Validation of Radar Altimetry Lake Level Data
And
It's Application in Water Resource Management

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By

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Dedicated to my late parents
Kaba Ayana and *Manyahilishal Alemu*

Abstract

Altimeters are primarily designed to operate over uniform surfaces such as oceans and ice-sheets, not to sample small freshwater bodies, thus height and along track resolutions are not ideal. Altimetry on inland lakes therefore shows deviation from in-situ gauge measurements. Part of such a deviation is attributed to the geographically varying corrections applied to account for atmospheric effects on radar waves. This thesis will focus on validation of altimetry data for inland lakes in Ethiopian highland and Rift Valley, devise alternative RS supported validation technique and explore potential application of radar altimetry in water resources management. Altimetry data obtained from ERS (ENVISAT), and Topex/Poseidon (T/P) missions are compared with gauge data for selected lakes. Topex/Poseidon and ENVISAT data sets for Lake Tana are in strong agreement with gauge data having RMSE of 0.019 and 0.091 respectively. A hybrid of the two data sets improved the temporal resolution to an average of 7 days but with RMSE increased to 0.11. The histogram analysis for error distribution shows the errors are not normally distributed and hence FGDC's recommendations for accuracy determination can not be applied. With remote sensing supported validation technique, the lake level was estimated with an RMSE of 0.72 and an accuracy of ± 1.41m, accuracy far to use for operational hydrology but good enough for tracking variation trend. For other smaller lakes considered, either levels couldn't be retracked or fall short to measure lake level. The method however is found to be an invaluable tool for monitoring lakes and rivers in trans-boundary river basins thereby contributing to confidence building among riparian.

Key words: Radar Altimetery, Lake level validation, Bathymetry of Lake Tana, RS supported lake level measurement

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1. Introduction

1.1. Background

It has almost always been said that '*Water is life'*. Mankind's history however is endowed with pages narrating about an aftermath of events directly related to water. Let alone problems pertaining to water of poor quality, disasters resulting from an enormous quantity of water bursting out from its confinement cause untold misery on ancient and modern civilizations. On the other hand prolonged draughts have become no more 'once in a time' agonies but rather happens to be frequent experiences with devastating consequences.

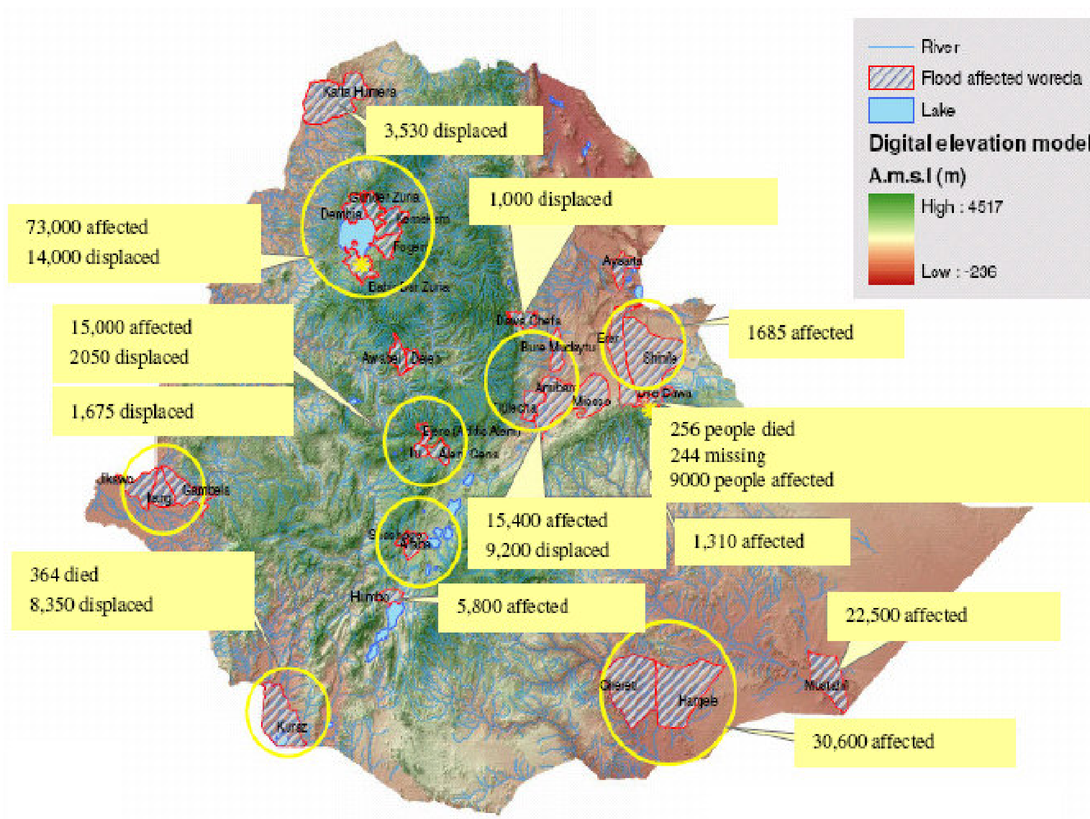


Figure 1.1 The aftermath of August 2006 flood event in Ethiopia, (WFP, 2006)

The prospects for prosperity entailed with the availability of abundant water resources with in a nation often are associated with the capability to adequately monitor the water resource in space and time. Even under the highest level of application of water management system setups the risk associated with *abundance* or *scarcity* of water are hardly avoidable. Moreover, building such a capability demands a considerable amount of planning and investment.

The most accessible water resources available for human consumption and the ecosystems are contained in lakes and rivers. The volume in these water bodies corresponds to 0.27% of the global fresh water and only 0.008% of the Earth water budget (*Gabriel L.*, 2006). Being a scarce resource strained by competing demands it has become crucial to develop and improve the techniques to observe the temporal and spatial variations in water volumes of lakes, rivers and wetlands. At the core of such an observation lays the acquisition of data related to the quality and quantity of water. A robust, consistent and reliable method of water quantity measurement infrastructure is required to effectively monitor the spatial and temporal variation of surface water sources.

Most countries operate national network for river discharge, lakes and reservoirs level, and groundwater depth measurements to meet information requirements for the development of water resources, disaster mitigation and international collaboration. However, the availability and access to hydrological data is severely limited due to decline in number of observation stations, fragmented data holdings, and low data quality. Since the mid-eighties a decline of reporting hydrological stations can be observed in many developing countries mainly due to political and institutional instability as well as economic problems to support adequate networks (*GRDC*, 2006).

