PECAD's Global Reservoir and Lake Monitor: A Systems Engineering Report

Version 1.0

Applied Sciences Program Integrated Product Team for Agricultural Efficiency
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Executive Summary

Agricultural Efficiency is one of 12 National Application areas of the Applied Sciences program, a component of the Earth-Sun System division of NASA's Science Mission Directorate. The focus of Agricultural Efficiency is on assessment and prediction of production and yield through the integration of NASA capabilities into decision support systems (DSS) operated primarily by the U.S. Department of Agriculture (USDA). The first such DSS targeted for integration of NASA data is operated by the Production Estimate and Crop Assessment Division (PECAD) of the USDA's Foreign Agricultural Service (FAS). The PECAD DSS supports the FAS mission to collect and analyze global crop intelligence information for use in production assessments and food security applications.

The initial evaluation of the PECAD DSS identified an ongoing collaborative project between FAS, the Goddard Space Flight Center, and the University of Maryland to develop a decision support tool called the Global Reservoir and Lake Monitor (GRLM). The GRLM tracks the variation in water level of certain large inland surface waters, including lakes, reservoirs, and inland seas. The observations that enable this monitoring effort are made by two NASA radar altimeter missions: TOPEX/Poseidon (T/P) and Jason-1. The GRLM tool provides PECAD analysts with critical water availability information to support their production estimating mandate.

Using a systems engineering process, the Applied Sciences Program Integrated Product Team for Agricultural Efficiency captured the current status and future course of the GRLM tool for the assimilation of lake/reservoir level variation estimates into the PECAD DSS. This process included 1) documenting the requirements definition and implementation stages of the GRLM tool, 2) analyzing FAS operational requirements to identify options for effective deployment of the GRLM tool, 3) studying the results of verification & validation (V&V) efforts of the scientific community to date and performing independent V&V of the GRLM tool, and 4) employing an initial benchmarking process to evaluate how the tool has been used by FAS to date and what effect the tool has had on the PECAD DSS output.

Surface water information helps complete the PECAD DSS intelligence on regional water balance, which also includes precipitation data and soil moisture estimates. Crop water availability is usually the key variable affecting final yield within an agricultural region. In many intensively irrigated parts of the world, the amount of water stored in accessible reserves is the driving factor in final production. Early season intelligence on water availability can provide insight into the overall season production capacity for an irrigated agricultural region. PECAD analysts must factor surface water level variation into their regular monthly production estimates and also into their food security mission. Before the development of GLRM, FAS analysts relied on crop attaché reports and qualitative analysis of imagery for information on lake/reservoir levels. Nominal PECAD surface water requirements driving the development of the GRLM tool include 1) 10-cm height accuracy, 2) 10-day information cycle, 3) 7–14 day data latency, and 4) coverage for all key agricultural production regions globally.

The development of the GRLM tool was funded directly by FAS in a two-phase process beginning in September 2002. The development effort was led by Dr. Charon Birkett of the University of Maryland, who had conducted much of the seminal research into the use of ocean radar altimeters for monitoring inland water bodies. The GRLM method for estimating water level variation in inland water bodies represents a modification of algorithms developed to estimate sea surface height. The GRLM uses the Interim Geophysical Data Record product from Jason-1 as the input data source for near-real-time estimates and the more accurate Geophysical Data Record for historical estimates based on T/P. The semi-operational GRLM was publicly released as an additional decision support tool (DST) within PECAD's DSS in December 2003. By May 2004, the system included 52 lakes covering the continents of Africa, Asia, Europe, North America, and South America. Water height data was computed from the T/P mission for 1992–2002 and integrated with Jason-1 data from 2002 to present. GRLM output products include both tabular and graphical presentations of the water height information. The effectiveness of the GRLM has been diminished somewhat by data dropout problems associated with the fact that the Interim Geophysical Data Record data stream that is used to create the lake height data is optimized for making sea surface height measurements, resulting in the frequent loss of source data for numerous inland water bodies targeted by GRLM.

Scientific literature reviewed back to the early 1990s demonstrates that satellite radar altimetry from T/P and Jason-1 produced lake height accuracies for large water bodies, such as the Great Lakes, from 2–5 cm and for smaller lakes and large rivers from 10–60 cm. Comparisons made by the Integrated Product Team during the summer of 2004 between the lake height data in the GRLM with lake gauge data produced accuracies ranging from 4–8 cm for the Great Lakes, ~25 cm for two smaller lakes in the northern U.S. (not corrected for ice-related noise), and ~150 cm for Lake Powell in the western U.S. (a lake in an area of very challenging terrain for this procedure). A comparison of the overlapping T/P and Jason-1 data in the GRLM revealed an overall average bias of 10 cm for the Jason-1 data when compared to T/P. The mean latency of the GRLM data was computed to be 10.3 days. However, at the end of May 2004, over one-third of the lakes and reservoirs being monitored had not yielded a water level estimate in over 6 months, due primarily to the Jason-1 data dropout issue.

An initial review of the utility of the GRLM by PECAD management stated that it has made critical impacts on the analysis of FAS analysts, as well as the intra-government and public users of the data through the FAS Crop Explorer application. The most extensive use of this data has been in central and southeast Asia and Africa, where the GRLM tool has been used in food aid, crop assessment, and planning decisions. Benchmarking activities will be ongoing in FY05 as NASA and FAS collaborate to benchmark the integration of several new NASA products into the PECAD DSS, including the GRLM.

The prospect for long-term sustainability of the required radar altimeter data stream is secure through the planned Jason-2 and National Polar-orbiting Operational Environment Satellite System missions. As the GRLM system development matures to full operational status, several options are identified for sustained operation and maintenance of the tool, including 1) continuation of FAS direct funding to the Goddard Space Flight Center/University of Maryland team to operate GRLM, 2) automation and transition of the GRLM algorithms to FAS for inclusion in their contracted technical support tasks, or 3) integration of the GRLM tool into the offerings of a NASA Distributed Active Archive Center. A more detailed analysis of operational options will be conducted in FY05 as part of the Synergy Project.

By developing the GRLM tool and integrating the tool into the PECAD DSS, the Goddard Space Flight Center/University of Maryland team has made great strides toward meeting the immediate needs of PECAD, FAS, and their external users. Early benchmarking efforts have shown a strong positive response from users outside of the FAS/PECAD group. In V&V results, latency typically falls within the desired range, distribution of estimates span the globe and touch many important crop production and crop security regions, and product accuracy is sufficient for many of the lakes and reservoirs that have been incorporated to date. Recognizing that the GRLM decision support tool has broadly achieved its aims, several recommendations are included for potential improvement to the system:

- Increasing the coverage by integrating additional sources of radar altimetry data from other spaceborne sources.
- Working with the Jason-1 team to resolve the data dropout issue.
- Revisiting the FAS accuracy requirement to allow for inclusion of lakes in GRLM that have lower height accuracy but still provide valuable water availability information.
- Integrating an image-based water mask product into GRLM to estimate surface area coincident with water height.

While GRLM development, implementation, and benchmarking is ongoing, it has been demonstrated to be a valuable and viable decision support tool for USDA that has successfully integrated NASA Earth-observing data into routine decision support. Looking beyond the current context of integration of the GRLM into the PECAD DSS, this tool could play an even greater role as part of a systematic approach to monitoring drought as identified in the draft Strategic Plan for the U.S. Integrated Earth Observation System.

1.0 Introduction

In 2002, NASA's Earth Science Enterprise (now known as the Science Mission Directorate), working through its Earth Science Applications Division, initiated a partnership with the U.S. Department of Agriculture's (USDA's) Foreign Agricultural Service (FAS) to enhance the decision support system (DSS) used by FAS' Production Estimates and Crop Assessment Division (PECAD). An element of NASA's Science Mission Directorate at the John C. Stennis Space Center (SSC), the Applied Sciences Directorate (ASD) (formerly known as the Earth Science Applications Directorate), is using a systems engineering approach to analyze the assimilation of NASA data into the partner-agency DSS.

In 2003, NASA's ASD produced a report titled *Decision Support Tools Evaluation Report for FAS/PECAD* that analyzed the PECAD DSS to identify potential opportunities for integration of NASA measurement and modeling capacity that could improve the efficiency of the FAS/PECAD system for making global crop production estimates. The discovery process employed in the development of this report identified the first significant assimilation of current NASA data into the PECAD DSS through a decision support tool (DST) called the Global Reservoir and Lake Monitor (GRLM). The GRLM tracks the variation in water level of certain large inland surface waters, including lakes, reservoirs, and inland seas. The observations that enable this monitoring effort are made by two radar altimeter missions: TOPEX/Poseidon (T/P) and Jason-1. The GRLM tool provides PECAD analysts with critical water availability information to support their production estimating mandates.

1.1 Purpose of the Report

The purpose of this report is to capture, through the application of systems engineering principles, the current status and future course of the GRLM tool for the assimilation of lake/reservoir level variation estimates into the PECAD DSS.

1.2 Applied Sciences Directorate Objectives

The NASA vision and mission statements include a clear focus on the Earth and on life on Earth. NASA's Science Mission Directorate is the primary manifestation of NASA's mission in Earth science and applications. As part of a systematic approach to extending the benefits of NASA's Earth science to the broader community, NASA identified 12 applications of national priority using such criteria as consideration of potential socio-economic return, application feasibility, appropriateness for NASA, and partnership opportunities. The Applied Sciences Program of the Science Mission Directorate, in partnership with public and private organizations, employs a systems engineering process to integrate and benchmark NASA inputs into operational DSSs across these 12 application areas. This report is an element of the Agricultural Efficiency national application.

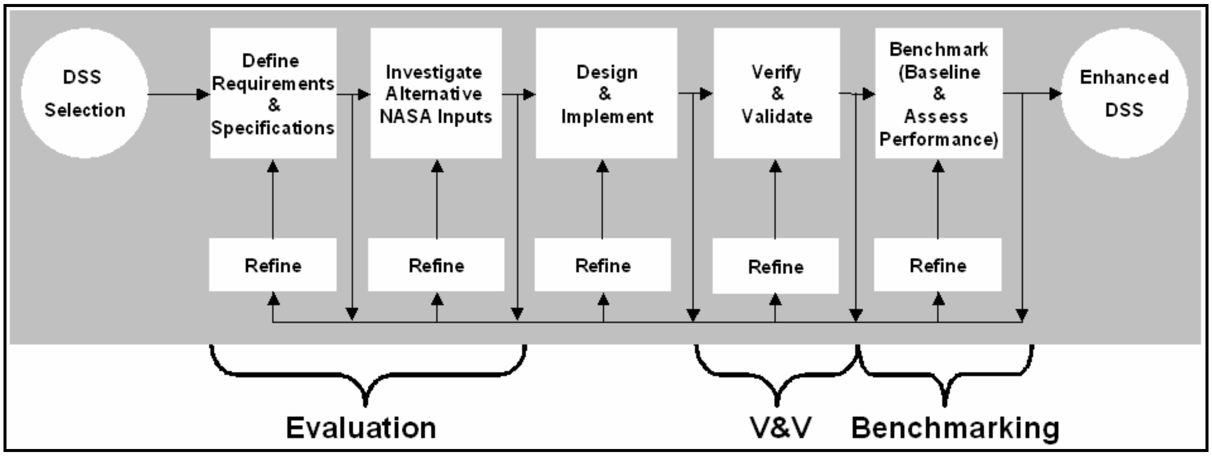
1.3 Agricultural Efficiency Application Element Overview

Agriculture is a crucial component of American society, and the agricultural sector plays a fundamental role in the national and global economy. Observations from airborne and spaceborne platforms have been used for decades to help the agricultural community, from individual growers to national policy makers, make decisions that affect agricultural management and policy. The USDA is a key partner with NASA in ensuring that new NASA technology is evaluated and, where appropriate, is integrated into the USDA's operational decision-making process.

The agricultural efficiency program element focuses on prediction of production and yield through the integration of NASA capabilities, especially data and modeling capabilities in weather, climate, and natural hazards, into the global and domestic production and yield forecasting mandates of USDA. NASA is collaborating with the FAS to improve the timeliness and accuracy of the information and predictions that FAS supplies to the World Agricultural Outlook Board in the Board's monthly review of global agriculture. The inputs from FAS have an effect in the billions of dollars on agriculture decisions at all levels of agriculture – from individual operators to agribusiness and national agricultural policy and management. The collaboration between NASA and FAS is illustrative of the integrated system solutions that the Earth Science Applications Division seeks with its partners.

1.4 Applied Sciences Systems Engineering Framework

This report is based on the systems engineering approach outlined in Figure 1, which entails evaluation, verification and validation (V&V), and benchmarking of the DSS. In terms of this approach, the purpose of this report is to 1) document the requirements definition and implementation stages of the GRLM tool, 2) analyze FAS operational requirements to identify options for effective deployment of the GRLM tool, 3) study the results of verification & validation (V&V) efforts of the scientific community to date and perform independent V&V of the GRLM tool, and 4) employ an initial benchmarking process to evaluate how the tool has been used by FAS to date and what effect the tool has had on the PECAD DSS output.



Source: adapted from Bahill and Gissing, 1998

Figure 1. Systems engineering approach.

2.0 Evaluation

As of December 2003, the GRLM was added to PECAD's decision support resources as a semi-operational tool. To apply the evaluation, V&V, and benchmarking process to the GRLM from start to finish, it is necessary to begin with an evaluation summarizing the initial condition, or State 1 (Hutchinson et al., 2003), of the PECAD DSS, and also to itemize the NASA inputs that are potentially useful. The general evaluation of PECAD's DSS was carried out previously by

SSC/ASD's Agricultural Efficiency integrated product team (NASA, 2004), so this effort will only briefly recapitulate the general State 1 information and will focus on the specifics related to surface water monitoring.

2.1 History of Partnership Between PECAD and NASA

The partnership of the USDA and NASA to develop DSTs for crop condition assessment and crop yield prediction goes back to the 1970s and 1980s with the Large Area Crop Inventory Experiment and Agriculture and Resources Inventory Surveys Through Aerospace Remote Sensing (AgRISTARS) programs (Reynolds, 2001a). PECAD's existing DSTs are the operational outgrowth of those seminal programs.

PECAD continues to receive operational support from NASA from the Global Inventory Modeling and Mapping Studies (GIMMS) group of NASA's Goddard Space Flight Center (GSFC). GIMMS is part of the Biospheric Sciences Branch of GSFC's Laboratory for Terrestrial Physics. The GIMMS group provides PECAD with a carefully cross-calibrated global time series of Normalized Difference Vegetation Index maps from Advanced Very High Resolution Radiometer (AVHRR) and SPOT-Vegetation extending to 1982.

In 2002, the GIMMS group was instrumental in introducing FAS to the potential of satellite radar altimetry working together with the Earth System Science Interdisciplinary Center (ESSIC), a joint center pooling resources from NASA's Earth Sciences Directorate at GSFC, the National Oceanic and Atmospheric Administration's (NOAA's) Cooperative Institute for Climate Studies, and the University of Maryland's Meteorology, Geology, and Geography Departments. GIMMs acted to facilitate two projects funded by FAS to prove the concept of reservoir and lake monitoring for agricultural intelligence and then to implement a semi-operational prototype. Dr. Compton Tucker of GIMMs served as Principal Investigator for these projects with Dr. Charon Birkett of ESSIC leading the technical team. The second project is scheduled to end in December 2004.

2.2 PECAD/CADRE Decision Support System Summary

Providing agricultural intelligence is one of the many responsibilities of the USDA. PECAD delivers this intelligence to customers ranging from the general public to cabinet-level decision makers. PECAD intelligence focuses on global agricultural production and conditions that affect food security. To that end, PECAD assesses current crop conditions and estimates planted area, yield, and production for grains (e.g., wheat), oilseeds (e.g., soybean), and cotton (USDA, 2002). Taken as a whole, PECAD's production estimate processes constitute a DSS, supporting both PECAD's internal analytic process and PECAD's information customers.

PECAD's intelligence mission includes targeting, collection, analysis, and dissemination. Targeting involves constant attention to agriculturally productive areas and particular attention to areas with special food security issues. Twelve PECAD regional analysts each cover one designated region of the world except for the United States, which requires two analysts. Specific areas around the world may be targeted because of various emergencies either on an ad hoc basis or because of a specific request from the USDA or another agency.

PECAD's intelligence analyses flow from their "convergence of evidence" methodology (Figure 2). This methodology is based on an analysis of various independent source data to achieve a level of agreement on the prevailing conditions that affect final estimates, a process intended to minimize estimate error. The methodology is flexible. While individual analysts reach their conclusions in different ways, giving different weight to various inputs, analysts join experts from the USDA's Economic Research Service and National Agricultural Statistics Service once a month in a "lock-up." In this setting, the convergence of evidence approach is fully realized as analysts join together in committees formed by commodity. Final commodity production estimates are achieved by committee consensus.

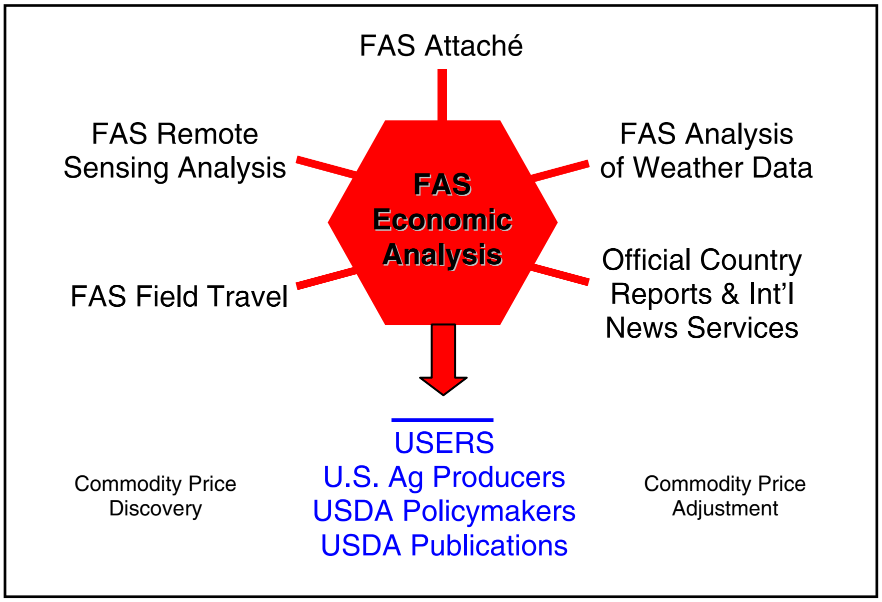


Figure 2. Convergence of evidence methodology.

FAS's primary intelligence dissemination is through the monthly World Agricultural Production (WAP) estimates. The WAP estimates must be approved by a 26-person World Agricultural Outlook Board. The users of the WAP estimates include USDA policy makers, commodity traders, the agricultural industry, and those involved with global food security. In addition to the WAP estimates, PECAD provides online maps of vegetation indices derived from AVHRR data, relevant weather data, and soil moisture estimates through a Web site called Crop Explorer. PECAD also releases weekly crop production/crop security highlights in a Global Crop Watch Summary and releases special reports and alerts as needed or requested.

The primary decision makers supported by this DSS are the 12 regional PECAD analysts. The DSS contains both automated and non-automated components. The main automated components include the following:

- Crop Condition Data Retrieval and Evaluation (CADRE) geospatial database management system (DBMS)
- Crop Explorer – delivers some of the information from CADRE to the Internet
- Archive Explorer – makes PECAD's extensive archive of higher resolution remote sensing data available to PECAD and other USDA users
- Commercial-off-the-shelf (COTS) software – image processing and geographic information system (GIS) functions provide integration of information from various scales and data types
- World Agricultural Production Archive – maintains a record of past production estimates

CADRE provides much of the decision support functionality of PECAD's DSS and also serves as a connection point for most of the other DSS elements. CADRE is the linchpin of decision support to the PECAD regional analysts, including such inputs as moderate resolution remote sensing, agrometeorological information, and baseline reference data. CADRE serves as an interface to a group of crop and soil models, providing model inputs and archiving the results, and outputs its data via GIS software, time series plots, and Web interface displays.

