continuously assess the system and the usefulness of the products within the DSS. At the end of Phase IV, a final report will list these findings along with technical issues and validation results and the revised program system requirements will be once more be re-examined.

2.13 Phase IV Tasks

Specific GRLM system revision tasks reside in four main categories with focus on specific mission data in each,

(i) Target selection, Data ingestion, Parameter database creation: This includes the identification of all targets of opportunity in terms of exact geographical location of satellite crossing from coastline to coastline.

(ii) Parameter database revision: This pertains to the refining of the parameter database based on benchmarking exercises.

(iii) Formation of new or enhanced lake products: For coastal regions and small targets where the radiometer-derived wet tropospheric range correction is absent, improvements to model-based atmospheric corrections or combination methods will be sought to improve current lake height products (see the chapters by Andersen and Scharroo, and Obligis et al. this volume). The main focus though will be on new ERS, Envisat, and Jason-2 products which will be derived using methods based on various retracking techniques to more accurately acquire the altimetric range (see Sect. 2.14). The

Envisat products will be water-level variations based on a mean height datum calculated using ~8 years of ERS elevation measurements. Improved Jason-1 (via GDR Version C) and GFO products will be sought.

(iv) Benchmarking: This entails project and program performance measures, and includes validation and verification exercises with additions and refinements to the mission parameter database.

Overall, there are three demonstration points within Phase IV, the time at which (1) the Envisat/ERS products go on-line, (2) the Jason-2 products go on-line, and (3) the refined Jason-1/GFO products are updated. Phase IV also includes a set of project management metrics and performance measures, the latter being observed on both the product creation and delivery side, and on the product utilization side. Project management metrics, for example, include the monitoring of the number of tasks started and completed on time, the percentage of achieved deliverables within a given quarterly period, and the number of iterations a product undergoes vs. its usefulness to the DSS.

Performance measures (product creation and delivery) will follow those of the first benchmarking exercise and will include a number of tracking measures to ensure project efficiency. Such measures include the weekly noting of raw data and product latency, the spatial coverage (continent) and target type (open lake/reservoir) of products, and the monthly compilation of end-user response and feedback to assess correct prioritizing of targets compared to regional focus requirements.

The USDA/FAS performance measures (product utilization) will be defined from the 2003 NASA benchmarking process and the decision support tools evaluation report for FAS/OGA (Hutchinson et al. 2003). The expectation here is that the performance metric program for GRLM will merge with the existing program through an initial benchmark update and if needed modification to the USDA evaluation questionnaires that are utilized. Four types of questionnaires are used. Two of these cover aspects of crop analysis, one concentrates on information technology, and the fourth includes aspects pertaining to management. One of the crop analysis questionnaires uses the Defect Detection and Prevention (DDP) methodology and tool that was developed by NASA's Jet Propulsion Laboratory (JPL) (Cornford et al. 2001). This DDP tool is intended to facilitate risk management over the entire project life cycle beginning with architectural and advanced technology decisions all the way through to operations. Each questionnaire type though targets the decision makers and DSS support functions. Therefore, the metric will be defined based upon improvements to analysis and efficiency of support. Improvements in analysis can be both subjective (e.g., relevance, quality, etc) and objective (e.g., latency, frequency, accuracy, etc) assessments and the evaluation periods are based upon ad hoc events (such as disasters) and growing seasons (crop estimates).

2.14 Anticipated Phase IV Results

The NASA/CNES missions are primarily aimed at ocean applications, but the ESA missions have multiple science objectives and their methods of tracking the ever-changing and complex terrain are more sophisticated. The radar altimeters onboard the ERS-1 and

ERS-2 had two tracking modes, ocean-tracking mode (for sea surfaces) and ice-tracking mode (for ice sheets and sea ice). While ERS-1 alternated between these two modes over land, ERS-2 spent the duration of its time over land in ice-mode. The significance here is that in an attempt to capture the echoes from more highly varying terrain, the altimetric range window size (in the time domain) increases by a factor of four. Early studies on the ERS data sets revealed some loss of lake/reservoir data in both the ocean- and ice-tracking modes although the latter clearly performed better over the smaller targets (Scott et al. 1992, 1994). However, compared to T/P and Jason-1, there should be no significant loss of data with Envisat because of a number of onboard trackers that enable "guaranteed tracking continuity" (Resti 1993).

Within the data sets, there will be a selection of range values (Envisat) and range retrieval methods (ERS, Envisat) to choose from according to the radar echo, the shape of which being variable according to surface roughness and complexity. Analysis of the radar echoes and associated range extraction algorithms are therefore expected in the revised GRLM-system as are multiple iterations to the altimetric range value based on the benchmarking exercises. Although the process becomes extended for ERS and Envisat, once the algorithms are finalized the system is expected to become fairly operational. The expected gains in lake and reservoir height measurements, particularly (a) along the coastal regions, (b) within small (<300 km^2) or narrow (<1 km wide) bodies of water, and (c) for targets in complex or highly varying terrain, are significant to warrant inclusion of such post-processing methods (see the chapters on retracking by Gommenginger et al., and Yang et al. this volume).