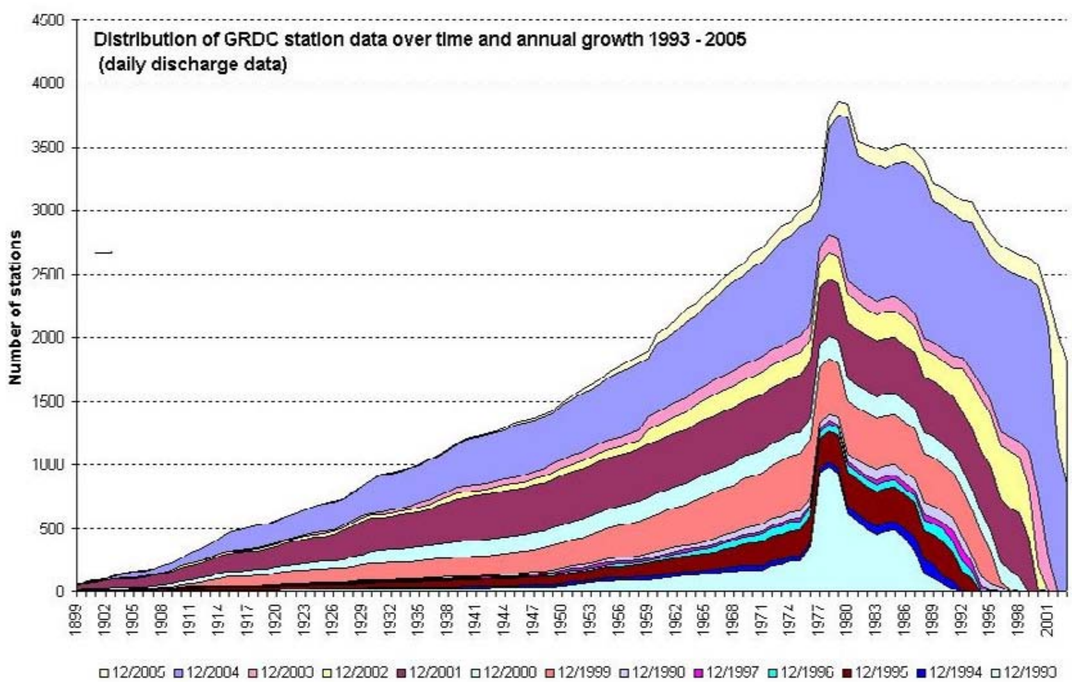


Figure 1.2 A decline in number of gauging stations world wide (GRDC)

As regard to lake level measurement the traditional in-situ gauging stations has increasingly become unviable for operation and maintenance, making them unsuitable and less reliable methods of continuous lake level data acquisition. High investment, maintenance and running costs and very slow data dissemination characteristics made such data collection mechanisms unpopular in all economies. For example, in 2002 the USGS on average spends $20,000 per year per station to provide real-time discharge gauge data which includes the costs of the regular calibration and the posting of the observations on the Internet. This large sum of money required to maintain gauging stations resulted in a continued reduction in the observational hydro-graphic network world wide (*Fekete* and *Vorosmarty*, 2002).

The situation is not different in Ethiopia. In his study on upgrading possibilities of hydro-meteorological stations in Ethiopia, Abebe (*Abebe*, 1999) had indicated four possible reasons for reduced number of hydrometric stations. These are:

i. budgetary constraints,

ii. low level of know how of the society and the decision-maker on the importance of hydro-meteorological data,

iii. lack of skilled manpower, and

iv. lack of access due to the mountainous topography

A cost effective lake level measuring technique could thus become an indispensable tool for lake level monitoring and water resources management in Ethiopia overcoming the above mentioned flaws of gauging stations.

1.2. Relevance of the research

In recent years radar altimetry proves to be an efficient alternative to monitor periodic variations in large water bodies (Oceans) at global scale. However, analysis on reflected waveforms has shown that more than half of echoes from even the largest lake targets are non-ocean-like in character (*Berry et al.*, 2004). Various retracking algorithms have been developed by researchers which had enabled to reprocess, analyze and interpret radar altimeter echoes from Earth's surfaces including inland water bodies using data of National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA) missions (*De Montfort University*, 2003).

The development of space borne radar altimeters has been driven by a need for height measurements over the oceans and ice sheets of Greenland and Antarctica. The 1970s marks the beginning of satellite radar altimetry enabling oceanographers to directly observe the shape of the global ocean surface for the first time. Retracked profile of the ocean profile from NASA's Geos-3 altimeter helped to analyze the global sea surface which in turn enables scientists to understand that sea surface topography contains a rich spectrum of information which could be used to draw conclusion on phenomenon related to oceanic water circulations. Then afterwards observation of ocean currents and eddies, refinement of tide models, monitoring of El Niño, improvement in hurricane forecasts, and measurement of global sea-level rise are made by using radar altimeter (*Miller.*, 2004). Most importantly this breakthrough had paved the path for searching the possibilities of retracking water level from radar echoes reflected from inland water bodies of small surface area and to estimate discharges in wide river channels.

Missions equipped with more advanced range measuring devices, more accurate orbit determination and wave form retracking methods, as well as fast data delivery techniques have revolutionized this relatively new but valuable remote sensing technology. However, important questions need to be addressed with in the context of altimetry data use. These include validation of radar altimetry measurements and identification of possible applications for solving local problems related to water resources management.

The outcome of this research will add to the geographic dimension of the validation works done previously such as the ones on the Amazon River (*Frappart et al.*, 2006) and Caspian Sea (*Kostianoy* and *Lebedev*, 2005). This is important due to the fact that radar altimetry data accuracy is indirectly influenced by geographic location of the water body due to a varying atmospheric correction is applied in the process of retracking.

1.3. Research objective

Retracking waveforms for inland lakes is often difficult due to the presence of reflective surfaces on or adjacent (vegetation, islands, satellite track near lake shore, etc.) to the lakes. For water surface where the footprint touches the shoreline the reflected wave is highly contaminated as the averaged time of the signal represents not only water surface (which is considerably smooth as compared to the ground surface topography) but also the ground topography. Height data from altimetry represents average of height values calculated for large number of echo reflected back which is mainly dependent on the foot print size of the signal.

Altimetry measurements made on inland lakes therefore shows deviation from in-situ gauge measurements due to a relatively narrow size of the water body, presence of vegetation, error in orbit determination, sea state bias, inverse barometric effect and atmospheric attenuation of the radar waves. Different models are established by researchers to accurately represent the effect of the atmosphere on radar waves and are applied for correction. Validation studies in the Amazon River (*Frappart et al.*, 2006) basin and the Caspian Sea (*Kostianoy* and *Lebedev*, 2005) had shown that radar altimetry can be used to measure lake level and discharge with high accuracy, even though the level of accuracy is varying. The main reason for this is that models used for correction of atmospheric effects are dependent on location (tropical, mid-latitude, and Polar Regions). For example the effect on radar waves of the troposphere region of the atmosphere is not similar in all places due to a varying thickness of the troposphere (About 6 km at the North Pole or the South Pole and 18 km at the equator). Thus a varying correction is applied and hence a varying accuracy will be attained due to the random distribution of error in the models that are meant to represent atmospheric effects.

1.4. Specific Objectives

The development of improved retracking algorithms had created the opportunity to extend the capability of radar altimeters to observe inland water bodies. However substantial validation work should be made before using these measurements in practical uses. Based on such a rationale the research objectives in this thesis are:

- To determine the accuracy of inland lake level obtained from various radar altimetry data sources over Ethiopian highland and Rift Valley lakes of different size
- To develop a satellite image (RS) supported validation technique based on the bathymetry of a lake
- To evaluate the use of the derived information for lake level and water volume management

1.5. Research Questions

In such approach important research questions will be:

- How accurate and consistent are the data sets as compared to actual gauging station data?
- How could high resolution image of a lake in combination with its bathymetric characteristics be alternatively used for validation of radar altimetry data?
- How can these data be used in water volume estimation?