Crop Explorer is a Web interface for a selection of PECAD archived information that is intended to make viewing of the CADRE database easier. The interface provides only visualization functions; data cannot be downloaded. CADRE's full content is accessible behind a firewall, but content is also publicly accessible with potential limitations. Regions or attributes of the public content can be blocked if necessary.

Through its Archive Explorer, PECAD provides access to the centralized archive of moderate to high resolution remotely sensed data that it maintains for the USDA. At present this archive includes Landsat, SPOT, IKONOS, and QuickBird imagery. PECAD gives the USDA a single point of contact with image providers, avoiding waste from possible redundant purchases and streamlining procurement procedures. Archive Explorer allows users to search an image database, providing thumbnails of holdings. Archive Explorer is available only to USDA users. Access is controlled by user name and password.

PECAD analysts complement customized DSS elements with certain COTS software. The primary geospatial integration software is ESRI's ArcGIS. The primary image processing software is Geomatica by PCI Geomatics. While these software packages are unstructured DSS components, they provide an essential space for convergence of evidence. None of the more structured components can bring together the full range of data types that exist in PECAD's database.

PECAD's DSS plays an indirect but significant role in the generation of another DST: the WAP global agricultural production estimate. This monthly assessment is a DST for users external to PECAD and is the result of the qualitative synthesis involved in the convergence of evidence methodology. As such it represents the integration of all the information available to PECAD. Monthly WAP estimates dating from October 1996 are archived as documents or tables at the World Agricultural Production Archives Web site (FAS, 2004).

In addition to the automated DSS components, the PECAD regional analysts receive critical decision support through the assessments of the foreign attachés and PECAD economic analysts. Altogether, all of the automated and non-automated facets of PECAD's DSS combine to provide PECAD decision makers (the regional analysts) with a variety of parameters related to global crop production. By allowing access, comparison, and integration of these independent sources efficiently, the DSS enables the analysts to apply the convergence of evidence methodology both individually and then corporately during the monthly lock-up.

<u>Other Elements Under Consideration:</u> Two other types of NASA input are being considered as potential enhancements of PECAD's DSS: 1) the addition of rapid response Moderate Resolution Imaging Spectroradiometer (MODIS) products, and 2) Tropical Rainfall Measuring Mission (TRMM) rainfall and rainfall-related products. These products are discussed at length in the general evaluation of PECAD's DSS (NASA, 2004), but both were in earlier stages of the implementation process as of

spring 2004. SSC/ASD's 2003 evaluation of the PECAD DSS also identified other potential NASA inputs into the system in areas such as evapotranspiration, soil moisture, and surface radiation budget.

2.3 FAS Requirement for Reservoir Height Information

Crop water availability is usually the key variable affecting final yield within an agricultural region. In many intensively irrigated parts of the world, in-season rainfall is insufficient to produce acceptable yields, so the amount of water stored in accessible reserves is the driving factor in final production. Often, lake/reservoir levels are established during the preceding rainy season, so early season intelligence on water availability can provide insight into the overall season production capacity for an irrigated agricultural region. Even in non-irrigated regions, surface water levels can serve as an independent barometer of long-term climatic trends.

PECAD analysts must factor surface water level variation into their regular monthly production estimates and also into their food security mission. These activities drive their information requirements. The information should be timely; it should be at least as frequent as the time step of the CADRE DBMS; and it should be accurate enough to show trends at the monthly time scale (Table 1).

Table 1. PECAD requirements for surface water level variation.

Category	Requirement
Surface water level relative accuracy	10 cm
Data time step	10 days
Latency	7–14 days
Coverage	Surface waters in all land regions important for crop production and food security*

Source: B. Doorn, personal communication, 2003

*Implied by PECAD mission, not directly communicated

2.4 FAS Historic/Current Practice for Monitoring Reservoir Height

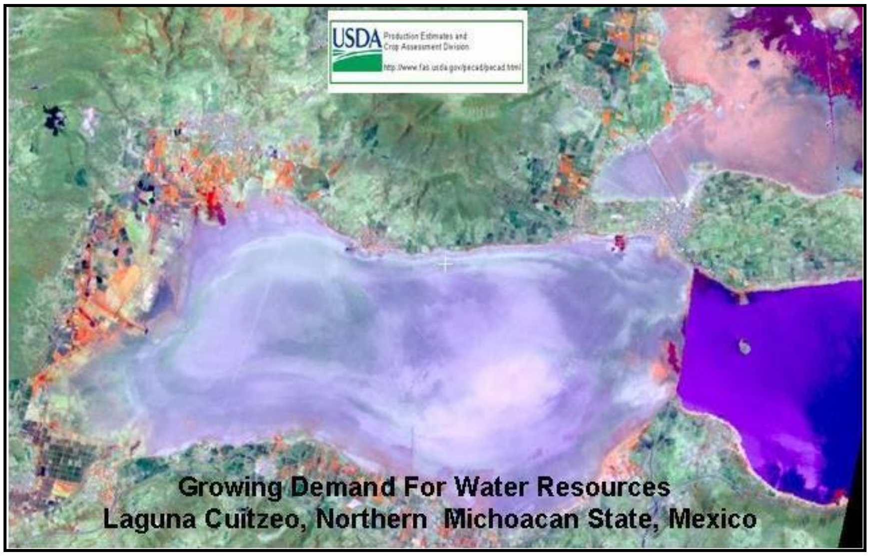
FAS has been interested in monitoring surface water levels for some time. Surface water information helps complete the PECAD DSS picture of regional water balance, which also includes precipitation data and soil moisture estimates. FAS attaché reports often refer to reservoir levels or capacity (Moussa, 2002; Ramos, 1999; Flores, 1996; Truran, 1995). This attaché reporting typically summarizes government sources in the subject country. PECAD regional analysts have often noted the importance of surface water reserves in their analysis (White, 2003; Crutchfield, 2002; Reynolds, 2001b; Crutchfield, 2000; Miller, 2000; Reynolds, 2000; White, 2000).

Source: Lindsey and Reynolds, 2003

Figure 3. MODIS image: Ataturk Reservoir/Harran Plains.

A case in point demonstrating the importance of surface water to crop yield is the Ataturk Reservoir in the Southeastern Anatolia province in Turkey. In 1994, water from the reservoir began to be delivered to the Harran Plains. The reservoir and the plains can be seen in Figure 3. PECAD has closely monitored the development of this irrigation project, noting that the planted area of cotton in the Harran Plains more than doubled from 160,000 ha to 341,000 ha from 1994 to 2001. In the same time period, Southeastern Anatolia's share of Turkey's cotton production rose from one quarter to one half (Reynolds, 2001c). The role of the reservoir has merited attention in attaché reports (Sirtioglu, 2003) and in at least one regional analyst crop tour (USDA, 2001), and it is featured prominently on the PECAD's country page for Turkey (USDA, 2004a). PECAD has used MODIS to observe the reservoir and associated irrigated land (see Figure 3), and PECAD's country page for Turkey shows an observation of the reservoir using Landsat 7 from 2000.

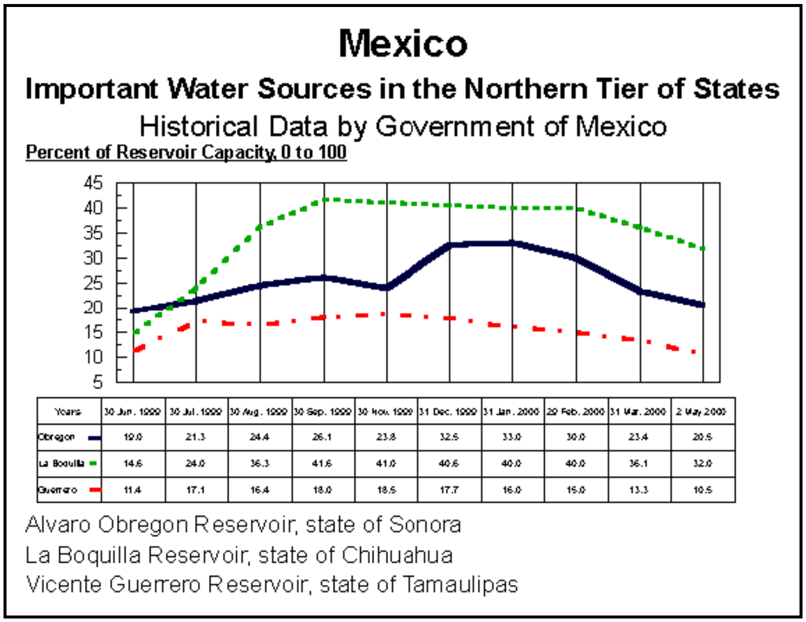
Other examples shed light on the extent and variety of PECAD's use of remote sensing to monitor surface water. A report concerning China in October 2003 used an AVHRR image to show reservoir and river levels. Through increased water surface area, the image revealed high water levels showing recovery from a severe drought in the fall of 2001 and 2002 (Sandene, 2003). Also in 2003, PECAD used Landsat imagery to highlight the plight of a Mexican lake named Laguna Cuitzeo in northern Michoacan province. Lack of rain and competing demands of development and agriculture have depleted Laguna Cuitzeo. In Figure 4 this depletion can be seen as lighter water color in the west end of the lake. The use of water color is another indicator of water quantity used by the PECAD analysts.



Source: White, 2003

Figure 4. Landsat image of Laguna Cuitzeo, Mexico.

When PECAD analysts go beyond reporting reservoirs as low or high, they typically describe water volume as percent capacity. Often these percent capacity estimates come from official sources within the subject country, as shown in Figure 5. Furthermore, it seems likely that such estimates are based on gauges or on some other direct estimate of depth coupled with assumptions about reservoir bathymetry. While these quantitative estimates may be more easily used than remotely sensed images to estimate availability of water for irrigation, the accuracy and even the availability of such estimates vary widely around the world.



Years	30 Jun. 1999	30 Jul. 1999	30 Aug. 1999	30 Sep. 1999	30 Nov. 1999	31 Dec. 1999	31 Jan. 2000	29 Feb. 2000	31 Mar. 2000	2 May 2000
Obregon	19.0	21.3	24.4	26.1	23.8	32.5	33.0	30.0	23.4	20.5
La Boquilla	14.6	24.0	36.3	41.6	41.0	40.6	40.0	40.0	36.1	32.0
Guerrero	11.4	17.1	16.4	18.0	18.5	17.7	16.0	15.0	13.3	10.5

Source: White, 2000

Figure 5. Historical reservoir data.

2.5 Data Sources Relevant to Changes in Surface Water Quantity

NASA's Surface Water Working Group (SWWG) has given the issue of surface water monitoring close attention as a science question and has suggested several types of sensors that could be integrated in a comprehensive monitoring scheme. These sensor types included radar imaging, passive microwave imaging, interferometric synthetic aperture radar (SAR), and satellite altimetry (both radar and LiDAR) (Alsdorf et al., 2002). The SWWG also points to the use of gravimetric measurements as described in Ward (2003). These sensor types are listed in Table 2 along with some example sensors and potential uses.

Table 2. Spaceborne surface water sensing suggested by SWWG.

Sensor Type	Examples	Uses
Radar imaging	RadarSat	Inundation, volumetric change, discharge
Passive microwave imaging	Special Sensor Microwave Imager	Soil moisture, inundation
Interferometric SAR	Spaceborne Imaging Radar-C	Inundation and water height
Satellite altimetry	TOPEX/Poseidon; Jason-1; Environmental Satellite (Envisat) (radar); and Ice, Cloud, and land Elevation Satellite (LiDAR)	Water height
Multispectral imaging	Landsat	Sediment load
Gravimetric	Gravity Recovery and Climate Experiment (GRACE)	Terrestrial groundwater storage

Among these sensor types, only satellite radar altimeters can approach the PECAD requirements for surface water level variation. While other sensor types can provide measurements related to storage capacity, none of them can presently match the combination of near-real-time delivery combined with near-global distribution.

Another category of Earth observations that has potential application to the monitoring of lake level change is multispectral imaging. Multispectral systems such as MODIS, Landsat, and the Advanced Spaceborne Thermal Emission and Reflection Radiometer could provide data (as in Figure 3 and Figure 4) that could be used to generate estimates of the surface area of lakes and reservoirs, and these systems offer global coverage over time. But imaging systems are subject to inconsistent acquisitions due to cloud cover, and the higher resolution systems cannot match the repeat times of the TOPEX/Poseidon–Jason-1 altimeters. MODIS provides a 1-2 day repeat time, but its best spatial resolution is 250 meters. Generating a generalized global dataset of lake and reservoir surface areas would be daunting, but a system monitoring lakes and reservoirs critical to irrigation for important crop regions might be developed.

Given application maturity, the primary data sources under consideration in this report are satellite radar altimeters. Satellite radar altimetry provides the capability to produce a globally distributed relative lake level change from a synoptic perspective. The altimeters can obtain data in remote areas during day or night and under any weather conditions. Birkett (1995) used TOPEX/Poseidon geophysical data record datasets to derive relative lake level changes. The results proved the data could be used to accurately monitor closed lakes, open lakes, and reservoirs.

NASA is a partner with France's space agency, the Centre National d'Etudes Spatiales (CNES), for two current satellite radar altimeter missions: TOPEX/Poseidon (T/P) and Jason-1. Additionally, the U.S. Navy operates the Geodetic Satellite (GEOSAT) Follow-On (GFO) altimeter, and the European Space Agency (ESA) has radar altimeters as part of the Envisat mission. Some basic facts regarding these missions are found in Table 3. The trade between repeat time and coverage is particularly noteworthy. T/P and Jason-1 have the shortest repeat time at 10 days, which allows a denser time series, but this repeat time is achieved by having fewer passes per cycle (254). Envisat, with 1002 passes per cycle, has more surface water targets, but these targets are acquired on a slightly less than monthly basis.

Table 3. Comparison of present satellite radar altimeter systems.

Mission	Owner	Ground Track Repeat	Passes per Cycle	Sea Surface Height Accuracy Claim	Waveform Data Rate	Most Poleward Latitude	Time of Operation
T/P	NASA/CNES	10 days	254	4.2 cm	20 Hz*	66°	1992–present
Jason-1	NASA/CNES	10 days	254	<4.2 cm	20 Hz	66°	2002–present
GFO	Navy	17 days	488	3.5 cm	TBD	72°	2000–present
Envisat	ESA	35 days	1002	3 cm	20 Hz	81.5°	2003–present

*NOTE: T/P waveform rate is 20 Hz, but the height values on the GDR are only 10 Hz

While each of these systems can contribute to an integrated program of reservoir and lake monitoring, T/P and Jason-1 are the basis for the initial implementation of GRLM, so they are discussed in more detail in the following sections. The other satellite radar altimeters are given some consideration later in the report.

2.5.1 NASA Satellite Radar Altimeters

Figure 6. TOPEX/Poseidon.

In 1992, TOPEX/Poseidon was launched as a joint venture between NASA and the CNES for mapping ocean surface topography (Figure 6). Since its launch, T/P has delivered over 10 years of data. During this time it has measured sea levels to better than 5 cm accuracy, observed ocean topography, monitored global climate change currents, monitored large ocean features known as El Niño and La Niña, mapped changes in heat storage for upper ocean waters, and produced accurate global maps of tides. T/P had a 3-year prime mission, and as of early 2004, has successfully extended its mission for more than 8 years. The orbit is circular at 1336 km and has a 66 degree inclination with a 10-day ground track repeat at ±1 km accuracy. T/P covers 95% of ice-free oceans on a 10-day interval. The payload consists of a NASA dual-frequency C and Ku band altimeter and a CNES single-frequency (Ku band) solid state altimeter that measures height above the sea. It has a NASA microwave radiometer that measures water vapor along the altimeter path and corrects pulse delay. The satellite also contains a NASA GPS instrument to provide precise orbit ephemeris data and a NASA laser retroreflector array that coordinates with ground stations to track the satellite and to calibrate and verify altimeter measurements. T/P additionally carries a CNES Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) tracking antenna that receives ground signals for orbit determination, ionospheric correction data for the CNES altimeter, and satellite tracking (NASA, 2004).

Figure 7. Jason-1.

Jason-1, launched in December 2001, is the first follow on to the successful T/P mission and is also a joint NASA-CNES program (Figure 7). Soon after its launch, Jason-1 was maneuvered into a tandem orbit with T/P. This configuration was maintained for over 6 months, which allowed for cross calibration and validation of the two sensors. At the end of this period, Jason-1 maintained the original T/P ground track while T/P was maneuvered to a ground track that fell halfway between successive Jason-1 orbits. This complementary orbit configuration has been maintained through the writing of this report.

The Jason-1 altimeter data is part of a suite of data products provided by several NASA ocean-focused missions. Jason-1 altimeter data complements the Quick Scatterometer mission that measures winds on the ocean surface and the GRACE mission that uses two satellites to measure Earth's mass distribution accurately. The Jason-1 mission objectives are as follows: extend studies of ocean surface topography, supply a 5-year view of global ocean surface topography, increase understanding of ocean circulation and seasonal changes, improve climate event forecasting, measure sea level change, improve open ocean tide modeling, and provide significant wave height estimates and wind speed estimates over the ocean. Jason-1, which is scheduled for a 5-year mission, has a circular orbit of 1336 km at a 66 degree inclination with a 10-day ground track repeat at ±1 km accuracy. The payload includes a CNES Poseidon-2 altimeter (Ku- and C-band) to measure height above sea surface; a NASA Jason Microwave Radiometer that measures water vapor along the altimeter path for pulse delay correction; a CNES DORIS tracking antenna to obtain ground signals for orbit determination and satellite tracking; a NASA Blackjack GPS receiver that provides orbit ephemeris data; and a NASA laser retro reflector array that communicates with ground stations to calibrate and verify altimeter measurements (NASA, 2004).

2.5.2 NASA Ocean Surface Topography Data

Geophysical quantities that are typically estimated from T/P and Jason-1 measurements include sea surface height (SSH), significant wave height, and wind speed (above the ocean). The key parameter is SSH, but land and ice sheet altimetry are possible. Standard T/P and Jason-1 products are distributed through JPL's Physical Oceanography Distributed Active Archive Center (PO.DAAC) for NASA and through the "Archivage, Validation et Interprétation des données des Satellites Océanographiques" (AVISO) data center for CNES. PO.DAAC archives and distributes data related to the physical state of the ocean for NASA's Earth Observing System Data Information System (EOSDIS), and AVISO provides a similar function for CNES. The relationship between PO.DAAC and AVISO is cooperative in regard to satellite altimetry. The data centers even maintain a joint user handbook for certain Jason-1 products.

The centers provide open ocean products in two ways. The first way is to provide users with sensor measurements and a full set of geophysical corrections necessary for users to compute SSH or other altimetric estimates on their own, with users making the final judgments about how to account for geophysical effects. Alternately, the data is provided with a standard set of corrections applied. Data generated with the standard corrections is generally produced as sea surface height anomalies (SSHAs) or sea level anomalies (SLAs), which are residuals against multiyear SSH means.

The accuracy of the SSH estimate depends on the care that is taken with orbit determination and geophysical corrections. Three levels of post-processing are applied (Table 4). Geophysical Data Records (GDRs) apply precision orbit determination for high accuracy, but this post-processing incurs a greater latency. Intermediate Geophysical Data Records (IGDRs) apply a preliminary orbit determination for a greatly reduced latency but only a 1 to 2 cm increase in SSH uncertainty. Near-real-time approaches use orbits based on the onboard DORIS navigator to achieve latencies on the order of hours, but these approaches increase SSH uncertainty dramatically – approximately 20 cm for the Operational Sensor Data Records (OSDRs).

The GDRs, IGDRs, and OSDRs each provide users with altimeter range from the ocean surface based on certain assumptions about the waveform of the radar return from the surface. The nature of these waveforms will be discussed in the Implementation section that follows, but it is important to note here that these standard products do not give the waveforms. The waveforms are available only through Sensor Geophysical Data Records (SGDRs). The SGDRs are available on request through AVISO.

Table 4. T/P and Jason-1 data records.