Phase IV of the program will aim to have more automation of the weekly product updates and have a download facility to access all products at "one click". In response to public feedback, additional information on the use of individual lake reference datum will also be placed on-line. With the inclusion of the ESA and NASA/CNES Jason-2 data sets, we expect the following improvements and enhancements to the original products offered in Phases I, II and III.

(i) An increase in the baseline number of years of observations, maintaining continuity across the products.
(ii) An increase by at least a factor of 5, the total number of lakes and reservoirs in the GRLM. The ERS/Envisat missions cross over ~611 large (≥^{3}100 km^2) lakes compared to the baseline ~70 lakes via the T/P and Jason-1 missions (Fig. 2.7).
(iii) An increase (from 17 to 165) in the number of overall reservoirs.
(iv) Particularly notable is an expected gain of 70 small reservoirs (<300 km^2) and an increase (from 10 to 60) in the number of lakes that are situated within narrow valleys or are surrounded by rugged terrain.
(v) An increase of ~65% in the number of reservoirs in the specific regions of interest (a total of 39 reservoirs in India, Iraq, Iran, Turkey, Brazil, Argentina, Australia).
(vi) An increase by a factor of 10 the number of lakes being monitored in the USA (a new total of 100 of which 35 are reservoirs).
(vii) A greater spatial distribution of lakes spanning all continents with the combined synergistic efforts of NASA, NRL and ESA mission data. The products will enhance and complement each other across a 1992–2010 time span, with the potential for further extension of the baseline time frame to 2015 with future missions.

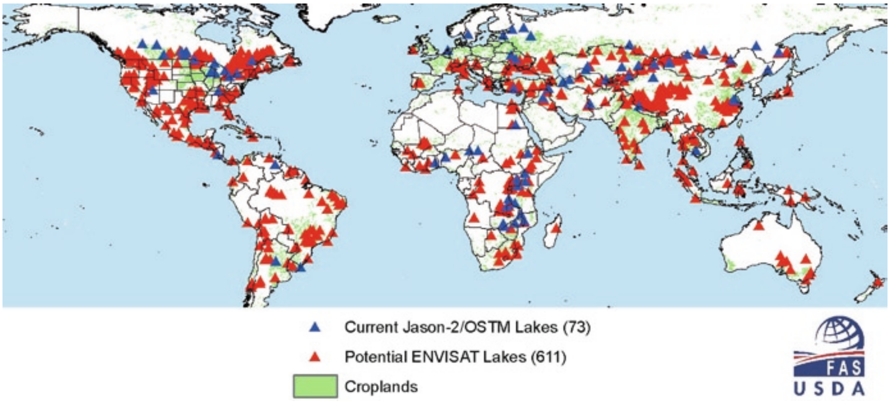


Fig. 2.7 Current lakes monitored by Jason-2 (OSTM) and potential lakes monitored by Envisat

(viii) Lake product accuracy is expected to be 10–30 cm RMS for the ERS-1 and ERS-2 products, 5–20 cm RMS for the Envisat products, and variable (5 cm to several decimeters) for Jason-2.
(ix) Enhanced Jason-1, GFO and Envisat products may improve by ~5–10 cm RMS.
(x) An indication of whether reservoirs <100 km^2 can be potentially monitored to the desired accuracy. This is most applicable to the central and northeastern regions of the USA, and the northern and eastern regions of Europe.
(xi) An increase in use of the products by USDA resource analysts and other end users. A greater efficiency and reliability within the assessments of drought or high water-level conditions across the globe, with improved downstream irrigation potential estimation. Consequences are improved knowledge of consequences on food trade and subsistence measures.

2.15 Summary, Recommendations and Future Outlook

An on-line database of water-level variations has been created for ~70 large lake, reservoir, and inland seas via a joint cooperative project between USDA, NASA and UMD. The elevation measurements have been derived using NASA/CNES and NRL satellite radar altimeter data, spanning an ~16 year time period ranging from 1992 to the present day. The focus is on the provision of near-real-time products in the form of graphical and text output and a semi-automated system, which updates the products on a weekly basis. Under new NASA sponsorship and continued USDA support, the program will also look to the incorporation of the ESA ERS/Envisat and NASA/CNES Jason-2 data sets to greatly expand the number of inland water bodies in the system and to enhance the number of smaller targets and reservoirs. The ultimate goal is the monitoring of at least 500 targets around the world, and the extension of the time line of satellite observations to ~20 years. Progress during the creation of an enhanced system will also contribute to the validation exercises of the various mission Science Working Teams and to future instrument design and data processing techniques in consideration of multi-disciplinary applications.