Assessing the accuracy of data sets for various locations from different data sources thus will provide a more complete picture on the accuracy of altimetry data products for global/regional use in water resources management. Validating these data products enables one to apply them in managing the water resources of the lakes more specifically with respect to flood hazard mitigation and water volume management. The research problems can thus be enumerated as:

- To what level of accuracy does radar altimetry measures inland lake level?
- Is it possible to apply the use of high resolution images in combination with lake bathymetry for validation of altimetry measurements?

- What are the potential applications of radar altimetry in water volume estimation?

1.6. Conceptual setup

The fact that varying correction applied to altimetry data products imposes a varying degree of data reliability that demands an extended validation over a wider geographic extent. The outcome of such a research will give an insight on the applicability of the technology in the global context. This research aims at the validation of altimetry lake level data sets for inland lakes in Ethiopia. It involves the following tasks:

- Retrieve lake level elevation data for selected lakes from altimetry data providers;
  Lake level elevation data from Topex/Poseidon and ENVISAT missions will be retrieved from data portals of the respective missions. For lakes where only raw data is available, responsible staff will be contacted to provide retracked lake level elevation data.

- Compare altimetry data with in-situ gauge data, determining the accuracy of radar data sets with respect to gauge data, and correlation analysis of altimetry data from various sources;
  The RMSE of each dataset will be determined using the corresponding gauge data. The comparison between altimetry lake elevation data and gauge data will further be examined by analyzing the correlation thereof.

- Develop an alternative validation technique by integrating lake surface area from satellite imagery with bathymetry;
  The storage characteristics of the lake derived from Elevation-Storage-Area relation will be used to develop and alternative validation technique. The lake surface area will be extracted from satellite image and used in estimating the lake level from the storage characteristics of the lake. Accuracy Assessment of the estimate will be made by calculating the RMSE of the estimated lake level with gauge level.

- Assessment on potential application of the radar altimetry for water resources management;
  The capabilities that a validated radar altimetry lake level data adds to the water resources management practices will be explained based on the outcome of the above mentioned works.

The methodology for the research work consists of three phases; Data collection, Data pre-processing and Data analysis. The data collection phase constitutes altimetry and gauge data collection, bathymetry data collection and satellite images retrieving. In the pre-processing phase minor analysis work such as data integrity check and synthesizing, interpolation of bathymetric data points, formulation of lake storage characteristics and satellite image classification are included. The final analysis mainly focuses on searching solutions for the research questions. The flow diagram shown in figure 1.3 depicts the process and methodology adopted in the research.

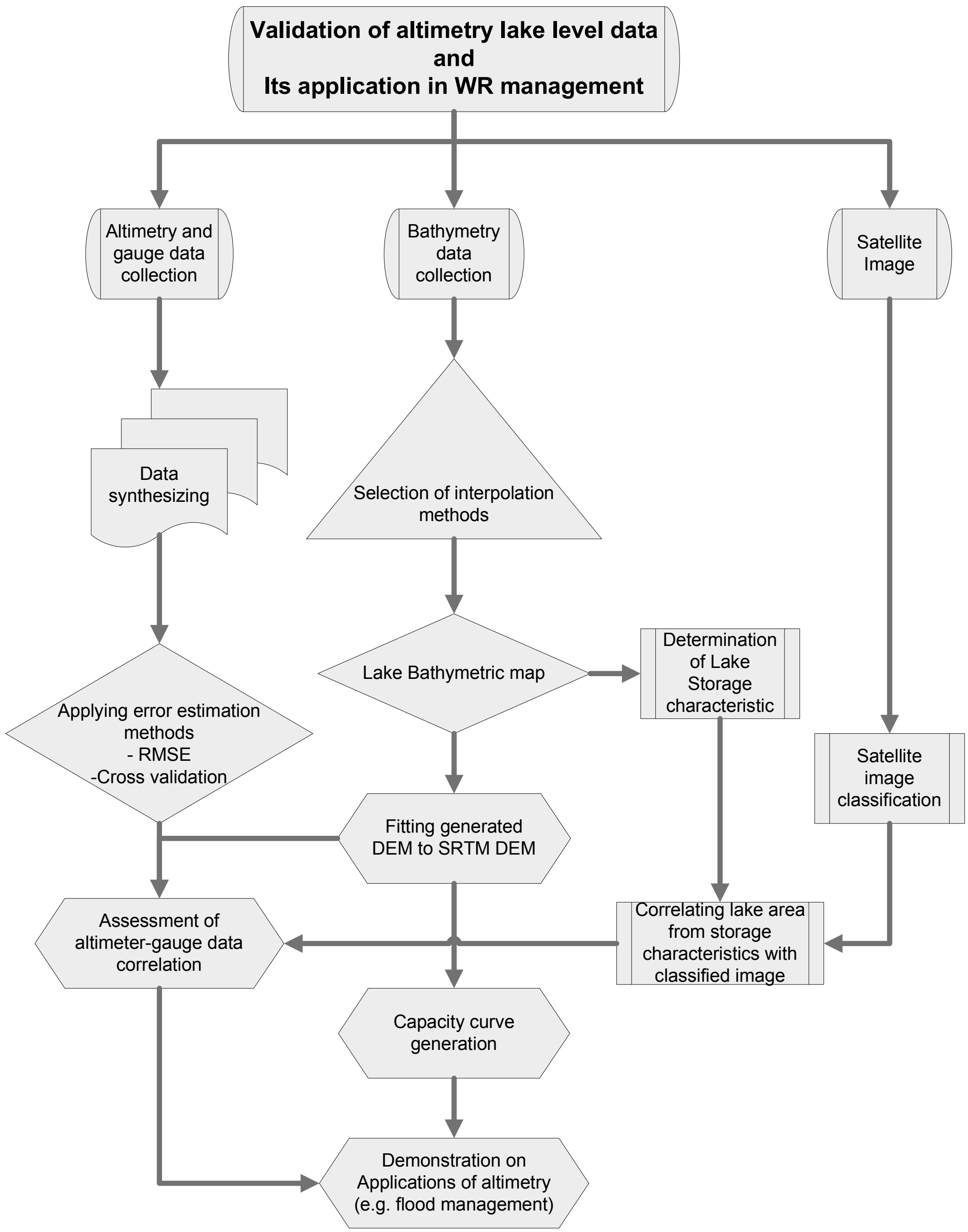


Figure 1.3 The research process and methodology

1.7. Thesis structure

The potential of radar altimetry for measuring lake level and the availability of near real-time data dissemination technology could make it a viable substitute to in-situ gauging stations which are often associated with decreasing reliability and high operation and maintenance cost. However, important questions have to be addressed to rule out the use of traditional gauging stations. These include: To what level of accuracy does radar altimetry measures inland lake level? On the other hand there are lakes with great deal of ecological relevance to the environment but not monitored or gauged due to inaccessibility and/or less economic relevance at present. In such cases lake level should be artificially generated by integrating information from satellite images with the bathymetric characteristics of the lake. Important research questions to be answered in this respect will then be, is it possible to use high resolution images for validation of such measurements? What are the potential applications of radar altimetry in lake monitoring? This thesis searches answers to these questions. A wholesome structure of the thesis is presented below.