Data Type	Data Latency	Sea Surface Height Accuracies (open sea)
Jason-1		
Sensor Geophysical Data Records	Available upon request	Up to GDR level
Geophysical Data Records	30 days	~2.5 cm
Intermediate Geophysical Data Records	1–3 days	<4 cm
Operational Sensor Data Records	3 hours	~20 cm
TOPEX/Poseidon		
Sensor Geophysical Data Records	Available upon request	Up to GDR level
Geophysical Data Records	30 days	3 cm
Intermediate Geophysical Data Records	5–7 days	N/A

3.0 Implementation

The GRLM was publicly released as an additional DST within PECAD's DSS in December 2003. The GRLM has been demonstrating the use of near-real-time Jason-1/Poseidon-2 satellite altimeter data to monitor water levels accurately in large lakes (≥100 km^2 in size). This public release could be said to be semi-operational, for while it is constantly available, the group of lakes and reservoirs has continued to evolve through May 2004, and DST information may not be as current as would be ideal for a fully operational system. By May 2004, 52 lakes were included in the system covering the continents of Africa, Asia, Europe, North America, and South America. The GIMMS/ESSIC team is currently funded to operate the GRLM through September 30, 2005.

3.1 Surface Water Level Variation Algorithm

The primary objective of radar altimetry from satellites is to measure the range to a water body surface. A radar altimeter produces a short microwave pulse that travels to a water surface. The leading portion of the pulse reflects from the water surface and begins a return journey to the satellite receiver. The irradiated region on the water surface grows as more of the width of the pulse is expressed upon it, which results in a growing return signal seen at the receiver. That is, the amount of power detected is directly proportional to the water surface area radiated by the pulse. As the trailing portions of the pulse reach the water surface, the power seen in the return begins to decline. Hence, the return pulse assumes the general shape of a ramp that reaches a maximum and then gently declines more or less linearly (Elachi, 1987). It is in the time of flight of this pulse from transmitter to water surface and back to a receiver that allows for the computation of a range value. The foregoing assumes that the water surface is free of disturbance, or that it is a smooth equipotential surface. However, real water surfaces experience disturbances in various forms. In ocean scenarios, wind-driven waves and swells are common. Tides and geopotential non-uniformities raise or lower local water levels. In lakes and reservoirs, water levels are influenced by the status of the local watershed (wet or dry periods), winds, and seiche effects (Morris and Gill, 1994b).

3.1.1 Basics of the SSH Algorithm – Satellite Radar Altimetry Over Sea Surface

When water surface roughness is considered, the characteristic radar return pulse will be convolved with the water wave distribution present within the footprint of the pulse. When irradiated by a radar pulse, waves preferentially affect the pulse energy, depending upon the part of the wave irradiated. The crest of the wave scatters the pulse energy away from nadir observing radars, whereas the troughs of the waves tend to direct the energy back to the radar receiver. This action pushes the ramp of the return pulse to later times; in other words, the action lessens the slope of the leading edge return, making the arrival time of the leading edge of the return pulse less distinct. The accuracy of the altimeter measurement degrades with increased height of wave fields (Walsh et al., 1978). This error is termed a sea-state bias, or an E/M bias. The correction for this error is estimated, either empirically or from a model, using the prevailing wave height present. Furthermore, this error source is managed by assuming errors are random and by averaging a large number of measurements over the footprint of the pulse at the water surface. The averaging of errors present in individual pulse measurements reduces the overall error. However, prior to this step, other sources of error must be considered and removed. Once done, smoothing these data along the topographic profile will reduce the error to more acceptable levels.

Ocean tide effects are a source of error that must be removed from altimetry to determine true water surface elevation. Such effects are normally countered by use of standard models. Similarly, Earth body tides must be considered. Because of internal elasticity, the Earth responds to the same gravitational forces as does the hydrosphere. The time periods of solid Earth tides are shorter than those of water bodies because of the natural modes of oscillation of the materials of the Earth.

The atmosphere creates a need to correct pulse time of flight data for several effects. First, atmospheric pressure alters local water levels. The varying weight (pressure) of the atmosphere inversely affects the height of the water level under it (Calman, 1987). This effect, termed the inverse barometer effect, can be corrected by knowing the atmospheric pressure for a given observation locale. Other atmospheric effects are due to direct interaction of the radar pulse and atmospheric gaseous components in its two-way passage to and from the water surface. The ionosphere is composed of several layers that produce free electrons when under the effects of solar ultra-violet and x-ray radiation. A radar pulse is retarded by the electron plasma present, affecting the pulse group velocity. The correction for this effect takes into consideration both time of day and sun spot cycle. Because this effect is dispersive, a two-frequency radar technique is used to compute the effect of the electron plasma on pulse retardation. When the pulse enters the troposphere, wherein the greatest air mass resides, two effects come into play: 1) the sheer mass of "dry" air present, and 2) the amount of water vapor present along the path of the pulse. A correction is applied that uses the surface temperature and pressure along with zenith water vapor values.

Until recently, imprecise estimation of the satellite's orbit was considered a large source of error. However, GPS satellite tracking has mitigated most of these concerns. Other potential sources of error might include Doppler corrections, center of mass offsets, oscillator drift in the internal electronics of the radar unit, tracking problems, and sundry calibration problems (Cheng, 2004). A discussion of altimetric height accuracies is provided by Birkett (1995).

After accounting for these sources of error, many individual range values are averaged and an analytic function is fit to the averaged waveforms (Figure 8). The fitting function uses three parameters: 1) the estimate of the range, given by T1; 2) the width of the ramp, which provides a value for the relative height of the waves present on the water surface, given by T2, and 3) the elevation of the ramp above the baseline (labeled Sigma_0), which allows an estimate of the surface roughness (which can be correlated to surface wind vectors).

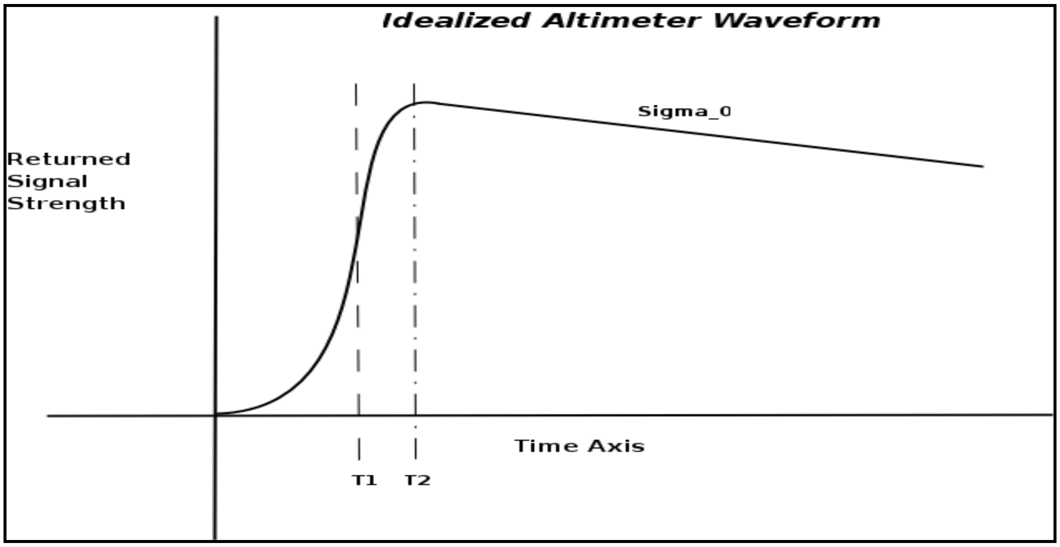


Figure 8. Idealized altimeter response.

3.1.2 "Repeat Track Method" for Reservoirs and Lakes

The standard SSH algorithm cannot be applied directly to most surface waters. The standard SSH algorithm can assume that succeeding passes are perfectly aligned, but greater care must be taken regarding the horizontal position of successive measurement over lakes and reservoirs. Also complicating the picture is the technique used to find the water/land boundary. The radar altimeters use "autotracker" to guess when the returning pulse will arrive. This range lock is used to keep returning waveforms from undershooting, saturating, or clipping. When the radar track goes from land to water surface, the sudden shift in range values forces the autotracker to go through a process of readjustment (the unit at this time is said to be "out of lock"), which invalidates range estimates acquired during the adjustment interval (Morris and Gill, 1994b).

Height Construction: First consider the following general equations:

$$Altimetric\ Height = (Altitude - Corrected\ Range) - Tides - Barometric\ Correction \quad (1)$$

where

$$Corrected\ Range = Range + Atmospheric\ Corrections + SSBias + Center\ Gravity \quad (2)$$

Sea State Bias (SSBias) is not applied in the GRLM. Atmospheric corrections use the radiometer-based wet tropospheric correction when valid, and use the DORIS ionospheric range correction.

Repeat Track Method: The primary objective of oceanographic-dedicated altimeter satellites is to determine the time-variable component of ocean circulation. This objective is achieved by maintaining the satellite's orbit to a nearly exact repeat period, thereby facilitating geoid-independent techniques to measure variations in the sea surface height based on the method of collinear differences. The term "collinear" indicates that sea surface heights for a particular "exact repeat orbit" mission have been geolocated to a specific reference ground track.

During collinear analysis, the repeat tracks are assumed to have perfect alignment to facilitate separation of sea 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 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 to attempt to co-align elevation measurements on various ground-tracks with the reference track. In some cases, perfect co-alignment is not the aim; instead, a nearest neighbor algorithm is applied by calculating the distance between elevation measurements on the ground tracks. In the USDA reservoir project, only along-track alignment is performed.

T/P and Jason-1 have the same ~10-day repeat orbit, and their ground-track positions vary by up to ±1 km from the nominal reference ground-track. In its original form, data from the T/P mission is given at a rate of 20 Hz (i.e., one altimetric range measurement every 0.05 s along the ground track), but the ground processing teams average the data, in pairs, to form the 10 Hz that is delivered to the user community. Data from the Jason-1 mission is given at the full 20-Hz rate. To construct time series of lake height variations, elevation measurements along a satellite overpass, from lake coastline to coastline, must be compared to elevation measurements along a chosen or constructed reference pass. For all of the lakes currently in the USDA database, a reference pass is constructed for each lake using the 10-year archived 10-Hz T/P dataset.

The construction of the 10-Hz georeferenced lake database follows many of the procedures employed in the development of the NASA-funded Ocean Altimeter Pathfinder 1-Hz database (Koblinsky et al., 1998).

1. Nominal 1-Hz georeferenced locations (lat,lon) along a reference track are computed using a Hermite 10th order interpolation algorithm. This GSFC Geodyne algorithm also assigns an index number to each (lat,lon) location along the satellite track. Index=1 denotes the first (lat,lon)

location above the equator on the ascending pass. The last index denotes the (lat,lon) location just below the equator before the following ascending pass. These (lat,lon) locations are the 1-Hz georeferenced locations.

2. Each lake will then be associated with a range of these indices denoting the extent of the ground track that falls across the target. The actual GDR/IGDR track data is then compared to the new reference track. Perpendiculars are drawn from the reference track 1-Hz locations to the real track. The time, T, at the intersect point can then be deduced from an interpolation.

3. The reservoir project thus creates a georeferenced database. For each target, the record will contain the lake ID number, the satellite revolution number, the index numbers across the lake, the mission cycle number, the 1-Hz reference (lat,lon) locations (fixed for each repeat cycle), and the 1-Hz interpolated time tag, T (variable with each cycle).

4. Although no across-track corrections are performed within the reservoir project, 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 sea surface height is computed from a linear fit of the track 10-Hz heights with the midpoint evaluated at the intersect point.

5. The database is then expanded to 10 Hz. For each time, T, there is the need to associate ten height values with each of the ten 0.1-s intervals from T. Rather than use interpolation, a closest neighbor approach is used to preserve as many lake height values as possible (noting poor or missing data across small targets). The 10-Hz heights are indexed and added to the database. For the Jason-1 IGDR data, the nearest neighbor approach searches for the closest 20-Hz data point along the actual ground track.

The maximum 10-Hz along-track alignment error for T/P 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 10 years (T/P cycles 1–364). Similar along-track alignment procedures are performed on the Jason-1 20-Hz heights, reducing the maximum expected error to less than 0.025 s or 0.14 km.

The resulting reference database has a structure that is based on direct access with 3-dimensional directories for each mission based upon repeat cycle, revolution within cycle, and indexed along-track 1-Hz georeferenced locations. Each lake that is over-flown by the satellite has an associated revolution number and a set of along-track time indices bounding the lake traverse. Each data record is of fixed length containing the 1-Hz and 10-Hz georeferenced heights along with all geophysical and environmental range corrections. This random read-write approach permits IGDR data to be processed upon receipt regardless of cycle order and permits immediate revisions. The organization of the georeferenced data directories and fixed record format enables the integration of a graphical user interface to generate near-real-time data reports and performs as a quality assurance device.

T/P and Jason-1 Elevation Bias: Inter-mission biases between T/P and Jason-1 are directly computed from collinear differences. During the validation 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 seconds, and the satellite observations were approximately coincident, both spatially and temporally (Menard et al., 2003). The instrument-independent height corrections that do not vary significantly over the 72 seconds essentially cancel in the direct comparisons at georeferenced locations. Analysis of global ocean colinear sea surface height differences between Jason-1 and T/P (Zanife et al., 2003) thus showed that a relative bias of approximately 11 cm (Jason-1 being higher than T/P existed between the range-measurement of the two missions. A similar analysis was performed using Jason-1 data from the interim GDR and over a suite of large lakes, which generated a relative bias of ~9 cm.

For the USDA reservoir database, the 9 cm range bias was selected and applied. However, an additional offset between the Jason-1 and T/P time series was applied for many lakes. Investigation of the atmospheric corrections within the T/P GDR and Jason-1 IGDR datasets point to differences in the models used to construct these parameters. Therefore, an extra check was inserted to calculate an additional bias (~10–15 cm) based on the difference between the given dry tropospheric corrections at the same location and time period during the validation phase.

Error Estimates for Individual Measurements: In addition to error sources significant in sea surface height estimation, lake and reservoir height estimation is affected by wind conditions, presence of ice, and surrounding terrain. High, sustained, unidirectional winds cause “wind setup” where lake water is lowered on the windward side and raised on the leeward side. Depending on the satellite altimeter ground track, the altimeter-based water levels may become out of step with an average lake or reservoir water level. Low winds, perhaps aided by the presence of screening terrain or vegetation or of a partially frozen surface, may lead to a smooth surface that departs from the “ocean-like” altimeter response shown in Figure 8. Completely frozen surfaces would certainly differ from this response. Although not highlighted in Section 3.1.1, both SSH and surface water level estimates are also affected by heavy rainfall events. Birkett (1995) gives a broad discussion of errors that can be found in surface water level estimation.

Error bars are generated as an estimate of the total error in an individual GRLM water level height. In brief, the error bars on each relative elevation measurement in a reservoir time series plot/file are estimated by combining three elements:

a. knowledge of the number of height measurements along the satellite track that have been used in deducing the final lake height value,

b. an estimate of the precision of the altimetric range, and

c. an estimate of the combined errors stemming from all the remaining corrections and parameters that are required to form a single altimetric height value (see Eq. (1)).

In general the third element (**c**) is a best guess based on published sources. It is the combination of the root mean square (RMS) errors on each of the terms (except the range value) in the height equations (1) and (2). Some of these terms may have options (microwave radiometers or, for example, the European Centre for Medium-Range Weather field for the atmospheric wet tropospheric correction), and some may be applicable only to lakes having ocean-like radar echoes.

Regarding the second element (**b**), the RMS error on the altimetric range depends on the surface in question. To first approximation, it is assumed that the scatter of the range values along the ground track, or in this case, the scatter of the height differences between overpass and reference pass, are representative of the RMS range error. This error can be improved by averaging over many radar echoes (**a**) along the satellite ground track (range error divided by the square root of N, where N=number of height measurements).

The final error bars are thus a combination of (**a**) plus the standard error on the mean height differences between pass and reference pass (**b**+**c**).

Note that the repeat track method employed ensures that each repeat pass over a lake is compared to a reference pass, which in most cases is an average pass formed from the T/P data archive (1992–2002). Because this reference pass is common throughout the resulting time series, the final error bars are taken to be a simple combination of **a**, **b**, and **c** (the combination of **a**, **b**, and **c is** not multiplied by $\sqrt{2}$ to indicate the difference between two measurements).

3.2 GRLM Development

The GRLM DST came into being by direct invitation from the FAS/PECAD team. This relationship was formalized with proposals that provided a mechanism for funding of algorithm and tool development. While the proposals captured snapshots of the stakeholders' understanding of capabilities requirements, the more complete understanding was dynamic and evolving over the course of the project. This understanding has continued to grow since the release of a prototypical public version of the GRLM DST that is accessible through the FAS/PECAD Web site.

3.2.1 Phase I Proposal

The Phase I proposal submitted by Tucker and Birkett (2002) to FAS described how near-real-time radar altimeter data could be used to monitor surface height variation in several African lakes and reservoirs. The proposal listed the 15 water bodies shown in Figure 9, but "20 lake targets" were mentioned elsewhere in the proposal. This work was proposed to occur from September 1, 2002, through September 30, 2003. A recommendation was made to utilize near-real-time Interim Geophysical Data Records altimetry data from Jason-1/Poseidon-2 to construct time series of surface water height variations for every 10-day repeat cycle. These datasets with 10–15 cm height accuracy in a common ellipsoid reference system could be delivered within 4 days after a satellite overpass from the AVISO ground processing teams. A semi-automated data ingest and analysis system was to be constructed.

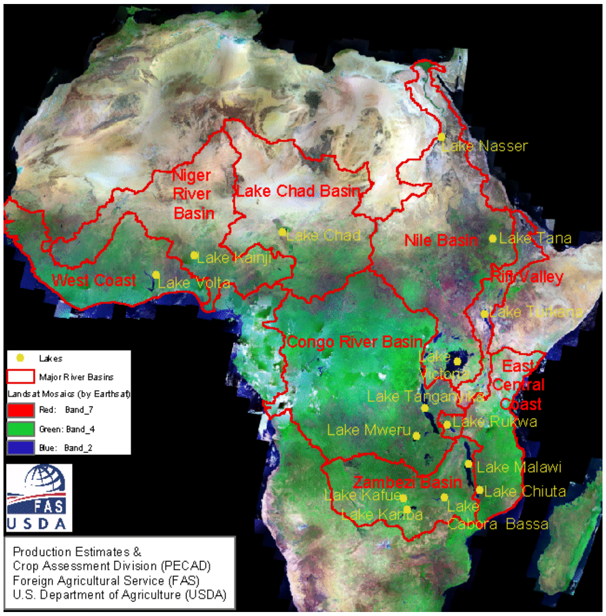


Figure 9. African Lakes monitored by Jason-1 (Phase I).

