BATHYMETRY FROM FUSION OF MULTI-TEMPORAL LANDSAT AND RADAR ALTIMETERY

Ron Abileah[1], *Stefano Vignudelli* [2]

[1]jOmegak, San Carlos CA, USA, [2]National Research Council (CNR-IBF), Pisa, Italy

ABSTRACT

Near shore bathymetry of Lake Nasser, Egypt was derived by fusing shoreline contours from 58 Landsat images spanning the years 1998-2003 with water levels from the various satellite radar altimeters operated by US and European agencies. A least-square fit is made on paired water area (from Landsat) with water levels (from the altimeters) observations. The fitted function is then used to assign a relative depth to each Landsat image shoreline. A series of shorelines are interpolated into depth contours at 1 m intervals. The bathymetry resulting from this process has rmse ~10 cm.

***Index Terms*—** Landsat, Radar Altimetry, Multitemporal, Bathymetry

1. INTRODUCTION

Earlier this year we combined Landsat imagery and satellite radar altimetry to measure water volume changes in Lake Nasser over a period of several years. Our results were presented in the International Water Technology Conference in Alexandria in May 2011 and a companion paper was published in the inaugural issue of he International Water Technology Journal [1]. As described in that paper the water volume estimation process results in several related products. One is the near shore bathymetry. The bathymetry is determined by a series of shorelines mapped at different times as the water level rises and falls in annual cycles. The bathymetry is essential to the volume estimate but is also a separately useful product for navigation. In this paper we focus on the methodology for mapping the bathymetry and assess and investigate the sources of errors.

Excellent background to the subject of radar altimetry over lakes can be found in [2-4]. These references discuss data processing, applications, and discussions of specific data time series, including that of Lake Nasser used here. Altimetry rmse is reported to be in the range of 3-5 cm for the largest lakes and when all corrections are known, and upwards of 30 cm and more for smaller lakes [2,Chapter 2]. Lake Nasser is a large lake but altimetry may be somewhat less accurate due to lack of some corrections.

2. PROCESSING METHODOLOGY

While details of our processing and fusion of Landsat and radar altimeters can be found in [1] we will summarize the specific steps related to bathymetry mapping in the following subsections.

2.1. Landsat images

The revisit frequency of satellites in the Landsat constellation is 16 days. There is thus a potential for several images per months, spanning years or decades. For reasons related to mission data collection policies and clouds, the frequency of usable images is usually much less, typically 0.5-1 month^{-1}. Still, this is frequent enough for mapping lake bathymetry.

Shorelines are delineated by the boundary between pixels classified as land and water. All the Landsat bands (three visible, three or four IR bands, and panchromatic) can be useful in land-water classification. However we find that band 5, 1.55-1.75 μ, is the most suitable and sufficient in a one-band land-water algorithm. There are several reasons for this: there is virtually no bottom reflected radiance in this band; the band has good penetration of light haze; insensitivity to water temperature artifacts; and most important, a high contrast between land and water reflectance.

In the simplest sense the algorithm finds the line of high contrast expected between land (bright) and water (dark). However the location accuracy of this line can be further improved by an iterative subtraction of adjacency radiance - that is radiance from land scattered by the atmosphere into adjacent water cells. Furthermore, we improve on the native 30-m Landsat image resolution by using a simple form of the pixel unmixing algorithm to locate the shoreline to 15 m or better. Figures 1 and 2 show two segments of the lake shoreline used for this paper. One area is referred to as "Airport" in reference to the Abu Simbel Airport at the bottom; the other is

 978-1-4577-1203-6/11/$26.00 ©2011 IEEE

referred to as "Pumping Station" in reference to the facility that transfers Lake Nasser water to the Toshka Lakes through the Sheikh Zayed Canal.

We used all imagery available for this area from Landsat 5 and 7 covering the period February 1998 - October 2003. There were a total of 58 images of which six were eliminated by an automatic cloud detector leaving 52 samples for the analysis to be described here. During this time period the water level at Lake Nasser varied by 10 m. We are thus able to map the bathymetry from the highest water line to 10 m below simply by following the shorelines. Other methods, which are beyond the scope of this paper, are used to extend the bathymetry below the low water level.