Chapter two explains the basic working principles of radar remote sensing in general and radar altimetry in particular. Factors contributing to increased acceptance of altimetry such as advances in accuracy of satellite position measurement, development of models for correcting atmospheric effects, currently available and proposed data dissemination facilities are explained in this chapter.

A description of the study area and the problem statements are presented in *Chapter three*. Previous studies related to the study area as well as the objective and research questions are presented here.

Materials and methods used in the study are presented in *Chapter four*. Description of data characteristics, procedures used to search for answers to the research questions and assumptions made thereof are also explained.

Chapter five mainly focuses on presentation and explanation of analysis results.

Conclusions and recommendations are presented in *Chapter six*. Limitation of the study is also summarized in this chapter.

2. Background

2.1. Introduction

Radar is an acronym for **Ra**dio **D**etection **a**nd **R**anging. Radar was developed during WWII to detect aircraft and to be used as a navigation aid during bad weather. A radar system directs short pulses of microwave energy toward a target and measures the strength of the reflected signal and the time it takes for the signal to return to the sensor. Hence a Radar system has three primary functions: It illuminates the scene with radio signals, receives energy backscattered from the scene, and measures the strength (commonly called as detection) and the time delay (called ranging) of the returned signals (*Aronoff*, 2005).

Radar is an active remote sensing in that it uses its own source of illumination. Radar remote sensing uses the microwave portion of the electromagnetic spectrum, from a frequency of 0.3 GHz to 300 GHz, or in wavelength terms, from 1 m to 1 mm. Radar can provide an all-weather day-and-night imaging capability as these wavelengths are not blocked by clouds. An important application of radar has been in the production of detailed digital elevation models, widely used in GIS applications and to rectify remotely sensed imagery. Satellite-based imaging radar can offer horizontal accuracies of ±10m to ±20m RMSE and vertical accuracies as high as ±10m RMSE. Features like ice, ocean waves, soil moisture, vegetation mass, man-made objects and geological structures can be seen better in radar images than ordinary images (*Aronoff*, 2005).

2.2. Radar remote sensing

Radar systems may be imaging or non-imaging type. Radars may also be ground based or mounted on aircraft or space craft. Imaging radar consists of a transmitter, a receiver, one or more antennas, and the electronic and computer resources to process and record the data. The basis to determine the radar backscattering coefficient σ_o, an important coefficient that provides information about the imaged surface is a function of two parameters: *observation parameters* and *surface parameters*.

Observation parameters are *frequency*, *polarization* and *incidence angle* of the electromagnetic waves emitted. Radar sensors operate with one or more different bands specifically in the frequency interval from 40,000 to 300 megahertz (MHz). The microwave spectrum consist a wide range of frequencies (up to 1024 Hz) various range having different physical qualities. The choice of use depends on regulation, mission objectives and technical constraints. Radar systems work in a wide band of transmitted frequencies. The higher the frequency of a radar system, the more it is affected by weather conditions such as rain or clouds. But the higher the transmitted frequency, the better is the accuracy of the radar system. Different bands provide information about different object characteristics. In general, shorter wavelengths provide higher spatial resolution but offer less penetration of clouds.

Atmospheric interference occurs at wavelengths less than 3 cm. This property is used to advantage to detect radar reflection from water droplets for use in weather forecasting.

K_u band is the most used frequency (in Topex/Poseidon, Jason-1, ENVISAT, ERS) as it is less sensitive to atmospheric effects and technological possibility in that it uses small sized dishes , where as C band posses the advantage of less sensitivity to the effects of atmospheric liquid water than K_u (*TechFAQ*).

Polarization refers to the geometry of the tip of the electric vector as it evolves with time as opposed to the magnetic field vector. Incidence angle refers to the angle made by the radar waves with the vertical and determines the strength of the backscattered signal.

The table below shows a band nomenclature of the most commonly used frequencies and their corresponding wavelengths (*Aronoff*, 2005).

Table 2.1 Commonly used frequencies as specified by band nomenclature

Band designation	Wavelength range	Sensors and usage
Ka	0.75-1.1 cm	Weather radar systems, RAMSES
K	1.1-1.67 cm	Weather radar systems
Ku	1.67-2.4 cm	Topex/Poseidon, CryoSat, , ERS
X-band	2.4-3.75 cm	SRTM, SAR-Lupe, TerraSAR-X, COSMO-SkyMed, GeoSAR
C-band	3.75-7.5 cm	Envisat; ERS-1 and 2; Radarsat-1, -2, and -3; SIR-C; SRTM
S-band	7.5-15 cm	Almaz (Russian radar)
L-band	15-30 cm	Spaceborne: Seasat, SIR-A, SIR-B, SIR-C, JERS-1, PALSAR
P-band	30-100cm	Airborne: NASA-JPL AirSAR, GeoSAR, AES-3, OrbiSAR

Surface parameter includes roughness, geometric shape and dielectric properties of the target (*Aronoff*, 2005). Inland water bodies tend to be relatively smooth, with most of the energy being reflected away from the radar and only a slight backscatter towards the radar. On the contrary, land surfaces tend to have a higher roughness. In the microwave region, the difference between respective properties of land and water can be extremely useful for flood extent measurement. Altimeters and scatterometers are among non-imaging radar systems which provide information on range and near-surface wind speed and direction.

2.3. Altimetry

Radar altimetry measures the time required for a pulse (released nadir to the target) to travel from the satellite antenna to the earth's surface and back to the satellite receiver. The time required by the microwave to illuminate a target and reflect back to the receiver antenna is used to calculate the range. The speed of electromagnetic waves multiplied by half of the total time gives the range (height) from the satellite to the ocean surface. An important quality of radar altimetry therefore is its accuracy with which it measures range. The limit of the range resolution of a radar system is defined as the ability to distinguish in time the return pulses from two idealized point targets (*Aronoff*, 2005). Large surface undulations resulted in wider footprint and consequently wider range in return period. These near polar nadir looking satellites have a certain revisit time and as the result a time series of water surface level data can be generated. The instruments are very sensitive to water within the footprint due to which the accuracy of range measurement is prone to error near coastal areas.