The GRLM has proven useful to quickly assess drought conditions in various parts of the world and in its enhanced form its use within the FAS DSS will have greater relevance to agriculture efficiency and water resources management in the future. With products in the public domain, the GRLM has also proven useful to many other users across the commercial, government, research, military, non-profit, and private sector domains. The extension of the timeline to almost 20 years, for example, is raising interest within the Intergovernmental Panel on Climate Change (IPCC), where the products are being considered as potential short-term proxy climate data records. The products have also been noted by the United States group on Earth Observations (GEO), in terms of water resources and drought records, and to the Global Earth Observation System of Systems (GEOSS) as a series of comprehensive, coordinated, and sustained observations that can serve as indicators of environmental health status.

Since inception, a number of project and data issues have arisen. To maintain product continuity, continued funding is essential at the satellite follow-on mission, product development, and routine operation levels. Manpower effort also needs to include backup for operational tasks, and the time allotted to respond to USDA and public feedback queries should not be overlooked. Many users felt the need for further detailed information on the products and maintaining a contact point between product developers and end users has been crucial. Benchmarking the program, in terms of ensuring product accuracy and delivery with respect to the original specifications, is also a task that requires regular assessment and revision, noting a level of accountability to both the USDA and other end users.

Regarding the satellite data, the quantity and quality of the products are dependent on a number of factors. With no currently operating dedicated inland water altimetry instrument, there are limitations on target size, and the lack of swath viewing does not achieve global coverage. While ground-based elevation data are reliant on gauge installation and maintenance, satellite-derived products are dependent on the lifetime of the mission and both satellite and instrument will be subject to various operating anomalies affecting data drop out and product latency. Acquiring a particular target and maximizing the number of elevation measurements across its extent (to improved range accuracy) will also depend on the tracking logic of the instrument and any onboard or ground-based data-processing steps that occur prior to delivery of the data to the project team.

Enhancement of the current technologies to allow for wide-swath viewing, and/or the reduction of effective footprint size, and an increase in along-track resolution from multiple synergistic nadir-viewing instruments would greatly assist the acquisition of additional targets. Improvements in tracking logic so that the lake surface can be more quickly acquired in highly varying terrain, or in proximity to coastlines and islands, is also recommended. Robust retracking (post-processing) methods that would uniquely identify the signal response of a small target within a complex field of view are also highly sought. Improvements to model-based wet tropospheric range corrections are also called for, particularly for small lakes lacking an instrument-based correction. As time progresses, the ability to update an average lake reference pass with additional cycles of data and the ability to replace the near-real-time (IGDR) products with archival (GDR) data becomes feasible. This is encouraged as a means of validating the near-real-time products and improving the accuracy of the on-line time series. With limitations on ground-based gauge data, both absolute (gauge) and relative (via other satellite products within the GRLM or from other teams) validation checks on product accuracy (whether near-real time or archival) are also strongly encouraged to meet the requirements of the various application programs.

Some improvements will be gained via the next generation of satellite radar altimeters that will not only ensure continuity of the GRLM program well into the 2015 time frame but also utilize enhanced technologies (see the chapter by Raney and Phalippou, this volume). Future missions include the Indian Space Research Organization's (ISRO) SARAL (Satellite with ARgos and ALtika) that will employ a Ka-band radar altimeter. Delay-Doppler (or SAR mode) altimetry will be utilized on ESA's Sentinel-3 (Table 2.1). Both of these instruments are nadir viewing but offer potential improvements via improved tracking, smaller footprints and finer range precision. Wide-swath techniques allowing for global coverage are also being considered. Current focus is on the Ka-Band Radar INterferometer (KaRIN) on the proposed NASA/CNES Surface Water and Ocean Topography (SWOT) mission (Fu 2003; Alsdorf et al. 2007). This mission was recommended within the U.S. National Research Council's (NRC) Decadal Review (NRC 2007) with a potential launch date around 2015.

While radar altimeters continue to be the focus of the program, recent attention has also turned to satellite laser altimetry (Lidar). Although the capability of lidar is limited by cloud cover, this additional tool could offer water-level information at certain resolution and accuracies. The current Ice, Cloud, and Land Elevation Satellite (ICESat) mission does offer some height retrieval capability that could be used as a Phase IV validation tool, but plans to launch an ICESat-2 follow-on mission, and a Deformation, Ecosystem Structure, and Dynamics of Ice (DESDynI) mission focused on hazards and environmental change are also being keenly noted.

With continued funding, the team hopes to achieve a multi-instrument operational lake-level observing system with the temporal and spatial resolution merits of each instrument being synergistically combined to maximize product output and consistency.

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