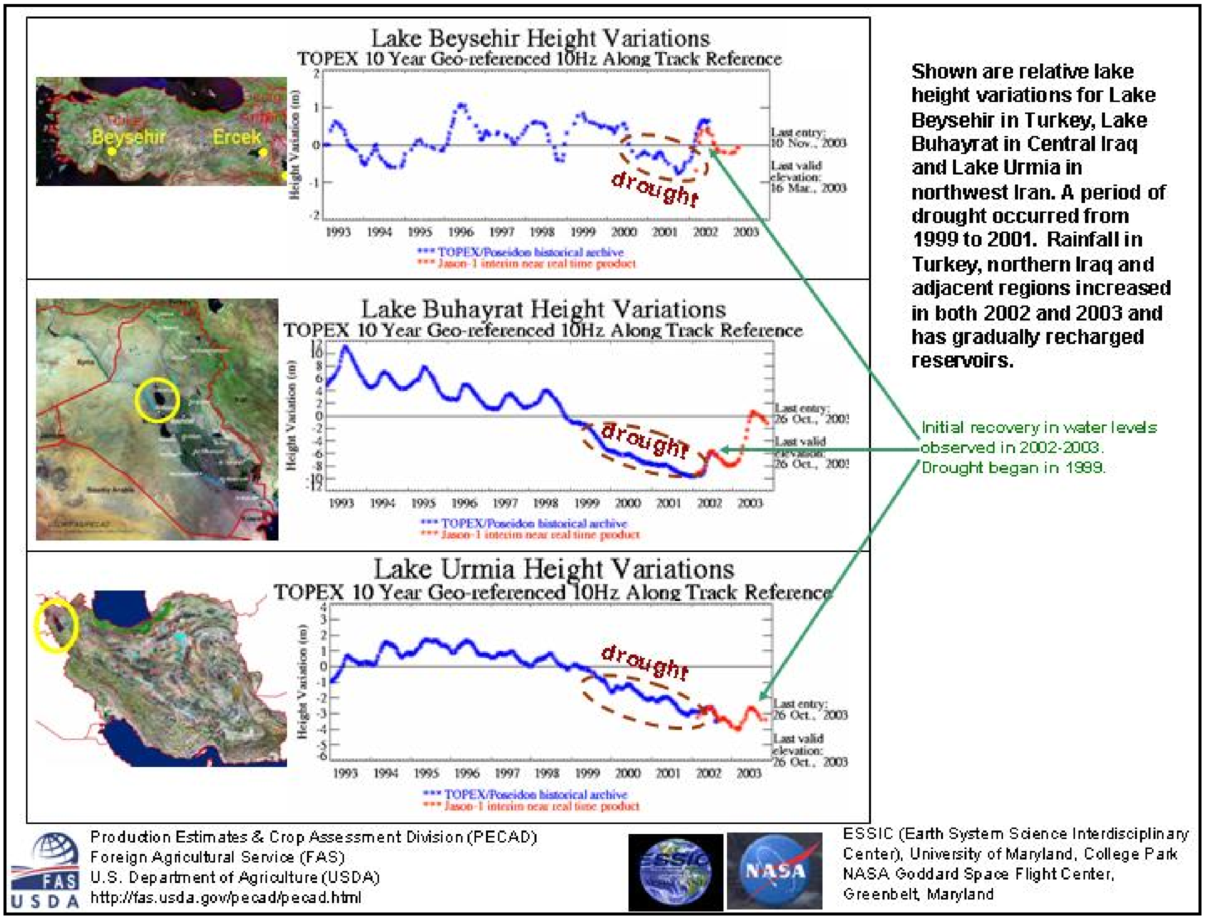
Deliverables would consist of graphic plots and ASCII test files revealing the relative change in surface elevation as the Jason-1 mission progresses. Final products were to be delivered to PECAD for flood/drought observations and for analysis of reservoir volume and irrigation potential. A password-enabled Web site would include links to graphic images showing the Jason-1 overpasses, text files containing date/time, height variations, estimated errors, and graphs displaying variation of height with time for each African lake. Product availability would begin in October 2002 and would continue throughout the lifetime of the mission if funding was available. New, incoming IGDR data would be posted within 24 hours of the delivery date (i.e., an overall 5-day delay after satellite overpass). At the end of 2002, derived T/P time series from archive data spanning 1992–2002 would be appended to the Jason-1 results after checking the height bias between T/P and Jason-1 and determining a satisfactory procedure for merging the two time series.

3.2.2 Phase II Proposal

The Phase II proposal submitted to FAS extended the reservoir monitor development work through September 31, 2004. Phase II is a continuation of the objectives and tasks outlined in Phase I (Tucker and Birkett, 2003). Expansions to the original proposal were as follows:

- Global outlook
- Specific hardware/software upgrade purchases to create a stand-alone monitoring system
- Validation exercises using ground-based stage data to determine root mean square accuracy of the Poseidon-2 instrument aboard the Jason-1 satellite
- Performance of Jason-1 radar altimeter assessment in terms of height accuracy, target size, temporal and spatial resolution, and improvements over the T/P altimeters
- Merge of Jason-1 results with T/P archive data (1992–2002)
- Investigation into the potential of the data to reveal variations in target width
- Full public domain access (without password protection as proposed in Phase I)

The Phase II products proved useful for PECAD analysis. The graphic in Figure 10 was used to support a PECAD regional analyst’s discussion regarding a drought recovery in the Middle East (Anulacion, 2003). Both regional wheat production and state of the reservoirs were linked by the analyst with regional weather trends.



Source: Anulacion, 2003

Figure 10. TOPEX/Poseidon historical data.

3.3 Description of GRLM Tool as Released in December 2003

3.3.1 GRLM Products

Products are graphs and associated tabular information. On graphs (such as Figure 12), the x-axis refers to time (in months) and the y-axis represents height variations (in meters). Blue and red represent data from T/P and Jason-1, respectively. Tabular data products list water height variations (relative to 10 years of T/P mean altimeter observations), associated errors, and date/time in which the data were collected. An abridged sample results table is provided in Appendix A.

3.3.2 GRLM Web Site

A description of the Global Reservoir and Lake Monitoring system is provided at the Crop Explorer background information page (USDA, 2004b). The site provides a world map with circular targets that represent available lakes and reservoirs (Figure 11). Each target is linked to detailed information regarding water levels for each monitored lake or reservoir. The targets are color coded with a blue-to-red scale that indicates whether the most recent valid height variation was higher or lower than the T/P mean water level.

Source: http://www.pecad.fas.usda.gov/cropexplorer/global_reservoir

Figure 11. Global Reservoir and Lake Monitor.

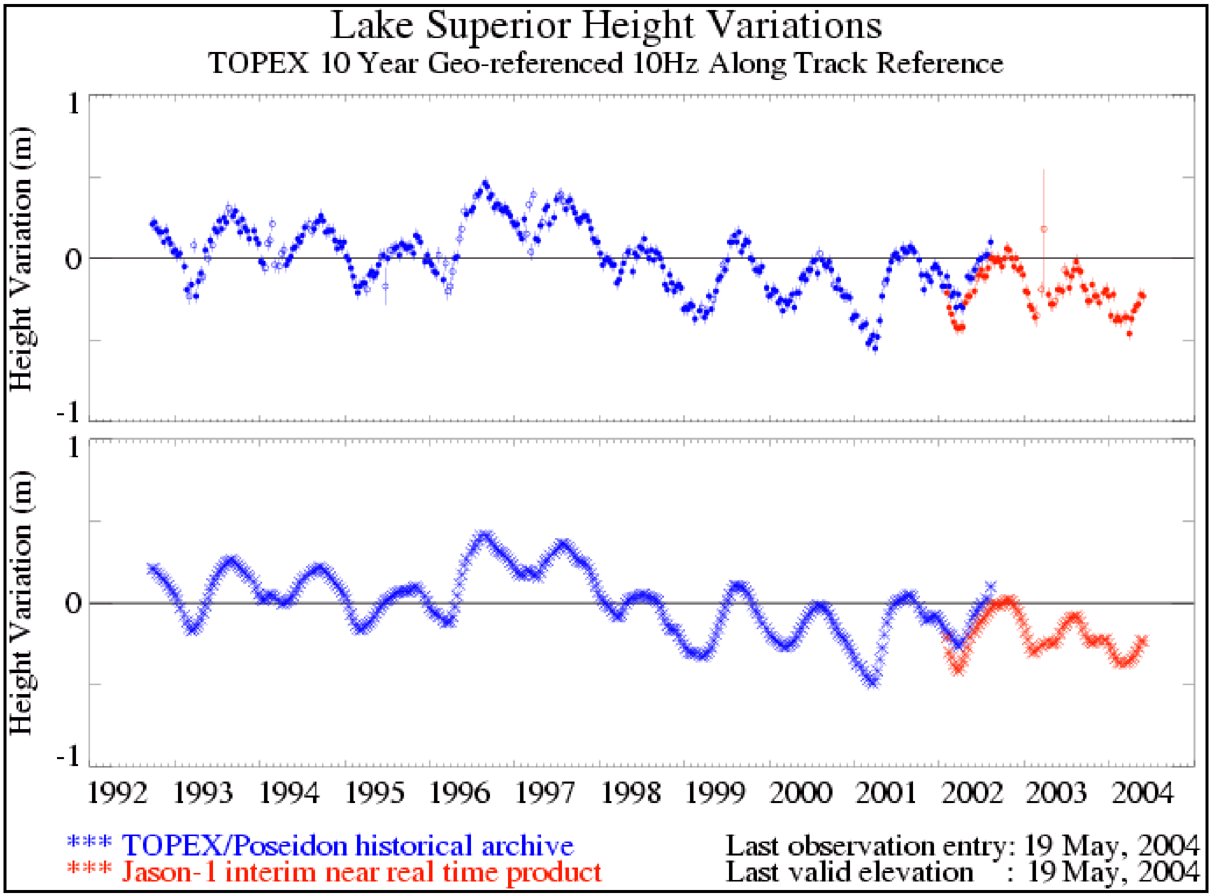
MODIS land cover images, Landsat 5 thumbnails (with Jason-1 ground tracks displayed over the image), and graphic displays of water level changes per lake over time can be found following links from the initial site. For example, variations in water levels for Lake Superior are presented in Figure 12. A "Lake Net Profile" link provides information describing physical characteristics, watershed management, biodiversity conservation, organizations, resources, and the latest news releases concerning each target.

3.4 Data Drop-Out Problems

Elevation measurements may be absent or have erroneous values over inland water targets for several reasons. First, many satellite radar altimetry missions are designed with ocean (and ice-sheet) science objectives in mind. The instruments are designed with certain tracking capabilities that generally encompass the ability to retrieve and retain radar echoes (and therefore achieve good height measurements) over gently sloping ocean/ice terrain surfaces. The more rugged and/or complex the topography, the more sophisticated the tracker logic must be to keep in step with the rapidly varying topography. The tracking logic differs between the T/P, Jason-1, European Remote Sensing Satellite (ERS), and Envisat missions.

For example, if buildings, ravines, a set of hills, or mountainous terrain exist on the approach path to a lake or river target, T/P and Jason-1 may "lose lock" on the surface. Lake coastlines and river banks will also cause temporary data loss. On average, T/P takes about 1 second to regain lock on a gently undulating surface, by which time the satellite may well have passed over and beyond the intended water target. In such loss-of-lock cases, the elevation parameters in the data stream are set to some default value by the ground-processing teams, or the period of lost data will simply be removed from the data stream.

A second problem has arisen regarding data drop-outs within the Jason-1 data stream. Altimetric data streams contain both satellite orbit altitude and altimetric range measurements. The difference between these two parameters, with appropriate geophysical and instrument corrections, enables the construction of the elevation values. For oceanography purposes, the low-rate, 1-Hz elevation measurement is normally required. For inland water applications, the 10-Hz T/P or the 20-Hz Jason-1 elevations are required for the smaller targets.



Source: http://www.pecad.fas.usda.gov/cropexplorer/global_reservoir/gr_regional_chart.cfm?regionid=useast&region=&reservoir_name=Superior

Figure 12. Lake Superior TOPEX/Poseidon and Jason-1 ground tracks and associated time series graphs.

Within the T/P data stream, the user has access to one 1-Hz range value and up to ten range-difference values. Adding the latter to the former gives the full 10-Hz range measurements. The ground processing teams (e.g., AVISO, PO.DAAC) have access to the full 20-Hz rate data, which they first average in pairs to form a 10-Hz dataset. The 1-Hz value is then deduced by performing a least absolute deviation (LAD) fit 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, but contingencies exist. If the LAD fit fails to converge, if more than two erroneous range values exist, or if the slope of the fit is too high (3000 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 observation of the data streams in these cases (over severe terrain or narrow river regions), as few as two 10-Hz range values can be accepted and can pass unhindered into the data streams for the user to examine.

The raw Jason-1 dataset is 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, AVISO does not average these 20-Hz measurements into pairs to form 10-Hz values. Second, 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 three valid 20-Hz values do not exist, then the 1-Hz and the 20-Hz values are all defaulted in the data streams. 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 has resulted in data loss over some lake targets, particularly in calm-water lakes lacking significant wave formation and having a greater standard deviation of range values along the ground track.

The ESSIC technical 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 November 2003 Jason-1 Science Working Team meeting in Arles and issued a “Request for Modification” on February 24, 2004. This request proposed several solutions that try to limit the effect of data loss on the ocean community.

Recent correspondence between the ESSIC team and AVISO discussed the problem of missing Jason-1 data. AVISO stated that a solution to the problem will be implemented in October 2004.

4.0 Verification and Validation

For verification and validation of the GRLM DST, the performances of similar algorithms and altimetric systems were established as a baseline in a review of the literature.

The altimetric performance of the GRLM was characterized using a selection of North American lakes and reservoirs. The objective in altimetric characterization was to focus on near-real-time performance, so primarily Jason-1-based water heights were considered. It should be noted that the Jason-1 estimates based on IGDR products have inherently more orbit error than the archival T/P estimates based on GDR products. An exception was made to include Lake Powell, which has no valid Jason-1 water height estimates, because it represented performance in more challenging terrain. In addition to characterization against these references, the differences between coincident T/P and Jason-1 height estimates resulting from ~200 days of coincident orbits were computed. This characterization was carried out for all reservoirs and lakes available in the GRLM as of May 2004.

The temporal performance of the GRLM was characterized for the same May 2004 time frame. All sites estimated in that period were used to generate a snapshot of data delivery in a semi-operational state.

4.1 Review of Published Literature

Although satellite-based radar altimetry has traditionally been used to study changes in oceanic water and ice levels, studies dating back to the early 1990s indicate that this technology could also be used to monitor inland continental lakes and reservoirs, as well as polar ice sheets. Fluctuations in inland lake water levels have been correlated with regional and global climatic changes related to rates of evaporation and precipitation over lakes and catchment areas.

Validation was performed by comparing satellite radar altimetry data of inland water bodies with the closest *in-situ* gauge measurements over identical times. The first well-validated radar altimetry data were collected with the GEOSAT mission. GEOSAT was a U.S. Navy satellite launched in 1985. In 1986, GEOSAT was put into a 17-day repeating orbit, and the satellite collected sea surface topography data until 1989. Birkett (1994) and Morris and Gill (1994a) evaluated level heights using remotely sensed GEOSAT radar altimetry and ground based *in-situ* tidal gauges. Ground-based values were representative of peripheral areas around the Great Lakes. The RMS resulting from this study ranged from 8.5 to 13.8 cm. GEOSAT data analysis of a moderate sized local lake resulted in RMS of 17.0 cm. Increased RMS was due to interference radar reflections from such effects as tree canopy and rough shoreline topography. Ground vegetation from smaller inland water systems also caused lost or invalid data.

Because of increases in altimeter sensitivity, the T/P and Jason-1 missions that followed were able to measure inland water levels more accurately. Errors due to backscatter from complex shorelines and island terrain, loss of lock, and seiche effects could be overcome by collecting data only at the center of individual reservoirs. Studies were conducted in which NASA's dual-frequency altimeter and the CNES solid state radar altimeter were compared with averaged *in-situ* Great Lake level measurements (Morris and Gill, 1994b). Mean RMS levels of 3.0 cm and 2.9 cm were observed for the NASA and CNES sensors, respectively. Similar results using T/P data were obtained by Birkett (1995) of 4 cm accuracy and by Ponchaut and Cazenave (1998) of 2 cm accuracy. These results were all obtained over larger inland water bodies and may not be representative of smaller lakes or lakes with complex surfaces (i.e., those containing several islands or a large amount of vegetation). Smaller bodies may be somewhat similar to rivers and wetlands. Birkett (1998) validated accuracy ranges for rivers and wetlands on the Paraguay and Amazon Rivers between 10 cm and 60 cm.

4.2 V&V of Altimetry Product Properties

4.2.1 GRLM vs. Gauge Data for Select North American Lakes and Reservoirs

The Agricultural Efficiency Integrated Product Team compared the GRLM measured water height variation to readily available gauge data from North American sources. Sources included the Great Lakes, Lake Winnebago in Wisconsin, Lake of the Woods on the border of Minnesota and Canada, and Lake Powell in Utah. For the Great Lakes, data from three to four gauges nearest to the satellite track were averaged and compared with Jason-1-based estimates from January 2002 through May 2004. The reference data were taken from hourly averages from gauges operated by the U.S. and Canada. The U.S. gauges are maintained by NOAA's National Ocean Service Center for Operational Oceanographic Products and Services. The Canadian gauges are operated by the Canadian Hydrographic Service of Canada's Department of Fisheries and Oceans. The Lake Winnebago and Lake of the Woods measurements were compared with Jason-1-based estimates from January 2002 through September 2003 (October 2003 through May 2004 estimates had not yet been validated by the U.S. Geological Survey (USGS)). The USGS reference data were taken from daily gauge data distributed by the USGS Water Resource Discipline. Lake Powell measurements could not be compared to Jason-1-based estimates because of the data dropout problem, so those measurements were compared with T/P-based estimates from October 1992 through July 2002. The Lake Powell daily reference data is distributed by the U.S. Bureau of Reclamation, Upper Colorado Region. Hourly reference data were linearly interpolated to the time of satellite overpass. No comparisons were made where gaps existed in the reference records.

The Great Lakes provide a sufficient characterization test over large inland water bodies and have been used repeatedly for this purpose as mentioned in Section 4.1 above. Lake Winnebago and Lake of the Woods provide a spot characterization of smaller surface area inland bodies, and Lake Powell represents a water body in challenging terrain. In general, water height estimates were considered "as is." However, performance was considered with and without outliers; with outliers defined to be points with a semi-studentized[1] residual from reference that was ≥4; and in one case, Lake of the Woods, an attempt was made to remove potentially ice-contaminated data points. The characterizations over Lake Winnebago, Lake of the Woods, and Lake Powell should be viewed as first-order approximations of the system performance because these comparisons were made with only a single gauge in each case. In particular, the Lake Powell gauge was over 80 km from the satellite overpass area. Details about the gauges are provided in Table B-1, Figure B-1, and Figure B-2. The verified performance of the GRLM DST over the full set of lakes is summarized below in Table 5.

Table 5. Verified GRLM performance over select North American surface water bodies.

Name	σ (all points) (cm)	σ (no outliers) (cm)	Data points	Outliers
Lake Superior	7.3	7.3	81	0
Lake Michigan	5.3	5.3	75	0
Lake Huron	8.3	6.2	80	2
Lake Erie	7.4	6.5	73	1
Lake Ontario	29.6	4.5	79	3
Lake Winnebago	27.0	27.0	24	0
Lake of the Woods	51.9	26.1	42	1
Lake Powell	186.1	140.6	244	6

NOTE: All lakes and reservoirs were characterized using Jason-1 IGDR-based estimates with the exception of Lake Powell. No Jason-1-based estimates existed for Lake Powell as of May 2004, so TOPEX/Poseidon GDR-based estimates were used. Details regarding gauge sites for each lake are provided in Table B-1.

Overall, the accuracy of the GRLM DST ranged from 4 to 7 cm RMS over the Great Lakes after removing suspect data points. Over two of the smaller lakes – Lake Winnebago (~550 km^2) and Lake of the Woods (~1900 km^2) – the accuracy fell into the 25–30 cm RMS range. When potentially ice-contaminated data points were removed from the Lake of the Woods comparison, the results improved considerably with the RMS falling 14 cm. The greater variability during ice-covered periods can be observed in Figure 13.

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[1] A semi-studentized residual is a residual standardized by the overall standard deviation of the error.

Figure 13. Lake of the Woods comparison with likely ice contamination.

Lake Powell is also a smaller lake (~550 km^2) that is long and narrow and surrounded by canyon walls that rise hundreds of meters at the sides of the reservoir. The accuracy was computed to be about 1.5 m. Some of the inconsistency between the GRLM and the reference is due to separation between the Jason-1 track and the gauge (~84 km) and to the gauge's being in a well in the face of the Glen Canyon Dam itself, so the level at Lake Powell will be much more affected by water release events. Still, much of the variance is likely due to terrain effects on the altimeter. While significantly larger than the other lakes, the 1.5-meter accuracy estimate corresponds to about a 1.5% uncertainty in the associated lake volume at Lake Powell's current level.[2]

A complete set of GRLM vs. reference comparisons is provided in Appendix B.