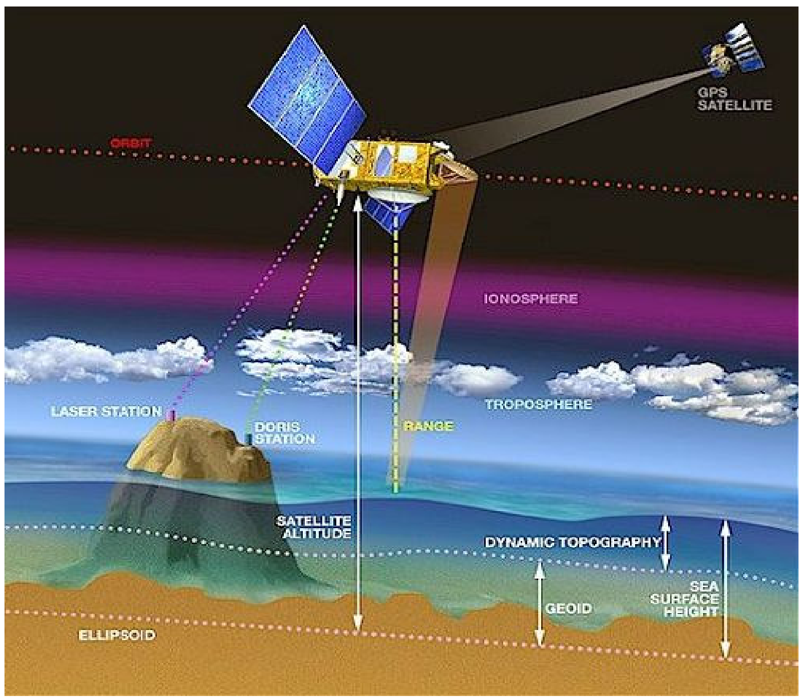


Figure 2.1 Working principles of sea level measurement (CLS)

Microwave pulses are sent at the nadir of the satellite at a frequency of about 1 kHz. These pulses reflected on the ground (water, land…) and part of the transmitted signal goes back towards the satellite. The shape and arrival time of the returned signal gives information about the characteristics of the reflecting surface. A plot of received power versus time is used to represent the shape of the returned wave and is called waveform (*Aviso/Altimetry*., 2006). The continuously varying reflecting characteristic of the surface introduces distortion of the waveform and noise. An altimeter waveform (or radar echo) represents the histogram of the energy backscattered by the ground surface to the satellite with respect to time (*Elachi*, 1980). By comparing the shape of the waveform averaged over a surface with the theoretical curve various parameters can be extracted which primarily include (*Rosmorduc et al.*, 2006), *Epoch at mid-height*: this is the time taken by the pulse to travel back and forth

P: This is the amplitude of the useful signal with respect to the emission amplitude and gives the backscatter coefficient, σ_0

P_o: thermal noise generated by thermal agitation of electrons

Leading edge slope (σ): that can be related to the significant wave height, SWH

Trailing edge slope (ξ): this is linked to the deviation of the radar antenna from nadir

These parameters are used in the retracking process to fit an approximation mathematical function to the power histogram of the reflected back echo recorded by the sensor. The following figure gives definition sketch of the parameters associated with waveform retracking.

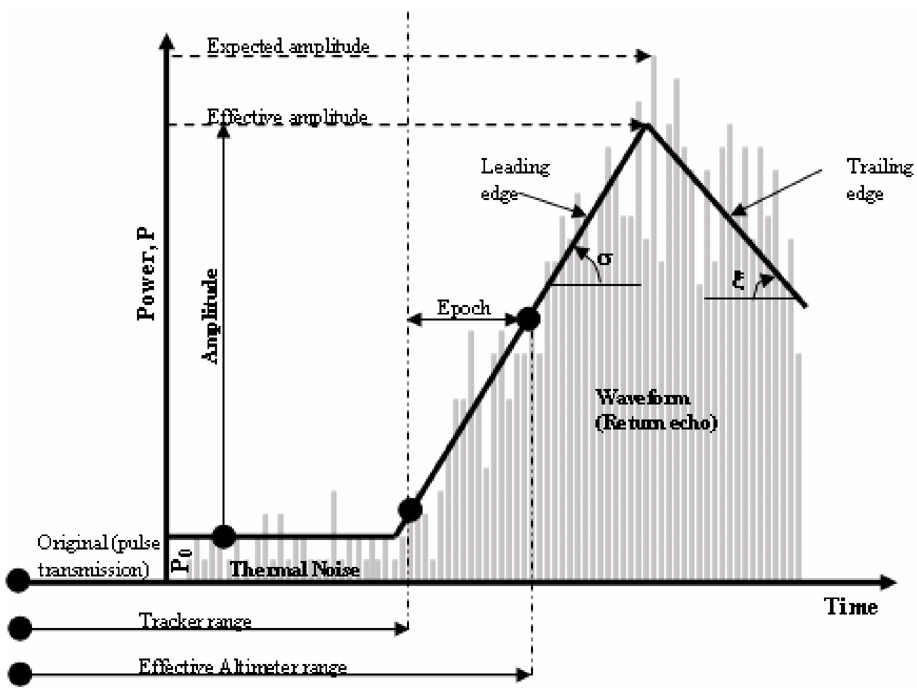


Figure 2.2 Components of reflected waveform (CLS)

Altimeters are primarily designed to operate over uniform surfaces such as oceans and ice-sheets. Presently operating radar altimeters are not built to sample small freshwater bodies, compared to the surface of the open ocean, thus height and along track resolutions are not ideal for inland water bodies. This is mainly because smaller water bodies are often accompanied by vegetation, islands and shore topography which have a major impact on the echo shape returned to the altimeter, distorting it so that mathematical model used in open oceans can not be used in retracking such waveforms (*Berry et al.*, 2005). The shape and timing of the returned radar pulse contains the information about the reflective surface.

Irregularities on the surface, larger than the pulse width, cause the returned pulse to be distorted and stretched. The effect of this is to impose an additional slope on the leading edge of the returned signal strength curve. This slope is related to the ocean wave height and the mid-point of this leading edge slope is equivalent to the reflection from the average position of the surface (i.e. the mean sea surface). By measuring the total area under the curve, the average reflectivity of the surface may be obtained. The control of the radar is varied according to the mode of the Radar Altimeter. The most important is the acquisition mode, during which the radar finds the approximate distance to the surface and then switches to one of the tracking modes, ocean or ice. The diameter of the footprint depends on the surface roughness, but can typically range between 200m (for open pools of water in calm conditions) to a few kilometres (open water with surface waves). Real echoes are composed of the sums of signals from many point scatterers, each with individual phase and amplitude. Therefore, the individual echoes have statistical characteristics superimposed on the pulse shape. In order to reduce uncertainties in the determination of pulse characteristics, the altimeter averages pulses together to reduce this statistical effect. When in ocean tracking mode, the mean sea-level point (mid point of the leading edge) on the time axis is maintained in the centre of the range window. The time interval between the transmitted pulse and this point is effectively the classical radar measurement of range (*CEOS/CNES*, 2000).

The difficulty of measuring surface topography is a combination of knowing exactly where the instrument is at the time of the measurement and being able to characterize all the other variables that influence the delay time of the echo. Therefore in addition to the wave form retracking, various corrections have to be applied before the altimeter data is put in to use for different applications. Short details and corresponding corrections applied to the variables are given below.

I. Orbit determination

The accurate determination of the ocean height is made by first characterizing the precise height of the spacecraft above the centre of the Earth. This is achieved through a technique called "precise orbit determination" (POD) and basically involves satellite tracking information.