2.2. Radar Altimeter levels

Raw satellite altimetry data requires sophisticated knowledge and processing to turn into useable water levels. For this study we relied on already reduced and published levels for Lake Nasser. We used the American TOPEX based lake levels as published in the USDA web site [5] and the European systems data in the LEGOS web site [6]. The various altimetry systems in the mix have varying trajectories over Lake Nasser with revisit intervals in the range of 10 to 35 days. By combining the TOPEX and European data we have lake levels at more frequent intervals than with just one or the other. In the combination there are levels for Lake Nasser at <10 day intervals over most of a 4.5-year period..

TOPEX and LEGOS levels are published on different baselines. To combine them we interpolate the data of each into a time series at fixed 0.01 year intervals. Than we estimate a constant bias such that LEGOS interpolated time series + bias term = TOPEX interpolated time series.

The combined altimetry data are then interpolated to the dates of Landsat images. Some error may be introduced in this interpolation.

2.3. Model fitting Landsat area and altimeter levels

The shorelines encompass an area of water. From this area we subtract the area of all enclosed islands - of which there are many. This area is plotted against the corresponding altimeter levels (Figure 3). As expected the levels are monotonically increasing, except for random data errors, with respect to area.

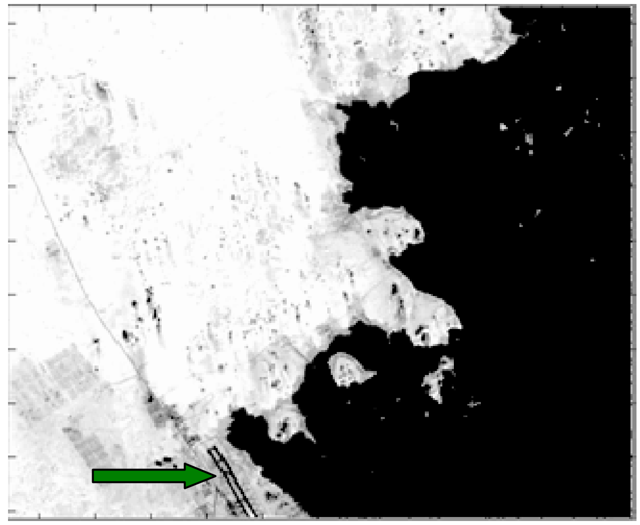

Figure 1 Airport shoreline. Arrow indicates the Abu Sinbel Airport.

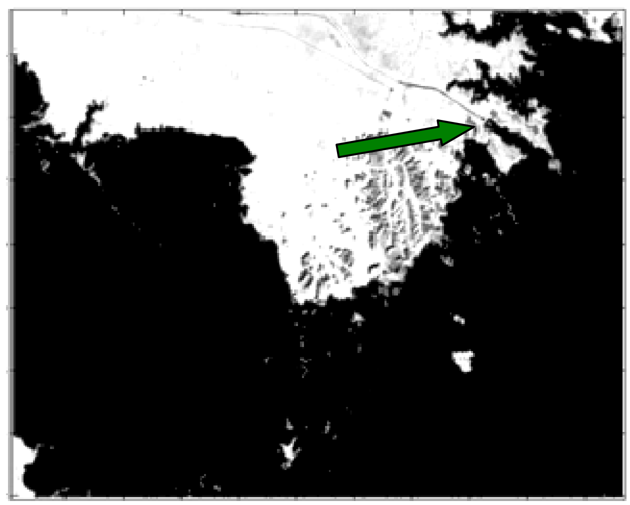

Figure 2 Pumping Station shoreline. Arrow point to the pumping facility and start of the Sheikh Zayed canal.

We fit the data with the Shape Language Model fit routine (SLMfit) developed by John D'Errico [7]. SLMfit finds a set of connected cubic splines with various user specified physical constraints. The one that is most useful to us is the Fritsch—Carlson monotonicity constraint [8]. The slope range can be specified (MinSlope, MaxSlope in SLM language). Knot points (breakpoints) can be provided by the user or determined automatically to specify where there is a slope discontinuity and a need for