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[2] This estimate was computed using recent Lake Powell water level and reservoir volume data. Water level and reservoir volume differences were obtained on two successive days. The estimated volume uncertainty was then the product of the successive day volume difference with the ratio of the 1.5 m uncertainty to the successive day water level difference. Finally, the estimated volume uncertainty was converted to a percent of the current volume. While this method is crude, it should be sufficient for discussion purposes.

4.2.2 Evaluation of Overlapping T/P and Jason-1 Data

As discussed in Section 3.1.2, Jason-1 and T/P were maintained in tandem orbits for more than 6 months, which allowed for careful cross-validation of the two sensors. Section 3.1.2 also detailed procedures for applying corrections for bias between T/P and Jason-1 in the GRLM water height variation products. The SSC Agricultural Efficiency Integrated Product Team compared the collinear height estimates to determine the efficacy of the bias corrections. For GRLM data published as of May 31, 2004, an overall bias of 10 cm remained. More than half the sites had an absolute bias greater than 10 cm (Figure 14). A site-by-site comparison is given in Appendix C. One possible source of this bias may be the added orbital uncertainty resulting from using the IGDR dataset as a starting point instead of the GDR dataset.

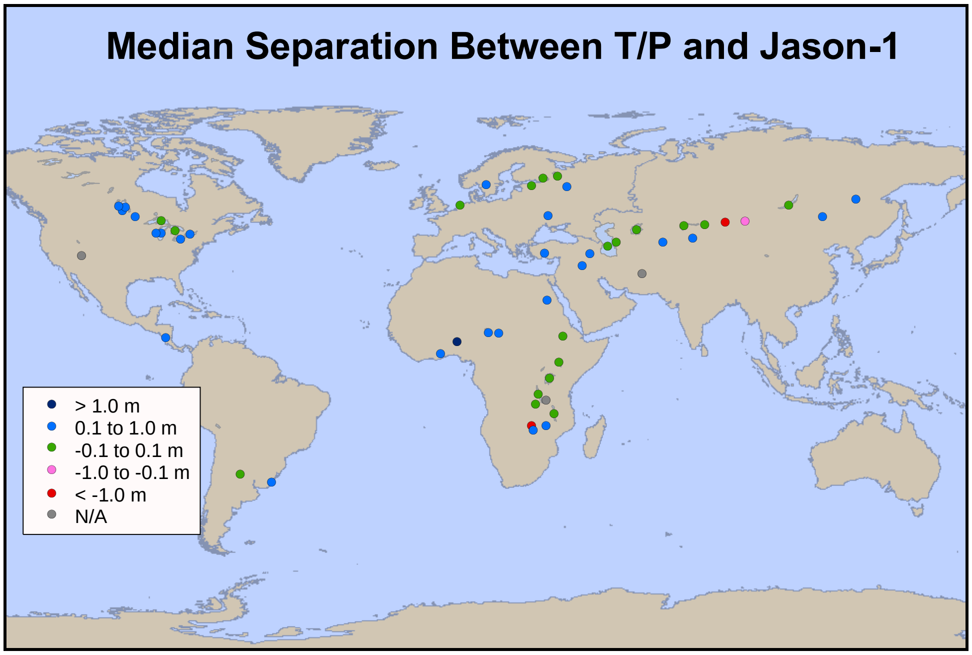


Figure 14. Map of separation between coincident T/P and Jason estimates for lakes and reservoirs included in the GRLM as of May 28, 2004.

4.3 V&V of System Temporal Properties

The SSC Agricultural Efficiency Integrated Product Team observed the GRLM DST throughout May 2004 to characterize its temporal properties. Significant uploads of data to the GRLM occurred on three occasions: Friday, May 7; Sunday, May 16; and Friday, May 28. The time step of the data recorded for individual lakes and reservoirs was 9.9 days as dictated by the T/P and Jason-1 orbital repeat cycle. The mean latency of the data, which is the average time delay from when the altimeter senses a lake surface until when the data is uploaded on the DST, was computed to be 10.3 days. The maximum latency was 19.2 days and the minimum latency was 2.0 days.

In addition to data frequency and data latency, the time since last estimated water level was also notable. Because of confounding conditions noted in Sections 3.1, 3.4, and 4.1, sometimes a water level estimate is not possible. In such case the GRLM DST does not record a point graphically but rather records an error code in the tabular product. At the end of May 2004, over one third of the lakes and reservoirs being monitored had not yielded a water level estimate in over 6 months. The key issue may be the data dropout problem, which is ultimately controlled by the satellite radar altimeter standard product algorithms and not by the processing for inland waters. The full breakout by "time since last usable data" is shown in Figure 15, and the geographic distribution is shown in Figure 16.

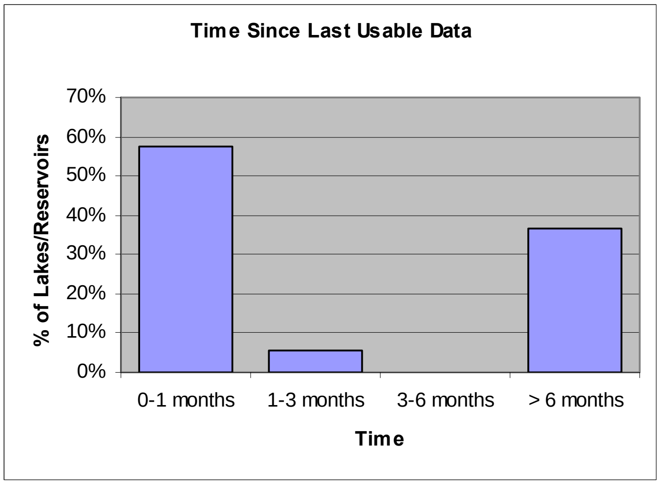


Figure 15. Histogram of time to last estimated water level as of May 28, 2004.

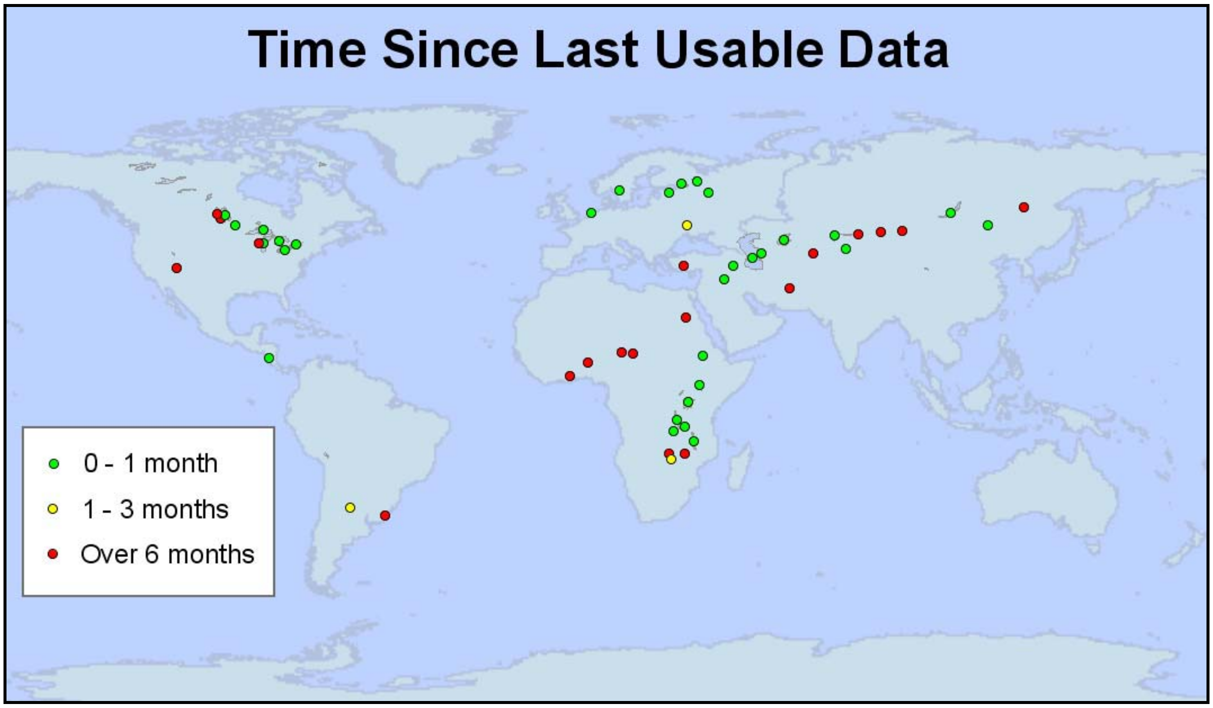


Figure 16. Map of time to last estimated water level as of May 28, 2004.

4.4 Summary of Product V&V Against FAS Requirements

Table 6 provides a summary of GRLM performance with respect to PECAD requirements.

Table 6. PECAD requirements vs. verified performance (primarily using Jason-1 IGDR based estimates).

Category	Requirement	Verified GRLM Performance
Water level relative accuracy	10 cm	
Larger lakes	<5 cm expectation	5-10 cm
Smaller lakes	<10 cm expectation	25-30 cm*
Calm-water lake surfaces	10–20 cm expectation	
Steep terrain lakes	Low expectations with current algorithm	1.5 m**
Data time step	10 days	9.9 days
Latency	10 days	10.3 day average, but 2–19 day range
Coverage	Surface waters in all land regions important for crop production and food security***	As of May 31, 2004, GRLM monitored lakes on all productive continents other than Australia

* May have been inflated by ice-contaminated data points

** From Lake Powell using T/P GDR-based estimates

*** Implied by PECAD mission, not directly communicated

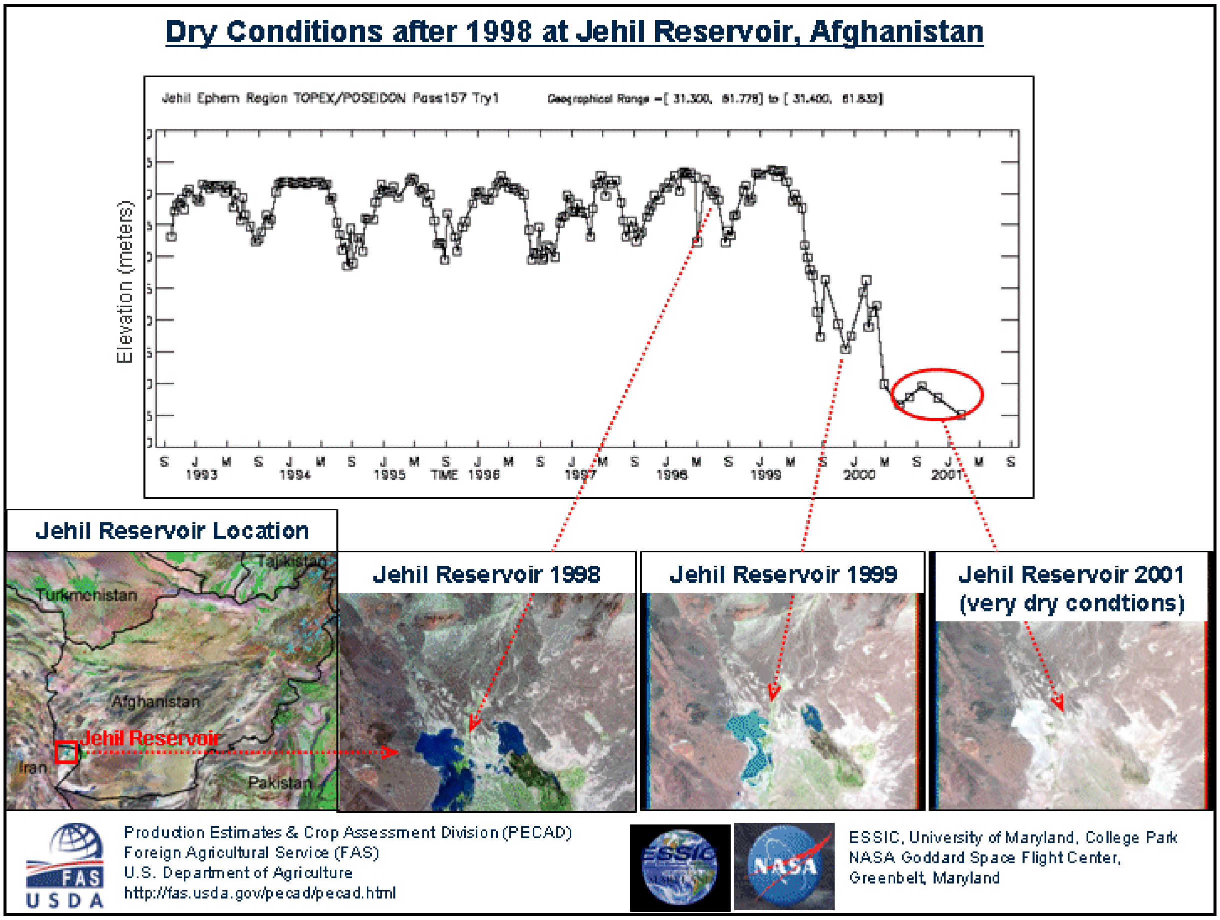
5.0 Benchmarking

5.1 Initial Evaluation of Product by FAS

Dr. Brad Doorn of FAS/PECAD submitted the following in August 2004 as an initial evaluation of how the GRLM has been used by the USDA in its early stages of implementation:

> *The Reservoir Monitor has made critical impacts on the analysis of FAS analysts, as well as our intra-government and public users of our data through the FAS Crop Explorer application. Users can access the data exclusively for reservoir information or as integrated with other agrometeorology information on a regional basis. Background information on the reservoir and a Landsat scene of the reservoir accompanies the reservoir height information.*
>
> *The most extensive use of this data has been in central and southeast Asia and Africa. Dr James Butler, Deputy Under Secretary, Farm and Foreign Agricultural Services, emphasized this application specifically at "Ministerial Conference on Harnessing Science and Technology to Increase Agricultural Productivity in Africa: West African Perspectives" in Ouagadougou, Burkina Faso on June 21, 2004 (Butler, 2004) and as quoted by the Department of State (McConnell, 2004).*
>
> *The record droughts through these regions have made reservoir and in-land lake capacities extremely critical to these food deficit regions.*

Central Asia reservoir information was included with Secretary Venemans briefing material on her trip to Afghanistan and Iraq. This information has been a key element of analysis for these planning, food aid, and agriculture assessments. See example in Figure 17.



Source: Birkett et al., 2003

Figure 17. Briefing materials using T/P lake levels.

Reservoir Monitor products are also provided through the Geospatial One-Stop, one of the 24 E-Gov initiatives sponsored by OMB. The Crop Explorer is the only link in the Agriculture and Farming portion of the Geospatial One Stop Portal that provides access to near real-time data.

A few examples of new customers (home Web site link to Crop Explorer for Lake and Reservoir information) specifically:

- *New York Fishing Forums*
- *LakeNet – LakeNet is a global network of people and organizations in more than 90 countries dedicated to the conservation and sustainable development of lake ecosystems. The network is guided by an international steering committee with regional representatives in Africa, Asia, Europe and the Americas.*
- *Great Lakes Information Network – The Great Lakes Information Network (GLIN) is a partnership that provides one place online for people to find information relating to*

> *the binational Great Lakes-St. Lawrence region of North America. GLIN offers a wealth of data and information about the region's environment, economy, tourism, education and more.*

While this initial report indicates the potential of the GRLM to affect the crop intelligence decision support of USDA-FAS positively, the system has not been available to FAS analysts and managers as an operational product for a sufficient amount of time to ascertain the real, quantifiable effect to their crop production assessment tasks. The tool must be available to FAS analysts during a number of growing seasons and production conditions to evaluate fully the benefits of the added water level information. Thus, the GRLM is included in the suite of tools developed for FAS from NASA data that is part of a more comprehensive benchmarking exercise. The results of this benchmarking exercise will be available at the end of FY2005.

5.2 Comparison with European Lakes/Rivers Product

Products comparable to the GRLM lake height variation are being developed by the European Space Agency. ESA’s River and Lake Project produced sample datasets over select inland water bodies in September 2003 and again in April 2004. The objectives of the River and Lake Project are as follows:

1. To provide about 10 years of surface height variation over select targets.

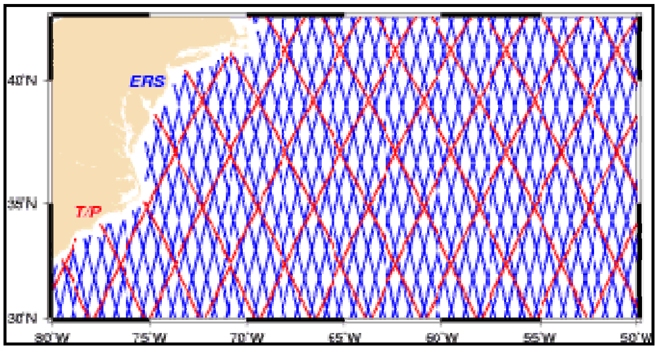
2. To expand to global coverage for the 10-year time span.

3. To deliver near-real-time products (latency of 3 hours or less via the Envisat mission, 2002–-2005).

The release of sample data has met the first objective, but no announcement has been made about when global coverage and near-real-time delivery are to be achieved.

The River and Lake Project is working with data from the Radar Altimeter 2 (RA-2) of ESA’s Envisat mission and with the Radar Altimeter instruments on ESA’s ERS-1 and ERS-2 missions. The Envisat and ERS missions have implemented a distinctive set of orbital design choices. The satellite ground tracks have a greater inclination angle than T/P and Jason-1 that allows them to cover somewhat higher latitudes. The Envisat/ERS ground track repeat time is 35 days as opposed to Jason-1’s 10-day repeat. However, repeat time has an inverse relationship with total ground track, and, as a result, the Envisat/ERS track covers about 4 times as much ground as the Jason-1 or original T/P track (see Figure 18).

ESA is working with a process to "retrack" inland water echoes using multiple algorithms that can significantly increases the amount of height data retrieved even for small targets (<1 km wide) over rough terrain (Berry et al., 1997). Retracking involves reprocessing satellite altimeter data with the original return waveforms preserved. In reprocessing, non-ocean-like waveforms can be identified with appropriate algorithms applied according to waveform. The River and Lake Project employs an expert system to identify the different waveforms or even combinations of waveforms. This process greatly reduces the possibility that data will be lost in rugged terrain or near the transition between land and water (Berry and Pinnock, 2003). Eventually, ESA intends to install operational software for free product delivery in near-real time of within 3 hours of acquisition via FTP or Internet connection for research interests.



Source: http://www.aviso.oceanobs.com/html/alti/multi_sat_uk.html

Figure 18. Ground track comparison: T/P–Jason-1 (red) vs. ERS–Envisat (blue).

ESA has two products for river and lake analysis: the River Lake Hydrology (RLH) and the River Lake Altimetry (RLA) products (ESA, 2004a). The RLH is designed for individuals with no extensive knowledge of radar altimetry technology. A single file for each crossing contains a processing header record with processing information and a series of height difference records for each cycle. Time, mean latitude and longitude, mean orthometric height (calculated from all available crossing point heights for a number of years), and a series of height variations from the mean are listed. The RLH product is the most analogous to the water height variation estimates provided through the GRLM. GRLM and RLH qualities are compared in Table 7.

Table 7. Comparison of GRLM product to River and Lake product.

GRLM Water Height Variation	River & Lake RLH
• 10-day repeat time for improved time series	• 35-day repeat time
• 52 lakes and reservoirs available globally as of May 31, 2004; all agriculturally productive continents except Australia represented	• ~4x Jason-1 ground track for better potential geographic coverage
• Semi-operational performance (lag time averaging 10 days)	• Samples updated once a year for the last 2 years; stated goal of near-real-time delivery
• Works with processed SSH data (reduces processing load)	• Employs retracking algorithm with raw data (improved performance in challenging terrain and smaller targets)

The RLA product is designed for radar altimeter experts and consists of a file for each altimeter orbit over a specific inland water location. This product will provide all crossing points over the water body, together with detailed information on all instrumental and geospatial corrections. Users can provide their own values for the geoid and the corrections to produce a more accurate height value.