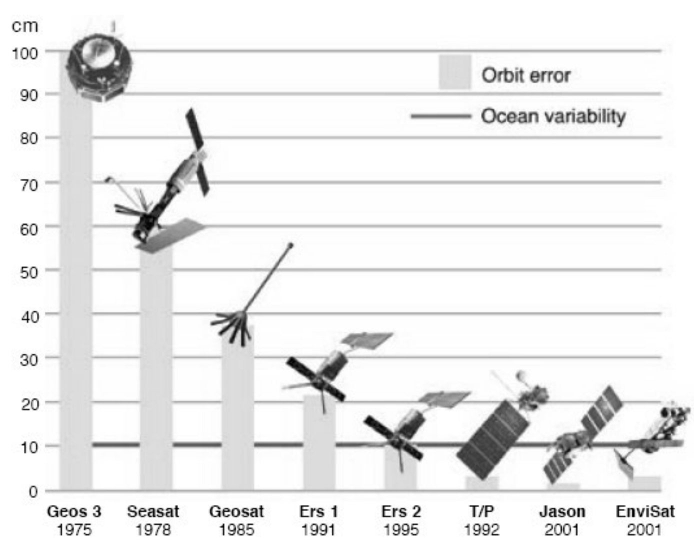


Figure 2.3 Improvement in accuracy of orbit determination (CNES)

A very precise orbit determination technique called the DORIS system (Doppler Orbitography and Radiolocation Integrated by Satellite) is applied for orbit determination. Ground stations that extending from Chatham to Guam (West-East) and Syowa (Antarctica) to NY-Alesund (near North Pole) have been setup worldwide since 1986 to serve as ground reference points to track satellite trajectories continuously (*IGN et al.*, 2005). Nearly half of these stations are on islands or in coastal areas.

A tracking system onboard the satellite consists of a reflector array which serves as a target for ground *satellite laser ranging* (SLR) stations. Similarly a GPS receiver onboard the satellite provides precise, continuous tracking of the spacecraft by monitoring range and timing signals from set of GPS spacecraft at the same time. In order to produce accurate estimates of the satellite orbital height, POD combines the satellite tracking information with models such as gravity and aerodynamic drag that govern the satellite motion. Radial orbital accuracy of 2-3 centimetres is achieved so far.

The second component of altimetry measurement is the range. This is the distance from the satellite to the ocean surface. The basic operation is based on the transmission of a pulse of duration, (t) which will travel at the speed of light (c). The two-way range distance between antenna and target and back to antenna again is therefore the velocity times the time delay.

Therefore 2-way range is:

$$r_{two-way} = ct$$

The range to the target is then,

$$r = \frac{ct}{2}$$

Radio waves passing through the atmosphere are affected by certain factors, such as temperature, pressure, humidity, and density. These factors can cause the radio waves to be refracted as they move from one medium into another in which the velocity of propagation is different. The Sea Surface Height represents the difference between the best estimate of the sea surface height and a mean sea surface. The sea surface height is corrected for atmospheric effects (ionosphere, wet and dry troposphere), effects due to surface conditions (electromagnetic bias), and other contributions (tides, and inverse barometer). A short detail of these corrections is given below.

II. The sea-state bias (SSB)

Sea-state effects are an intrinsic property of the large footprint radar measurements. Ocean wave's crests scatter the radar waves outward away from nadir while the troughs of the waves focus the energy back toward radar. Characteristics of the sea-state bias are dependent on significant wave height (SWH) and wave age. The SWH is the average height (trough to crest) of the one-third highest waves valid for the indicated 12 hour period. Wave height varies seasonally and hence can easily introduce a 5-10 cm bias (*Rees*, 2005). The shift referred to as the electromagnetic (EM) bias, causes the altimeter to overestimate the range (*Rosmorduc et al.*, 2006). In addition, a skewness bias also exists from the assumption in the onboard algorithms that the probability density function of heights is symmetric, while in reality it is skewed. Finally, there is a tracker bias, which is a purely instrumental effect. The sum of EM bias, skewness bias, and tracker bias is called 'sea state bias'. The current most accurate estimates of sea state bias are obtained using empirical models derived from analyses of the altimeter data (*Arnold et al.*, 2006).

III. Atmospheric effects

The Earth's atmosphere exhibits considerable variability and consequently affects microwave signals accordingly. In the troposphere that extends from the surface of the Earth to a height of about 6 km at the North Pole or the South Pole and 18 km at the equator temperature decreases rapidly with altitude, and hence much turbulence because of variations in temperature, density, and pressure. Moreover clouds form in this region of the Earth's atmosphere. These conditions have a great effect on the propagation of radar waves. Atmospheric effects basically constitutes three components,

a) *Effects due to Ionosphere*

This is the path delay in the radar return signal due to electron content in the atmosphere. Electron density varies with altitude at different times of the day as the result of which smallest ionospheric correction is applied at 6 AM and largest correction is applied at 12 noon (*Rees*, 2005). It is calculated by combining radar altimeter measurements acquired at two separate frequencies (C-band and K_u-band for Topex and Jason-1, K_u-band and S-band for ENVISAT) or from Doris measurements (Topex/Poseidon, Jason-1 and ENVISAT).

b) *Effects due to Wet troposphere*

Liquid water along the pulse's path reduces the energy returned to the altimeter, mainly at K_u band. This is called the wet troposphere effect and it causes delay in the radar return signal and hence degrades the performance of the altimeter. The delay due to wet troposphere is calculated from radiometer measurements and meteorological models. Data contaminated by rain are often ignored or displayed as flag.

c) *Dry troposphere*

This is a path delay in the radar return signal due to the atmospheric index of refraction. It is related to the surface temperature and pressure and is calculated from meteorological models.

IV. Inverse Barometer Effect

This is the effect caused by variation in atmospheric pressure at sea surface height. An increase in atmospheric pressure causes a depression of the sea surface, a phenomenon referred to as the inverse barometer effect. The instantaneous inverse barometer effect on sea surface height is computed from the surface atmospheric pressure, P_{atm} in mbar as:

$$Inverse\ barometric\ correction = -9.948 * (P_{atm} - P)$$

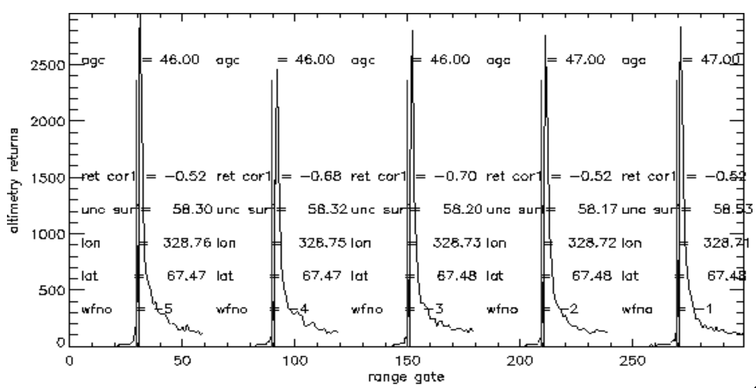
Where P= time varying mean of the global surface atmospheric pressure over the oceans