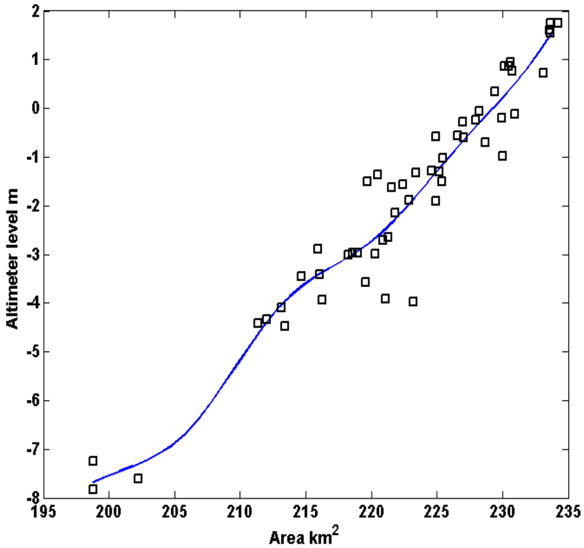

Figure 3 Water area and radar altimetry levels (squares); a model fit of the data (line)

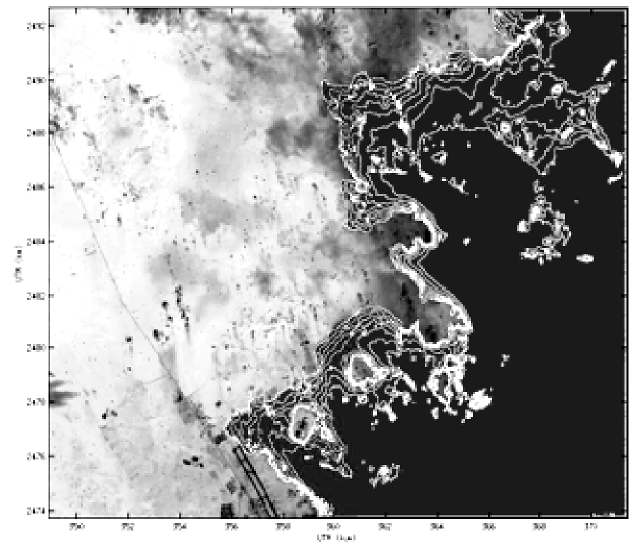

Figure 4 Bathymetry in the Airport area. Depth contours are at 1 m intervals.

fitting another spline. The automated method appears to work very well. SLMfit also incorporates data weighting which we use to desensitize the fit to data outliers.

The smooth curve in Figure 3 is one of the model fits of area vs. level. This example is for the Pumping Station but the Airport case is virtually identical in shape and distribution of residuals It is notable that individual data points deviate ± 1/2 m from the model, and in a few cases as much as 2 m.

The model fit smoothes out the errors. For bathymetry we evaluate the model at the corresponding water area measurement of each image. We assume most of the error is in the interpolated altimeter data (to be demonstrated in following section). A temporal series of shorelines, each labeled with the appropriate level, than leads to a bathymetry map at irregular depth levels. For the final product (Figure 4) the depth contours are interpolated to constant 1 m intervals.

3. ANALYSIS OF ERRORS

The source of data scatter around the smooth fit (Figure 3) can be collected into two pools: A - the interpolated radar altimetry data, B - the water area (and related shoreline estimation). The latter can include errors due to undetected clouds or haze and misclassification of land-water pixels.

In examining the model fits such as Figure 3 for other shoreline segments (we did 20 of which only two are described here) we noticed that the same errors repeated. I.e., a 1m deviation on one shoreline segment was also about 1m deviation on another shoreline segment. Figure 5 shows the correlation of the model errors in the Airport shoreline with the model errors in the Pumping Station shoreline. The background straight line is a slope 1, not the usual least square slope, since errors in the altimetry (A) must be correlated with a slope = 1. The high correlation in Figure 5 (and similarly for about 20 other shoreline segments) implies that the interpolated altimetry data (A) is the main source of the data scatter. To test whether combining TOPEX and LEGOS was the cause of model errors we repeated the analysis using only TOPEX or only LEGOS from start to finish. Only one or the other was used to interpolate altimetry levels to Landsat dates, and than to derive an area-level model fit. The following standard deviations (in units of m) were measured for Airport model errors (A), Pumping Station model errors (B), and residuals after subtracting the correlated portion of Airport-Pumping Station errors (A-B).