Some sample RLH and RLA products are now available for download through ESA Internet sites (http://earth.esa.int/riverandlake/). The RLH can be downloaded in ASCII, HTML, and XML formats (ESA, 2004b), while the RLA product is in a binary format. Samples include 39 RLH and 2 RLA products for 16 lakes/rivers from Africa, North and South America, Europe, and Asia. Descriptions and time series graphs links are provided for each sample lake/river. Clicking on a desired format for each RLH lake provides header information with processing time, coordinate, mean altimeter height, and records of heights variations series from 1995 to 2003. At present, the samples presented on the Web are the only ESA lake and river altimetry data available.

Figure 19 shows RLH water level estimates over Lake Ontario along with GRLM water level estimates and hourly gauge data. The RLH estimates have considerably more variability than the GRLM estimates. In Table 8, the error of the water level variation versus daily gauge data after removing outliers is only 8.2 cm for T/P-based GRLM estimates and is 4.5 cm for Jason-1-based estimates, but RLH estimate error fell consistently between 23 cm and 27 cm. Poorer accuracies are expected from the ESA ERS data because the instrument is in ice-tracking mode over most of the lakes, and onboard microwave radiometer data is absent for the wet tropospheric correction. The RLH is considerably greater than the 3 cm expectation for large lakes stated by the River and Lake Project on its Frequently Asked Questions site (ESA, 2004c) and at the upper bound of the 9–24 cm range found by Berry and Pinnock (2003) in their validation efforts over the rest of the Great Lakes.

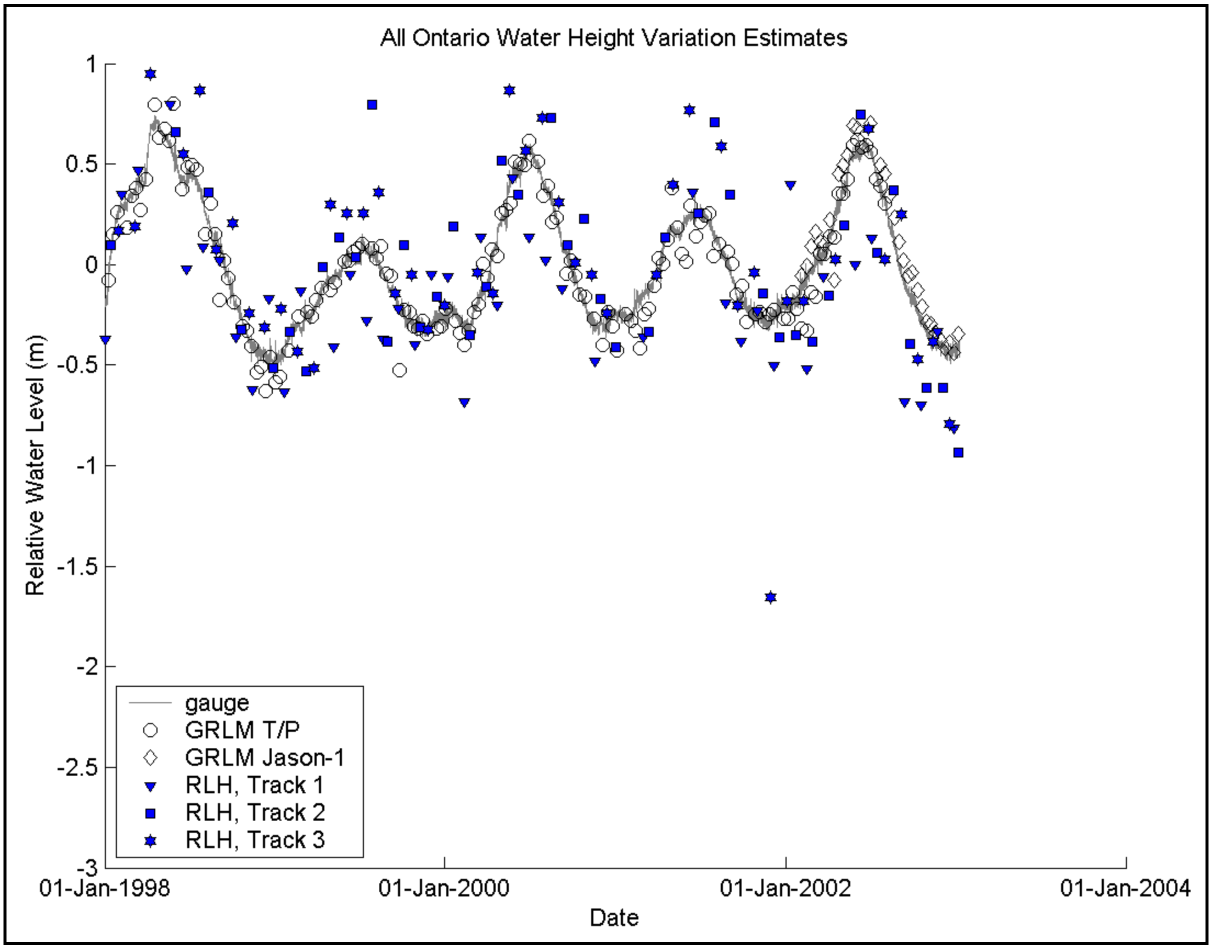


Figure 19. Comparison of GRLM to River and Lake water levels over Lake Ontario.

Table 8. GRLM/River and Lake performance versus gauge data.

Lake Name	σ_{Bias} (cm)	σ_{Bias} (outliers removed) (cm)	Data Points	Outliers
TP over Lake Ontario	8.2	8.2	147	0
Jason-1 over Lake Ontario	8.4	4.5	32	1
RLH over Lake Ontario (Track 1)	26.1	26.1	43	0
RLH over Lake Ontario (Track 2)	27.0	27.0	43	0
RLH over Lake Ontario (Track 3)	31.3	22.7	46	1

5.3 Long-term Operational Viability

The long-term viability of the GRLM DST depends on 1) the availability of compatible satellite radar altimeters that can provide the raw altimeter data to produce lake height information, 2) an operational mechanism for maintaining and updating the GRLM product, and 3) an understanding by FAS of the associated costs for and benefits of maintaining the GRLM data flow. As discussed in Section 2.5.1, the Jason-1 mission is on-going, having been launched in December 2001 with a 5-year primary mission. A redundant capability still exists with T/P, which as of August 2004 has provided more than 12 years of continuous radar altimeter data, although the T/P satellite is nearing the end of operational life and may not be a viable data option much longer. The Jason-2 or Ocean Surface Topography Mission was originally scheduled for launch in 2005, but current schedules now call for launch in 2007 or 2008. This delay potentially leaves a 1- to 2-year gap following the primary mission of Jason-1 if the mission does not extend beyond the planned 5-year timeframe. In the event of a Jason-1/Jason-2 data gap, alternate data sources exist that could be integrated into the GRLM tool, including the ESA Envisat mission and the U.S. Navy GEOSAT Follow-On mission. The Jason science missions are planned to transition to the National Polar-orbiting Operational Environment Satellite System (NPOESS) for sustained operational measurements. The first NPOESS satellite is likely to launch around 2009, and the NPOESS sensor suite will utilize a radar altimeter similar to the instrument used on Jason-1.

FAS has invested significant resources to date for the development, testing, and deployment of the GRLM. The maturation of the GRLM tool is nearing operational status, and the Phase II project, as discussed in Section 3.0, is to conclude with an operational product. Several options exist to sustain the data stream beyond the Phase II demonstration of the GRLM DST. The most straightforward option would be for the work of GIMMS and ESSIC to be transitioned from a demonstration project to semi-operational information support to FAS, with FAS continuing to provide financial support to the GSFC/UMD team, at a reduced level from the developmental phases of the project, to maintain the system and to provide operational updates to the lake/reservoir height database. In this model, FAS could also continue the developmental relationship with the team to augment the GRLM tool with potential desired improvements in coverage, accuracy, and/or product delivery. Similar existing arrangements are already in place with GIMMS to provide FAS with AVHRR global area coverage Normalized Difference Vegetation Index and SPOT Vegetation products for PECAD analysts. FAS has funded GIMMS to provide these services operationally since 2001 (Doorn, 2004).

A second possible option for sustaining the GRLM tool would be for the algorithms and procedures to be transitioned to the PECAD group so that they could assume the responsibility to extract lake/reservoir height information directly from AVISO or PO.DAAC raw altimeter inputs. This option would be more viable if the extraction of reservoir/lake height information is optimized for autonomous operation, which might require further developmental work by the GSFC/UMD team or an existing/planned PECAD technical contractor. To the extent that PECAD transitions its data preparation and handling to a central data mining facility/contractor, the production of the GRLM data could be included in the suite of data products produced for PECAD.

A third option for maintaining the long-term operations of the GRLM tool would be within the Distributed Active Archive Centers (DAACs) of NASA's EOSDIS. The DAACs are the data management and user services arm of the NASA EOSDIS. Each DAAC processes, archives, and distributes data from NASA satellites to users in a specific Earth science discipline. The GRLM tool could be integrated into the product lines of a DAAC such as PO.DAAC, which already archives the Jason-1 ocean products, or another center more focused on land processes or the water cycle, such as the Global Hydrology Resource Center at the Marshall Space Flight Center. The viability of this option increases as the scope of users of this information product increases. Thus, a DAAC that services the hydrology community would be more likely to adopt the operational provision of the GRLM product if the product is valuable to a significant proportion of its users.

Effective transition from product development to operations takes advance planning and careful consideration of costs and benefits. To this end, NASA is using resources within the EOSDIS Synergy project in 2004-05 to examine operational product provision for the current NASA EOS products under development for FAS, including the GRLM. A nine-month study is being initiated that will examine 1) the types of products needed/in development by FAS, 2) the interfaces required to provide product access to FAS, and 3) the infrastructure FAS needs to integrate the products into their decision support system. The result of the study will be an analysis of operational product provision options and a set of recommendations. The results of this study, coupled with the FY05 benchmarking of the use of the NASA-developed products for FAS decision support (including the GRLM), should provide the framework for developing a transition plan from development to operations for the GRLM tool.

Beyond the more immediate transition, the Foreign Agricultural Service will need to define requirements for inland water heights in the NPOESS era. In that context, satellite radar altimetry mission data can be expected to come from NOAA instead of from NASA. Further development of the GRLM tool and products should assume this end state.

5.4 Phase III Proposal

In September 2004, the USDA awarded a further grant to the GSFC/UMD team to continue the GRLM project through FY05. The scope of activities for this phase builds upon Phases I and II as outlined in Sections 3.2.1 and 3.2.2. The primary focus of the Phase III effort will be the continuation of the operational provision of the GLRM tool. In addition, several new development tasks are being considered for expansion of the GRLM tool:

1. Inclusion of datasets from the NOAA/GFO, NASA/CNES TOPEX Tandem, and ESA ERS and Envisat missions. The project has already gained permission from the Mission Program Managers to use the data in a semi-operational manner.

2. Re-work of the existing Jason-1 archived results using the GDR data to increase the accuracy of the Jason-1 elevations. The new near-real-time measurements would still come from the Jason-1 IGDR.

3. Investigation into the use of signal processing techniques to examine the raw altimetric waveform data. The objective would be to examine the potential increase in quantitative measurements over small targets and to look at the quality/quantity trade-offs.

6.0 Conclusions and Recommendations

In terms of the systems engineering process as described by Figure 1, the GRLM decision support tool enhancement to the PECAD decision support system has been verified and validated, and benchmarking has been initiated. The V&V effort has revealed a small but important set of gaps between the implemented tool's capabilities and the requirements of the Foreign Agricultural Service. These gaps indicate the necessity to review FAS requirements, to refine the tool's design, and to update its implementation as is planned in Phase III. Given that PECAD analysts are still learning the affect of the tool on their crop yield and food security assessments and that the tool is undergoing a final developmental iteration, it is desirable to continue benchmarking efforts into FY 2005.

The Agricultural Efficiency Integrated Product Team concludes that by developing the GRLM tool and integrating the tool into the PECAD DSS, the Goddard Space Flight Center/University of Maryland team has made great strides toward meeting the immediate needs of PECAD, FAS, and their many intra-governmental and public users. Early benchmarking efforts have shown a strong positive response from users outside of the FAS/PECAD group. In verification and validation results, latency typically falls within the desired range, distribution of estimates span the globe and touch many important crop production and crop security regions, and product accuracy is sufficient for many of the lakes and reservoirs that have been incorporated to date. Recognizing that the GRLM decision support tool has broadly achieved its aims, the following suggestions are offered toward achieving a robust operational status.

1. Coverage should continue to be increased. While continuing efforts should be made to add water bodies that fall under the Jason-1 ground track, many of the lakes and reservoirs that are visible to Jason-1 and are important to PECAD have already been added to the DSS; any new water bodies added will tend to be more marginal. In the upcoming period, new lakes and reservoirs should be added using other sensors, such as T/P (if it remains healthy), GFO, and Envisat. Decisions about which sensor(s) to add should based on FAS information requirements but should also weigh the health of the sensor and the revisit time. Further development of the similar ESA inland water level tool should continue to be monitored for possible integration into the FAS lake water level resource toolkit.

2. Data dropouts should be reduced. If no action is forthcoming based on the University of Maryland/Raytheon request to AVISO, then the request should be reiterated from higher levels within NASA. If AVISO is unable to improve the data stream, perhaps a separate channel for providing appropriate SSH data should be engaged at PO.DAAC.

3. While not all lakes are meeting the stated FAS accuracy requirement, perhaps the accuracy requirement should be revisited. For deep, narrow reservoirs, fairly large height uncertainty may be acceptable because the information regarding water volume is still readily discernable. For

shallow, closed lakes (e.g., Lake Chad), the current standards are appropriate. Furthermore, FAS lake water height requirements should be developed in more detail to include a comprehensive listing of water bodies that FAS believes are important to monitor.

4. Given that a surface area measurement could be an important complementary change indicator for certain shallow water bodies, such as Lake Chad or the Salton Sea, perhaps a MODIS-based area measurement could be prototyped as a DST enhancement

Given the strong outlook for continuity in the underlying satellite radar altimetry measurements into the NPOESS era, the GRLM is well positioned as a viable DST that should receive continued support and development. Looking beyond the current context of the integration of the GRLM into the PECAD DSS, it is apparent that this tool is extensible to other applications of national priority. In the recently released draft Strategic Plan for the U.S. Integrated Earth Observation System, reservoir and lake water levels were pointed out as an important part of a systematic approach to monitoring drought. In alignment with this national vision for Earth observations, the GRLM tool can give cross-cutting societal benefits to the areas of energy management, water management, and ecological forecasting.

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Appendix A. Example of GRLM Lake Level Variation Data

Results Table for lake level variation available from the GRLM. Table data (abridged here) consists of TOPEX/Poseidon (T/P) and Jason-1 altimetry measurements with respect to T/P 10-year mean level for Lake Superior. Data collection in this example starts on September 26, 1992, and continues to the last update (as of the time this list was accessed) on March 1, 2004.

```
0337 Superior            : Lake database id number and name
 47.83 273.00            : Latitude and longitude (degrees East) of lake mid-point
 48.11 271.67            : Start latitude and longitude (degrees East) of pass traversing lake
 46.49 273.29            : End latitude and longitude (degrees East) of pass traversing lake
 48.11  48.04            : Latitude range of pass traversing lake at which data is accepted
    76   38              : Satellite pass and revolution number designation

Column 1: satellite mission name
Column 2: satellite repeat cycle
Column 3: year,month,day of along track observations traversing lake
Column 4: hour of day at mid point of along track pass traversing lake
Column 5: minutes of hour at mid point of along track pass traversing lake
Column 6: lake height variation with respect to TOPEX/POSEIDON 10 year mean level (meters)
Column 7: estimated error of lake height variation with respect to TOPEX/POSEIDON 10 year mean level (meters)
Column 8: mean along track K-band backscatter coefficient (decibels)
Column 9: wet tropospheric correction applied to range observation (TMR=radiometer, FMO=ECMWF model)

TOPEX   1 19920926   2  5   0.20  0.042  11.03 TMR
TOPEX   2 19921006   0  4   0.21  0.042  11.43 TMR
TOPEX   3 19921015  22  2   0.17  0.042  11.14 TMR
TOPEX   4 19921025  20  1   0.16  0.042  11.42 TMR
TOPEX   5 19921104  17 59   0.15  0.042  10.51 TMR
```

…Intermediate text removed…

```
TOPEX 360 20020625  19 16  -0.01  0.043  19.42 TMR
TOPEX 361 99999999  99 99 999.99 99.999 999.99 FMO
TOPEX 362 20020715  15 13   0.01  0.042  17.30 TMR
TOPEX 363 20020725  13 11   0.01  0.042  14.83 TMR
TOPEX 364 20020804  11 10   0.10  0.042  14.86 TMR
Jason   1 99999999  99 99 999.99 99.999 999.99 FMO
Jason   2 20020128   1 36  -0.12  0.043  11.95 JMR
Jason   3 20020206  23 35  -0.18  0.042  11.33 JMR
Jason   4 20020216  21 33  -0.25  0.042  10.51 JMR
Jason   5 20020226  19 32  -0.26  0.042   9.64 JMR
```

…Intermediate text removed…

```
Jason  75 20040121  21 49  -0.25  0.042  12.68 JMR
Jason  76 20040131  19 47  -0.23  0.042  16.53 JMR
Jason  77 20040210  17 46  -0.25  0.043  14.41 JMR
Jason  78 99999999  99 99 999.99 99.999 999.99 FMO
Jason  79 20040301  13 43  -0.25  0.042  14.99 JMR
```

Appendix B. GRLM Results over Specific North American Reservoirs and Lakes

Characteristics of the gauge sites referenced are summarized in Table B-1.

Table B-1. Gauge site details.

Reservoir or Lake	Number of Gauges (cm)	Mean RMS between Gauges (cm)	Gauge Sites	Separation from Track (km)
Lake Superior	3	2.6	Thunder Bay, Ontario	73
			Rossport, Ontario	100
			Marquette C.G., MI	42
Lake Michigan	3	2.1	Milwaukee, WI	108
			Calumet Harbor, IL	13
			Holland, MI	31
Lake Huron	4	2.5	Tobermory, Ontario	1
			Parry Sound, Ontario	107
			Goderich, Ontario	90
			Harbor Beach, Mi	20
Lake Erie	4	2.6	Erieau, Ontario	42
			Port Stanley, Ontario	17
			Cleveland, OH	21
			Fairport, OH	35
Lake Ontario	3	1.9	Cobourg, Ontario	74
			Rochester, NY	9
			Oswego, NY	72
Lake Winnebago	1	N/A	Oshkosh, WI	7
Lake of the Woods	1	N/A	Warroad, MN	31
Lake Powell	1	N/A	Glen Canyon Dam	84

In the following pages, a time series of the GRLM estimates for each reservoir or lake is compared to average hourly gauge heights. The Y axis of each graph represents the displacement of water height from reference. The Y axes were generally held to ±1.5 m so the absolute amount of variation of each reservoir or lake would stand out. Lake Powell was an exception to this rule because its level varied by tens of meters.