V. Instrument errors

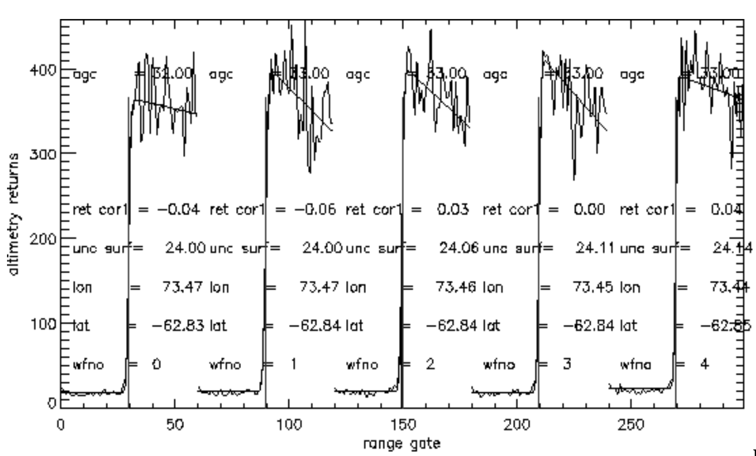
These are errors due to a drift in oscillators onboard the satellite, shift in satellite's centre of gravity (due to fuel consumption, solar panel orientation, and other factors) and filters applied to eliminate certain frequencies in the return radar signal.

2.4. Waveform retracking

Radar altimeters perform differently over ice, ocean and land surfaces. Information about the respective surface properties can be obtained by examining the return waveforms. Characteristic shapes of altimeter waveforms over sea ice and ocean are given in fig. 2.4 below.



a)



b)

Figure 2.4 Typical waveforms from a) Sea ice and b) Ocean (NASA)

A return waveform is the received power sampled at the satellite and results from the interaction of the altimeter's transmitted pulse with the scattering surface or volume directly beneath the altimeter. Accurate range estimates are obtained using refined procedures known as altimeter waveform retracking. Altimeter waveform retracking consists in ground-processing altimeter waveforms to obtain better range estimates than those obtained with on-board tracking algorithms. Different algorithms are applied to estimate range measurements obtained from different sensors on different surfaces. The objective is to make the measured waveform coincide with a return power model, according to weighted Least Square estimators. For example four different retrackers one for ocean, two for ice sheets, and one for sea ice are optionally applied for ENVISAT raw data to provide accurate height estimates. It is important to note however that none of them are developed to retrieve range values for inland water bodies. The algorithm retrieves the point of the radar echo corresponding to the effective satellite-to-ground range.

Various algorithms are developed and are in use by ESA and NASA and continued research is underway to improve the error margin of the retracking methods. The usual practice is that organizations entitled to administer the altimetry missions (ESA, NASA or CNES in this case) either set up a unit that will develop the retracking algorithms or enter a contract with specialists in radar signal analysis. ESA for example entered a contract with De Montfort and Lancaster Universities to produce the data products. In the retracking process random samples of returned signals are taken repeatedly for the retracking process. Thus more several set of samples will be randomly picked from the foot print and processed. Standard deviation of lake level estimates is often provided along with the lake level data as an indication of relative accuracy of estimate.

The error in altimetry measurements will aggravate with the depletion of lake level as bottom surfaces become exposed (*NASA*., 2005). Waveforms are categorized according to their shape and number of ramps which helps in interpreting the corresponding distinct surface features, and then applied several waveform retracking algorithms to assess their respective appropriateness. Typical ocean waveforms have a sharp ramp and slowly declining trailing edge (fig. 2.4). Over ice surfaces, the performance of the radar altimeters differs significantly from the performance over oceans due to the higher slopes of the ice surface, variations in the surface reflection and penetration of the radar signal in the snow surface, and generally irregular surface geometry (*NASA*., 2005).

2.5. Altimetry missions

The first altimetry mission dates back to the mid 1970's with Skylab to be the first experimental space station aimed at describing ocean state effect based on returned pulse characteristics. The Geodynamics Experimental Ocean Satellite, GEOS launched in 1975 is a significant improvement over Skylab in terms of global coverage as well as performance. GEOS is the first satellite to carry out measurement on sea level variability with time. The first-ever highly detailed radar images of ocean and land surfaces were obtained from Seasat launched in 1987. The instrument onboard includes a synthetic aperture radar and a scatterometer, which measured near-surface wind speed and direction; a radar altimeter, which measured ocean surface and wave heights; and a scanning multi-channel microwave radiometer measuring surface temperatures, wind speed and sea ice cover. The ocean topography is mapped using the altimeter product which helped scientists to determine phenomenon connected with ocean circulation.

With a primary intention of measuring the marine geoid Geosat was launched in 1985. The mission lasts for 18 months after which the satellite is placed on a 17-day repeat orbit to provide altimetry data. The European mission following Geosat was ERS-1 with a repeat period of 35 days.

A joint project set by NASA and CNES (French space agency) had launched Topex/Poseidon in 1992 with an objective of ocean circulation observation. A significant achievement in this mission was the introduction of a system called DORIS, a dedicated ground system for precise orbit determination and mission operation. Since then the DORIS system enables to measure satellite orbit with an accuracy of ±2 to 3cm, a significant improvement from GEOSAT which amounts to ± 25 to 100 cm. Topex/Poseidon was known for its short repeat period (10 days) and very high accuracy. In 2002 Jason-1 is launched overtaking Topex/Poseidon's orbit, after this is manoeuvred to a new orbit. This not only helped in cross validating the instruments on board but also provides the capability for wider aerial coverage at the same time and a continued long observation. Moreover the successful manoeuvring of these missions had demonstrated the scientific capabilities of a constellation of optimised altimetry satellites.

Current altimetry missions include ERS-2, GFO, Jason-1 and ENVISAT. ERS-2 is a follow-on mission from ERS-1. Altimetry data provided by this ERS-2 is limited to specific locations due to technical failure on the altimeter device. Geosat follow-on (GFO) is primarily designed for altimetry measurements providing ocean topography data with a 17-day repeat period. The successes achieved so far and lessons learnt in the past and current missions had become a basis for new missions with great improvements in accuracy and diversified environmental monitoring capabilities. Among future missions are Jason-2, Cryosat II, and NPOESS. The Jason-2 scheduled to take over Jason-1 in 2008 and will be equipped with the next generation of Poseidon altimeter characterized by lower instrumental noise and an algorithm enabling a better tracking over land and ice and the DORIS location system capable of measuring satellite orbit with in an accuracy of 1 cm. Cryosat is dedicated to polar observation, and more specifically on continental ice sheet and marine ice cover thickness prediction and the effect of global warming on the global ice cover. A previous Cryosat mission was lost during launch in 2005 while Cryosat II is being developed. A summary of past, present and future missions are provided in the annex.

2.6. Availability of data products

Altimetry data products are provided along with associated ancillary and labeling data that contains level of processing and details of the data format applied. The US physical oceanography Distributed Active Archive Centre (PODAAC) for example provides data in two types: Standard data product produced routinely or on-demand for use by researchers and Special data product produced at a Science Computing Facility by a research status algorithm. The level of the processing is also identified by the data levels designated to the product type as listed below (*CIT- PODAAC.*, 2006).