	TOPEX+LEGOS	LEGOS only	TOPEX only
σ_A	0.55	0.36	0.56
σ_B	0.61	0.37	0.62
σ_{A-B}	0.13	0.13	0.13

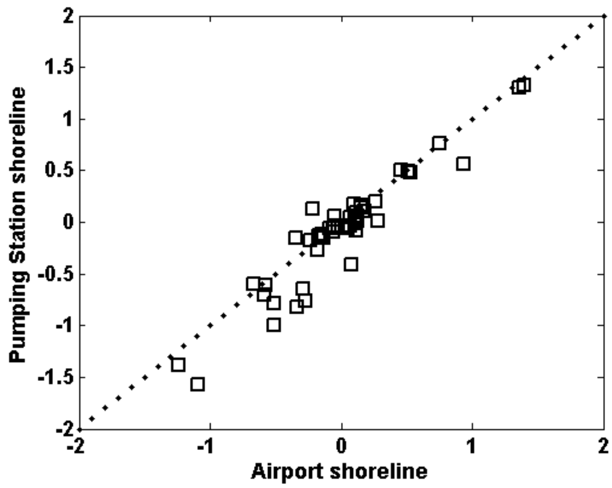

Figure 5 Model errors in Airport shoreline vs. errors in Pumping Station shoreline

4. DISCUSSION AND CONLCUSIONS

The model fit errors have a remarkable correlation between different shoreline segments. The implication is that most of the observed model fitting errors are due to these levels, and not the shoreline algorithm. Analysis based on combined TOPEX and LEGOS suggest that the altimetry errors have σ ~0.6 m. Taking out the portion that is highly correlated between the two shorelines the residual error drops to 0.13 m. Then the interpolated altimetry rmse is $\sqrt{\sigma^2 - \sigma_{A-B}^2} = \sqrt{0.6^2 - 0.13^2} = 0.59$ m. The rmse of TOPEX alone is also 0.59 m. The rmse of LEGOS data alone is $\sqrt{0.4^2 - 0.13^2} = 0.38$ m.

These altimetry rmse are considerably higher than claimed in [3 ,4]. Lake Nasser errors may be greater than typical due to lack of some corrections in the altimetry data reduction. Another possible source of error is in the interpolation from altimetry dates to Landsat dates. Further investigation of the errors is ongoing.

In any case the model fitting smoothes out these errors. The fitted function transforms Landsat water area into water level gauge independent of radar altimeter data. The water levels and bathymetry derived in this way are accurate to 13 cm (from the above discussion), which is considered very good for both hydrography and hydrology.

Further analysis is planned on the altimetry error issue. Also further validation of the altimetry and derived bathymetry with various in situ data sources. In the future we will extend the method to rivers, smaller lakes, and ocean fronting shorelines.

The practical use of this method to map bathymetry is still limited. Presently the constellation of satellite radar altimeters only provide data along relatively narrow ground tracks with (typically) 40 km spacing. The large lakes are likely to be crossed by at least one satellite track but most smaller water bodies are missed entirely. Our research is aimed at eventually using SWOT (launch ~2017) which will cover every point on the Earth surface.

10. REFERENCES

[1] R. Abileah, and S. Vignudelli, "A Completely Remote Sensing Approach To Monitoring Reservoirs Water Volume, International Water Technology Journal, Alexandria, 1 (1), 63-77, 2011.

[2] Vignudelli, S., A.G. Kostianoy, P. Cipollini, and J. Benveniste, (Ed.), Coastal Altimetry, Springer-Verlag Berlin Heidelberg, 2011.

[3] J. Crétaux and C. Birkett, "Lake studies from satellite radar altimetry," *Comptes Rendus Geosciences*, Volume 338, Issue 14, Pages 1098-1112, 2006.

[4] C. M. Birkett, "The contribution of TOPEX/POSEIDON to the global monitoring of climatically sensitive lakes," Journal of Geophysical Research, Vol.. 100, NO. C12, pages 25,179-25,204, December 15, 1995

[5] USDA global reservoir and lake monitor. http://www.pecad.fas.usda.gov/cropexplorer/global_reservoir/

[6] LEGOS Hydrology by altimetry portal. http://www.legos.obs-mip.fr/en/soa/hydrologie/hydroweb/Page_2.html

[7] J. D'Errico, SLM - Shape Language Modeling, MathWorks File Exchange portal, http://www.mathworks.com/matlabcentral/fileexchange/24443-slm-shape-language-modeling

[8] F. N. Fritsch and R. E. Carlson, "Monotone Piecewise Cubic Interpolation," SIAM Journal on Numerical Analysis (SIAM) 17 (2): 238–246, 1980