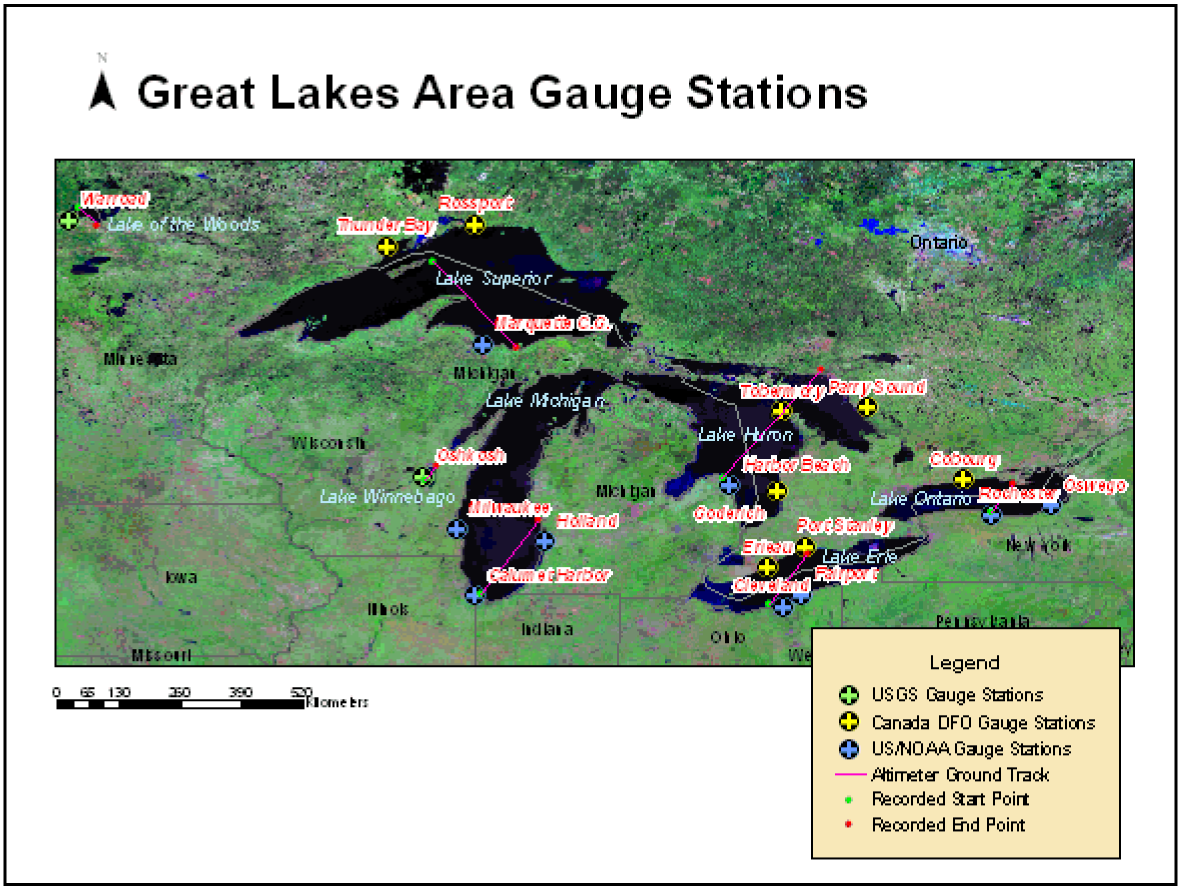

Figure B-1. Gauge stations in the general vicinity of the Great Lakes.

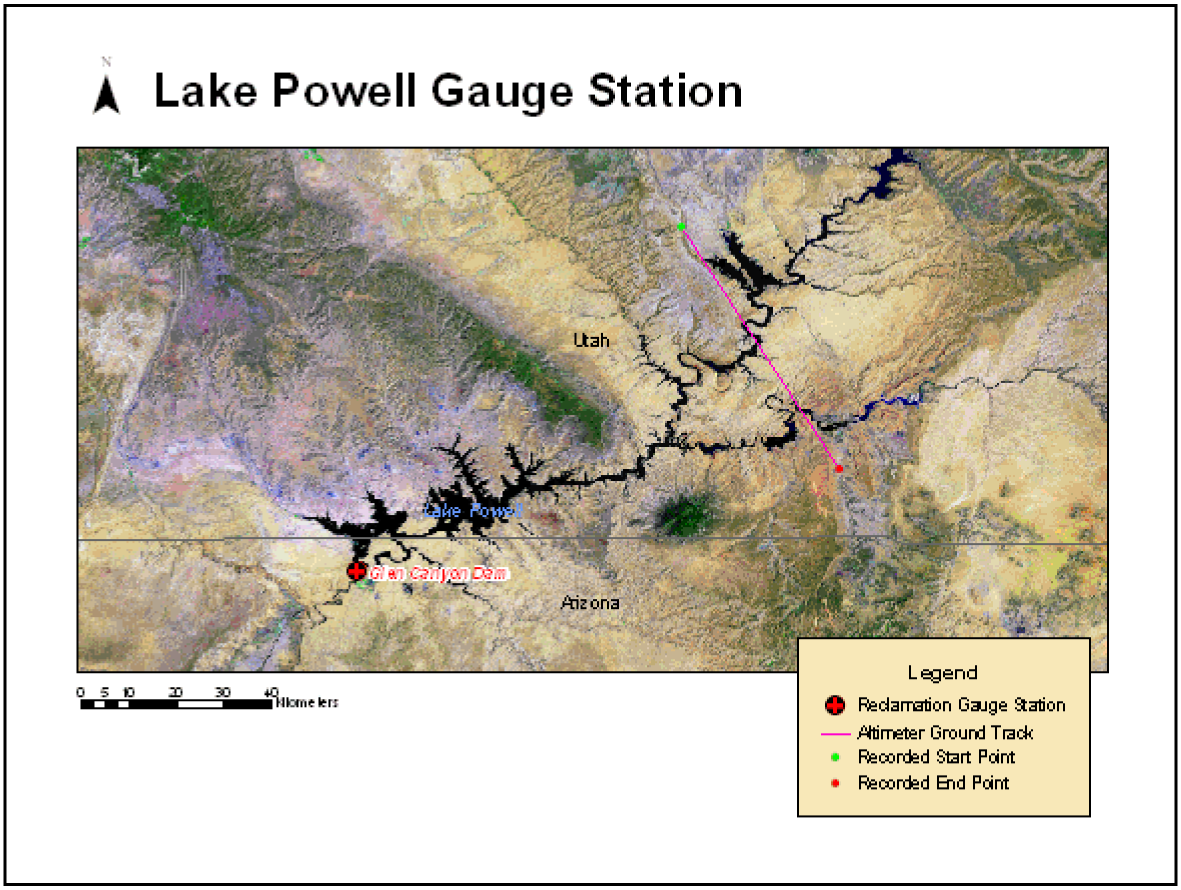

Figure B-2. Relationship of gauge and track at Lake Powell.

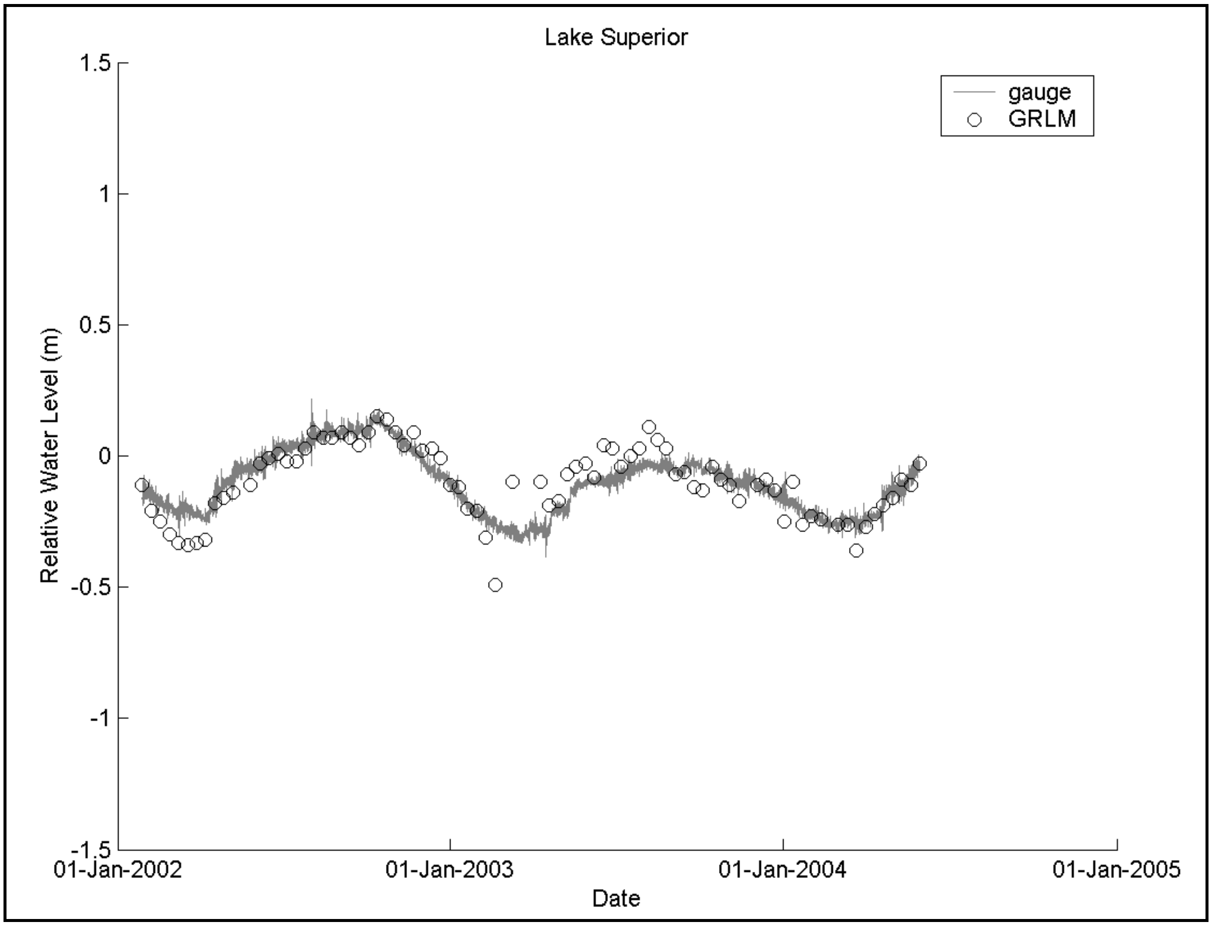

Figure B-3. Lake Superior comparison.

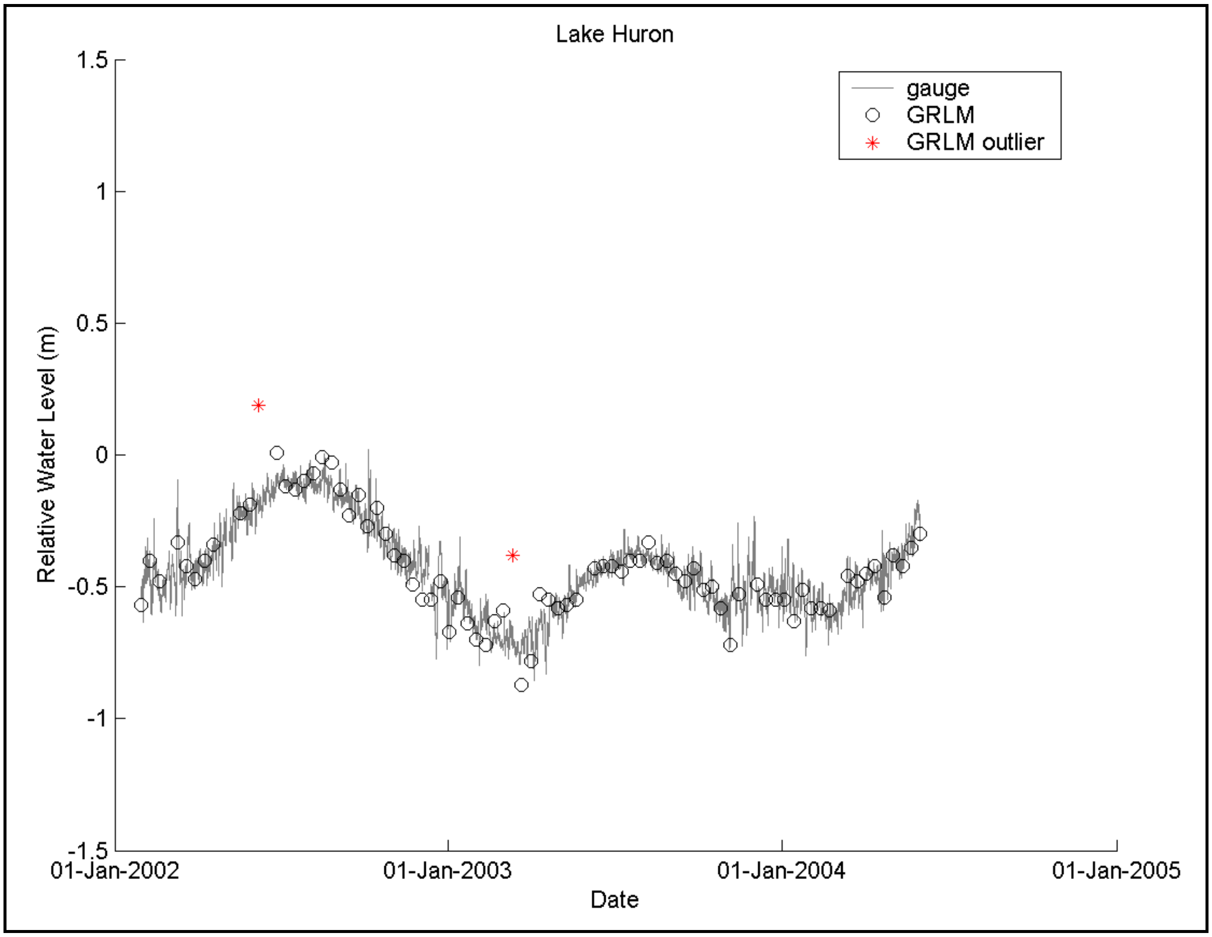

Figure B-4. Lake Huron comparison.

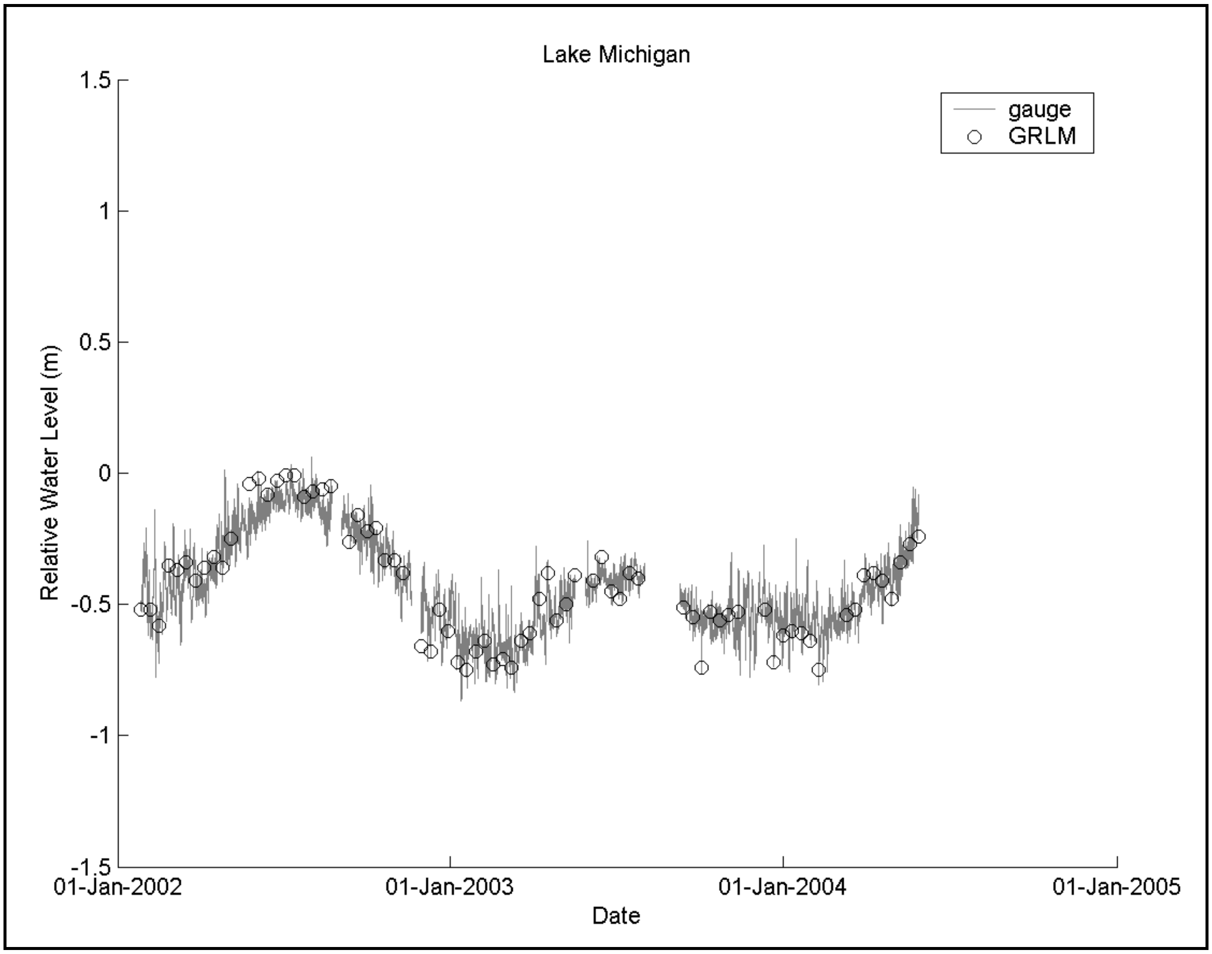

Figure B-5. Lake Michigan comparison.

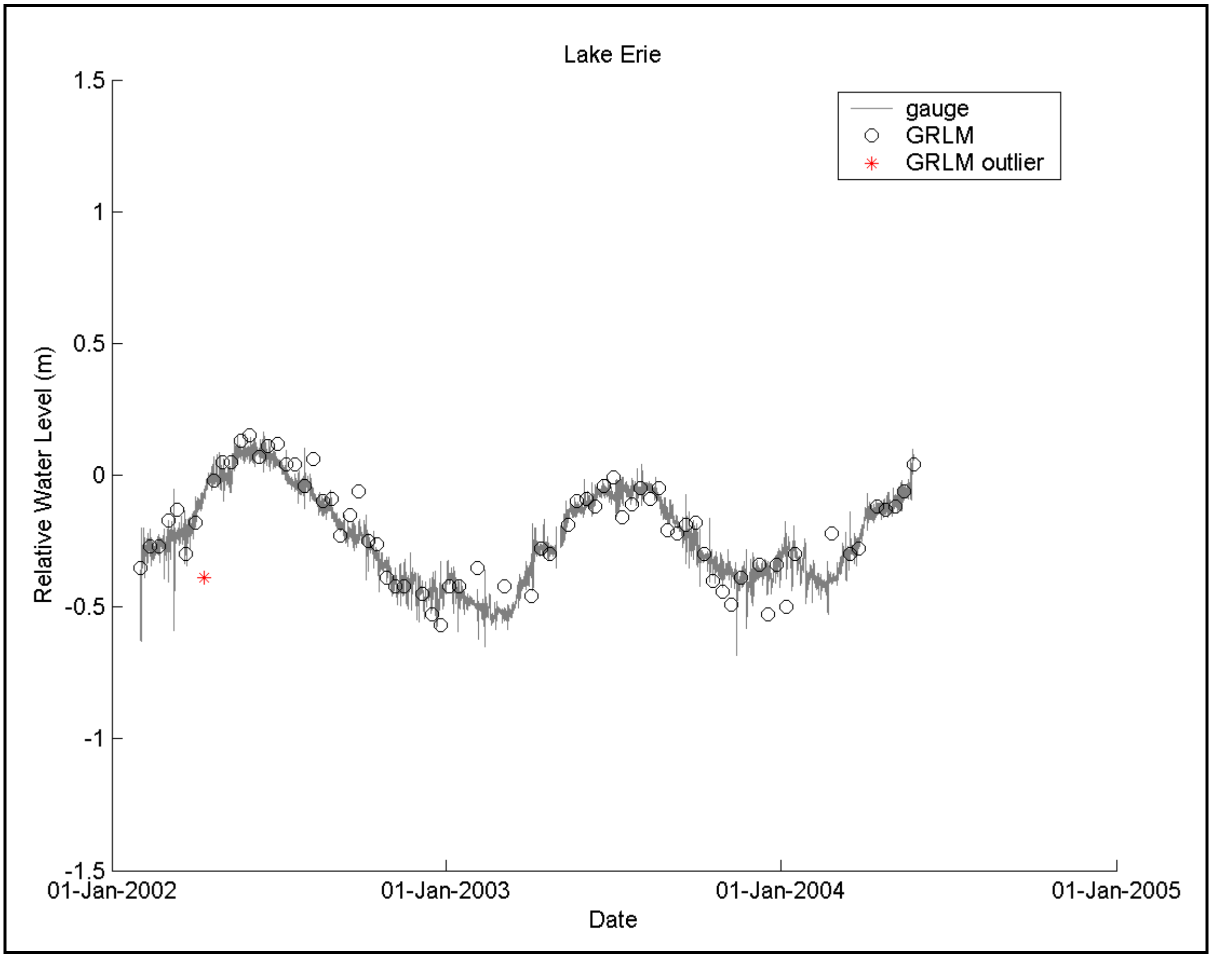

Figure B-6. Lake Erie comparison.

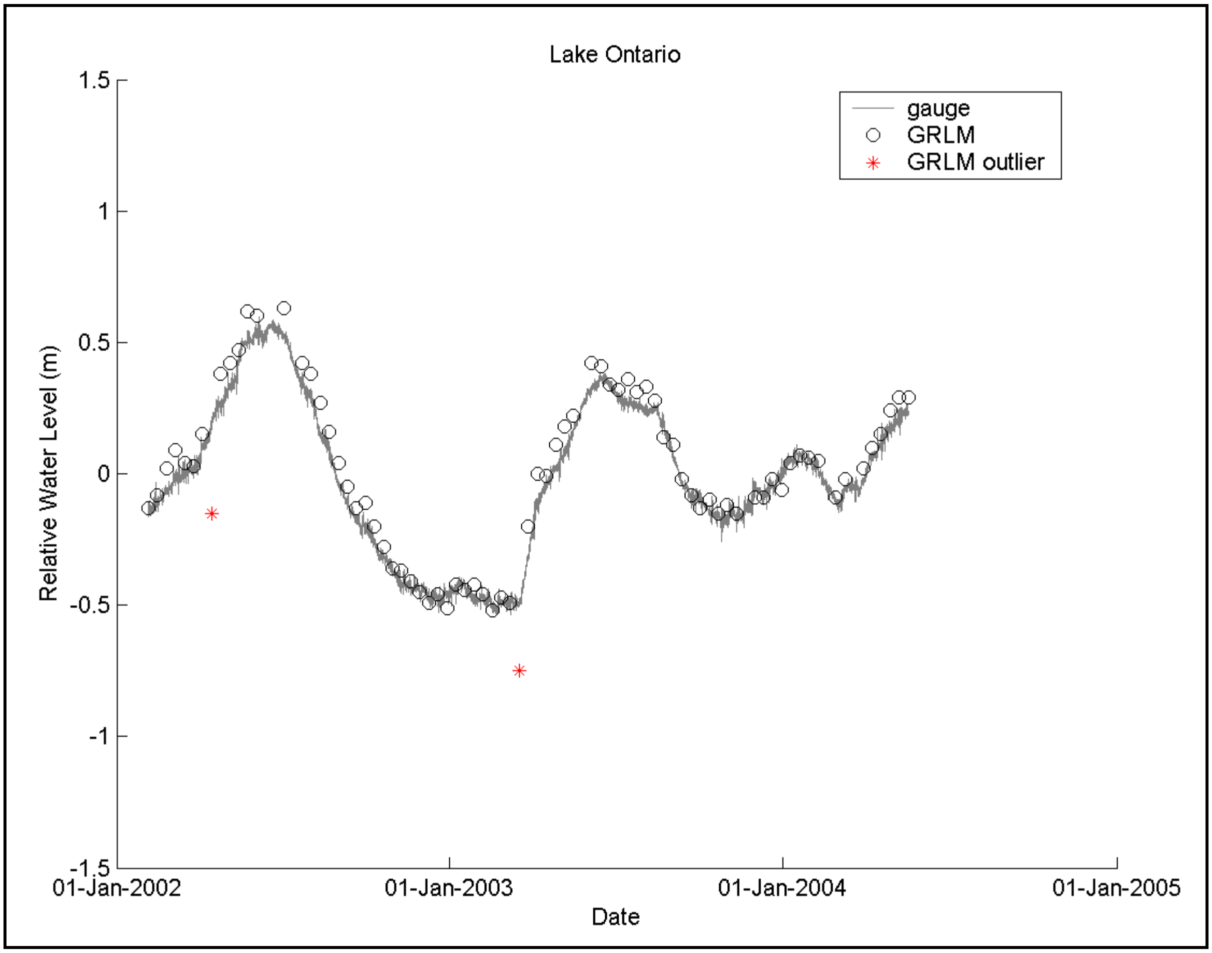

Figure B-7. Lake Ontario comparison.

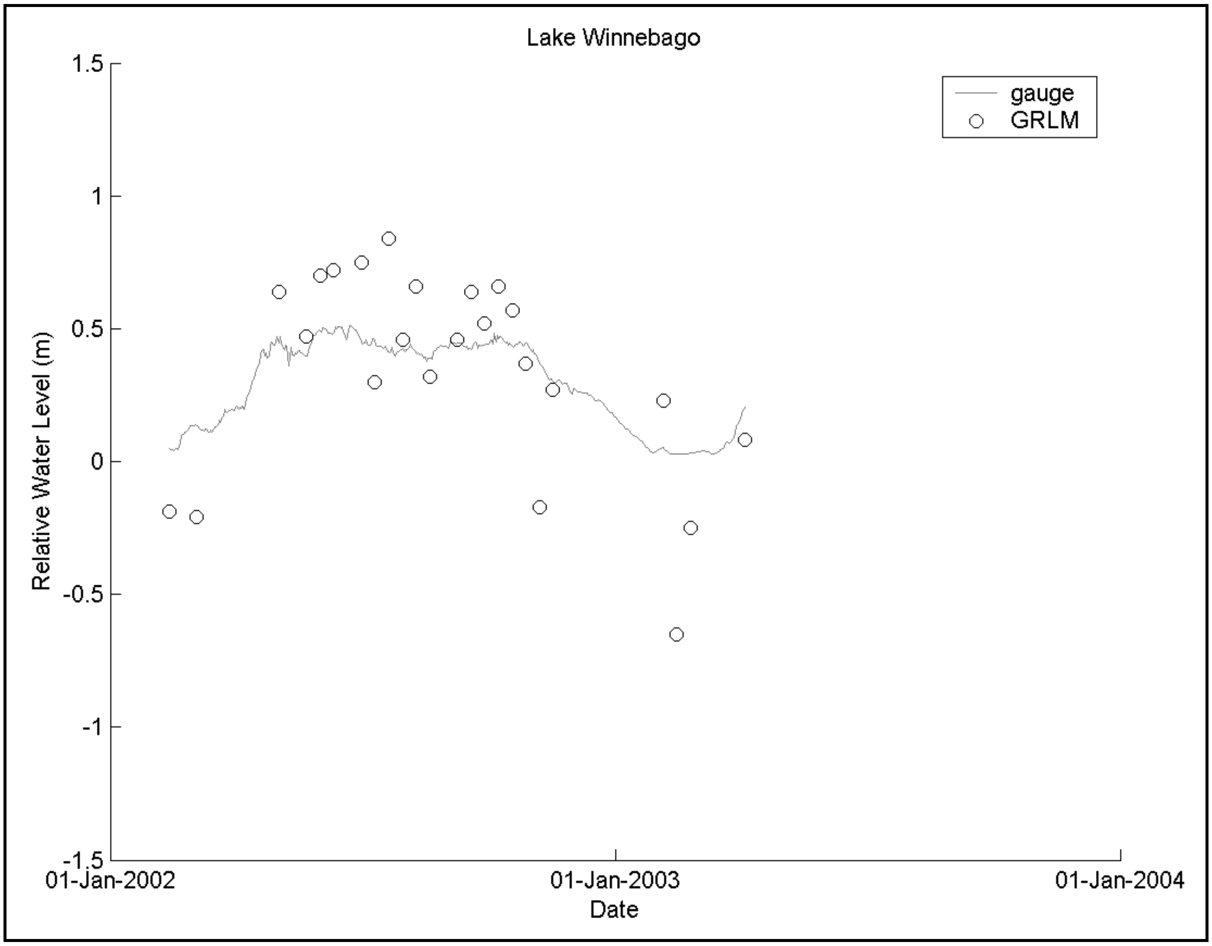

Figure B-8. Lake Winnebago comparison.

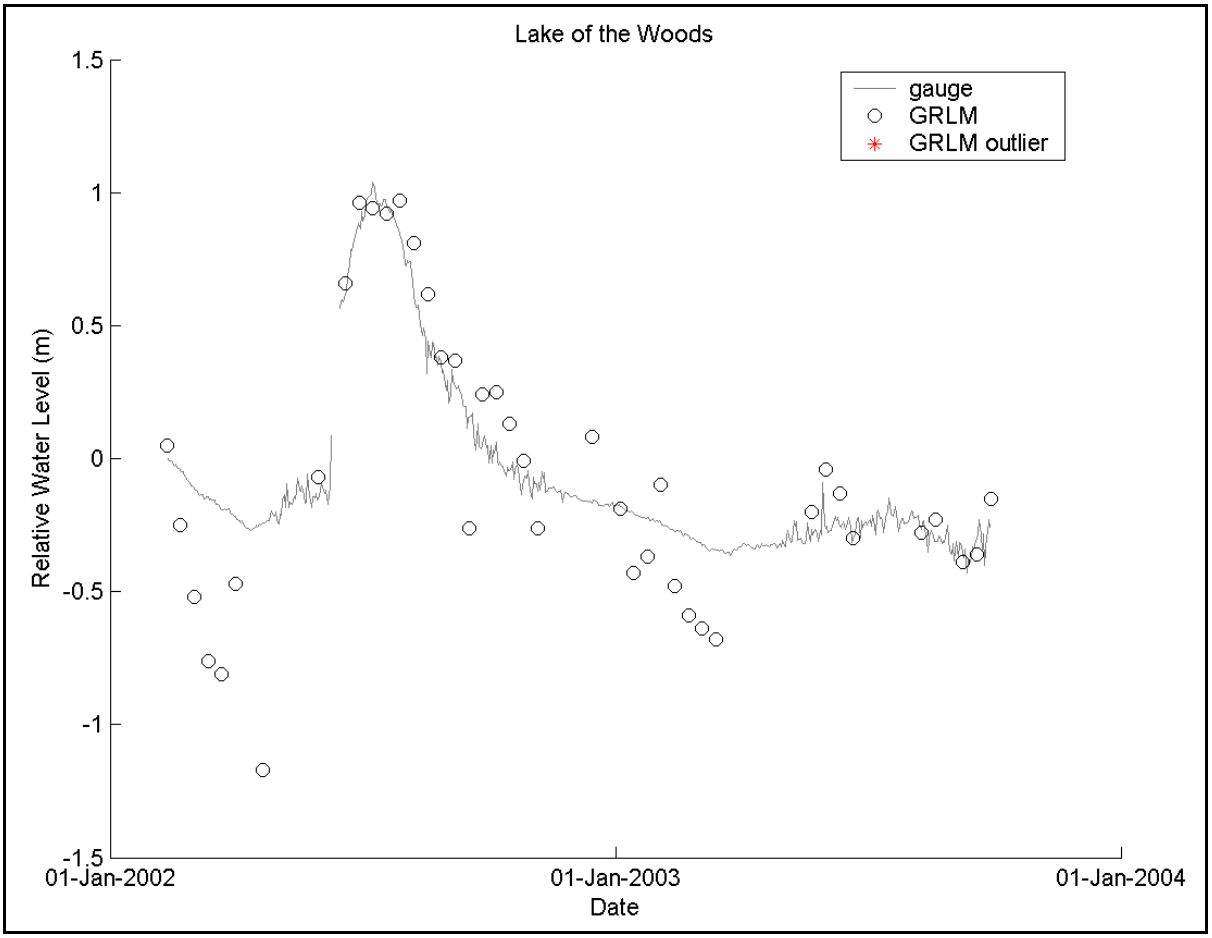

Figure B-9. Lake of the Woods comparison.

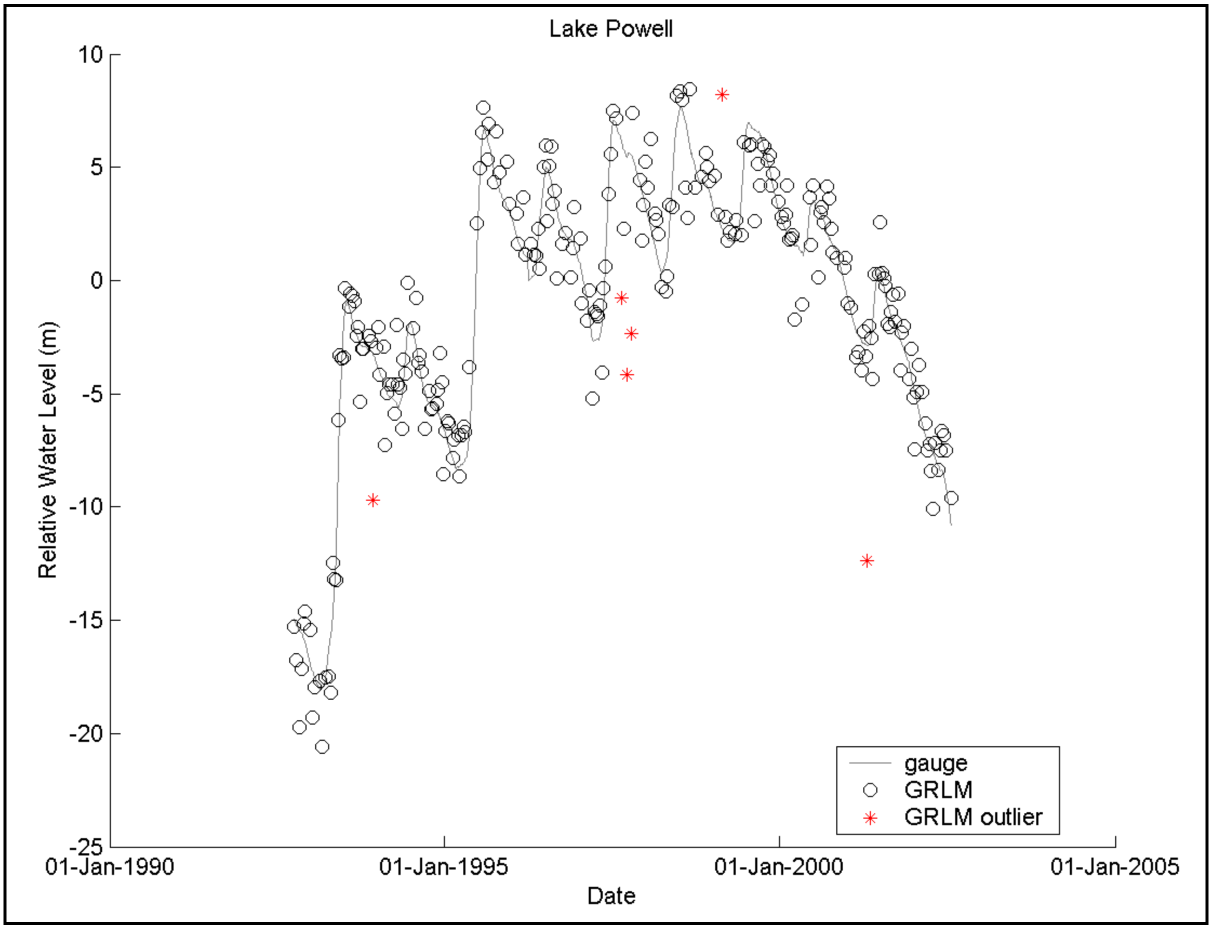

Figure B-10. Lake Powell comparison.

Appendix C. Cross Validation of Collinear T/P and Jason-1 Water Height Variation Estimates in GRLM

Note that σ_{std} is the standard deviation and σ_{iqr} is the interquartile range multiplied by 0.7413. The multiplier makes them equivalent estimates of spread given normal assumptions, but the interquartile range is less susceptible to outliers.

Table C-1. Site-by-site cross-validation results.

Code	Lake Name	Pairs	Mean Diff. (m)	Median Diff. (m)	σ_{std} (m)	σ_{iqr} (m)
12	Winnipeg	18	0.2444	0.2050	0.1670	0.1853
22	Onegh	12	0.0558	0.0600	0.2347	0.1001
26	Vanern	16	0.1781	0.1700	0.1922	0.1742
42	Manitoba	12	0.5592	0.6250	0.2214	0.2113
53	Mangueira	17	0.9053	0.8100	0.9114	0.7135
67	Fitri	17	0.6218	0.5900	0.4943	0.2706
68	Chad	5	0.5600	0.4400	0.2446	0.2669
82	Rukwa	0				
93	Turkana	20	0.0730	0.0650	0.0796	0.0482
107	Beysehir	7	0.0986	0.1600	0.3909	0.3058
115	Urmia	15	0.1933	0.2200	0.4981	0.4003
203	Winnipegosis	14	0.5836	0.5650	0.2446	0.2224
209	Ulungar	5	-0.5460	-1.2300	2.7832	3.4804
221	Peipus	11	-0.0545	0.0200	0.6978	0.2168
223	Rybinskoye	13	0.3192	0.3100	0.2054	0.2150
234	Sasykkol	16	-0.1363	0.0450	0.5150	0.5411
266	Woods	16	0.3244	0.2350	0.6994	0.2632
269	Buhayrat	15	0.1800	0.2200	0.1974	0.2002
270	Caspian	19	-0.0184	-0.0100	0.0499	0.0352
275	Kara_Bogaz	19	-0.0105	0.0000	0.0755	0.0463
277	Aral	19	-0.0205	-0.0200	0.0480	0.0519
278	Balkhash	12	0.1108	0.0450	0.1708	0.1520
314	Victoria	20	0.0200	0.0250	0.0427	0.0408
315	Tanganyika	20	0.0720	0.0700	0.0687	0.0445
316	Baikal	9	0.0622	0.0600	0.1081	0.0593
317	Malawi	19	0.0826	0.0900	0.0333	0.0297
331	Nasser	17	0.5865	0.5700	0.4132	0.3540
333	Erie	18	0.1061	0.1100	0.0371	0.0371
334	Ontario	16	0.1106	0.1050	0.0772	0.0778
335	Michigan	18	0.0906	0.1000	0.0253	0.0297
336	Huron	17	0.0894	0.0900	0.0683	0.0445
337	Superior	17	-0.0276	-0.0300	0.0358	0.0241
338	Issyk-kul	11	0.0982	0.1200	0.1136	0.1334

Code	Lake Name	Pairs	Mean Diff. (m)	Median Diff. (m)	σ_{std} (m)	σ_{iqr} (m)
340	Ijsselmeer	18	-0.0094	-0.0200	0.0888	0.1038
344	Chiquita	10	0.1010	0.0900	0.1363	0.1779
351	Nicaragua	18	0.1250	0.1000	0.0964	0.0519
353	Zeyaskoye	9	0.4211	0.6700	0.6833	0.3188
372	Dorgon	10	-0.4470	-0.2700	1.1886	0.8821
385	Hulun	11	0.3218	0.2800	0.2209	0.2428
393	Volta	7	0.7829	0.9000	0.5841	0.5041
394	Kariba	14	0.0521	0.5500	2.8892	0.7042
396	Ladoga	14	0.0193	0.0200	0.1365	0.0964
402	Tana	16	0.0150	0.0250	0.1065	0.0927
414	Cabora_Bassa	2	0.7650	0.7650	0.2192	0.2298
415	Kafue	13	-2.3477	-2.8600	1.9610	1.0063
416	Mweru	19	-0.0089	0.0300	0.3127	0.0593
417	Kainji	12	1.0117	1.3050	1.7750	1.1008
460	Chardarinskoye	3	0.5900	0.3200	0.5839	0.5949
462	Powell	0				
480	Winnebago	5	0.2720	0.3800	0.2036	0.1557
503	Kremenshugskoye	8	0.3312	0.3100	0.1336	0.1668
9999	Hamoun	0				