Raw Data - Unprocessed data in their original packets as received from the observer

Level 0 - Raw instrument data at original resolution, time ordered, with duplicate packets removed

Level 1A - Reconstructed unprocessed instrument data at full resolution, time referenced, and annotated with ancillary information, including radiometric and geometric calibration coefficients and georeferencing parameters computed and appended, but not applied to Level 0 data

Level 1B - Radiometrically corrected and georeferenced Level 1A data that have been processed to sensor units

Level 2 - Derived geophysical parameters at the same resolution and location as the Level 1 data

Level 3 - Geophysical parameters that have been specially and/or temporally re-sampled (i.e., derived from Level 1 or Level 2 data)

Level 4 - Model output and/or results of lower level data that are not directly derived by the instruments

Most commonly known missions that provide altimetry data includes TOPEX/POSEIDON, Jason, and ERS-altimeter. Each satellite is placed in a specific repeat orbit, so after a certain number of days the same point, on the Earth's surface is revisited. In this way, time series of water surface height changes can be constructed for a particular location along the satellite ground track during the lifetime of the mission. The satellite orbit and target size is a determining factor of spatial and temporal resolution. A temporal resolution of 35 days (ENVISAT) to 10 days (TOPEX/POSEIDON) is currently available. A compromise is usually made between temporal coverage and spatial coverage for every satellite mission. Jason-1 continues the task of providing the important oceanographic data time-series originated by TOPEX/Poseidon, carrying updated versions of the same instruments. The altimeter footprint for ocean applications is determined by pulse length (3.125 ns), the satellite altitude, and the significant wave height. At the TOPEX altitude of 1335 km, the footprint diameter varies from 2.0 km at 0 m SWH (not very realistic) to 5.5 km at 3 m SWH (typical of open ocean) to 11.7 km at 15 m SWH (about the highest observed during the TOPEX mission).

Table 2.2 Missions providing altimetry data

Satellite	Operation	Repeat Period	Remark
T/P	1992-2002	10 days	http://topex-www.jpl.nasa.gov
ENVISAT	since 2002	35 days	http://www.aviso.oceanobs.com
GFO	since	17 days	experimental mission
T/P(new orbit)	since 2002	10 days	Continuation of first mission

2.7. Advantages and Limitations

Most pronounced advantage of radar altimetry is its capability to provide continuous lake level data especially when difficulty of access arises due to harsh weather events. The revisit of the same area after a certain span of time (repeat period) helps to generate time series data of rivers, lakes, wetlands, inland seas and floodplains. As maintaining data continuity through traditional gauging stations is becoming increasingly difficult current altimetry missions provides a clue for monitoring large inland lakes globally. Once these systems are put in to place they could potentially provide data on multiple parameters such as temperature, and wind speed in addition to lake level providing a means to researchers and commercial data users to validate data from meteorological stations. The realization of missions continuity enables to monitor seasonal to inter annual variations during the lifetime of these satellites. Moreover an improved data dissemination capability can be achieved with higher possibilities of near real time data provision that is short in comparison to important time scales in the phenomena being studied.

As in any modern data acquisition systems however, radar altimetry has short comings in that data recovery (called retracking) needs complicated algorithms note easy to use by ordinary end users. To date fully finished data are made available for global sea level only. For inland lakes only a data file called Geophysical Data Record (GDR) is available and the user has to apply all the corrections provided on other data files which contain the error budget for each specific path. A centralized data storage and delivery facilities are yet not fully developed, even though recent efforts to create easy-to-use data extraction tools had shown promising progress.

Retracked height values are always averages of the heights in a footprint and not spot height values as in the case of traditional gauges (one final height value every 580m (TOPEX/POSEIDON) or 350m (ERS) along the ground track). This made them error prone and hence continuous validation should be made. The T/P pulses are themselves made up microwaves which have a peak-to-peak wavelength of 2.3 cm and 3 cm. This imposes an absolute lower limit of +/- 3 cm on range resolution since such a wave cannot discriminate distances shorter than its own wavelength. With regard to temporal resolution, the best achieved so far is 10 days, where as level variation may abruptly occur on inland lakes due a sudden out burst of storm at the upstream of the catchment. For small lakes with single track passing on them observation delays of at least 10 days, which is the revisit period of Topex/Poseidon mission, would be common.

2.8. Integrating satellite image with radar altimetry

The ability of radar altimetry to measure lake level could further be extended by integrating it with satellite imagery. The relation between the three parameters, namely, *lake level, lake surface area* and *lake storage volume* is the basis to integrate information from satellite image in to altimetry measurements. The elevation-storage-area characteristics of a lake can be mathematically described using the bathymetric characteristics of the lake. Similarly the surface area of a lake can be determined from satellite image using digital image processing methods. The surface area of the lake from satellite imagery can thus be used to calculate the lake level using the storage characteristics of the lake established from bathymetric survey. Once the accuracy of this method is validated using temporarily installed gauges it can be used to validate altimetry measurements based on lake surface area from satellite image that corresponds to the altimetry measurement. The potential use of this approach is to monitor lakes with little or no accessibility of gauging and even to fill data gaps in gauged lakes.

2.9. Future of Radar altimetry

The requirement to timely monitoring operations and the need for near real-time information assumes an ever increasing importance. A repeat period of 10 (Topex/Poseidon) and 35(ERS) is not suitable to continuously monitor water bodies. Temporal resolution is thus an important issue to be addressed in future missions. As the result many new approaches are underway to improve the accuracy and dependability of radar altimetry. The new approach is to launch a number of micro satellites with a single frequency radar altimeter and a precision navigation system in order to fill the gaps created by ENVISAT and JASON. The deployment of multi altimeter mounted on masts is supposed to address the limitation in spatial resolution of current instruments. More effective methods of sampling pulses from the foot print are also being (*Phalippou.*, 2002).

The altimetry state of the art has been changing rapidly over the last years, with new and improved orbits and corrections constantly being generated. However a responsible body which maintains the data obtained from each mission is yet not assigned. NOAA and AVISO are currently developing a multi-satellite data base which can be accessed through pre-compiled programs or custom-made tools with a configurable interface such that the user can create a customized data based on individual preferences (*Miller.*, 2004). Altimeter designed for specific spectral range (called K_a band) are being developed which will enable to lower ionosphere effects and achieve overall enhanced performances.

2.10. Bathymetry

Bathymetry is the study of underwater depth, of lake or ocean floors. A bathymetric map usually shows floor relief or terrain as contours or digital elevation model. Early techniques used pre-measured heavy rope or cable lowered over a ship's side (*NOAA/NGDC*, 2006). The greatest limitation of this technique is that it measures the depth only at a single point at a time, and so is inefficient. It is also subject to movements of the ship and currents moving the line out of true and therefore is inaccurate.

The data used to generate bathymetric maps typically comes from an echo-sounder (sonar) mounted beneath or over the side of a boat, sending a beam of sound downward to the seafloor. The amount of time it takes for the sound to travel through the water, bounce off the seafloor, and return to the sounder tells the equipment how deep the seafloor is.

Now days, a multi-beam (dual frequency) echo-sounder can be used, featuring number of very narrow adjacent beams arranged in a fan-like swath of perhaps 90 to 180 degrees across. The tightly packed array of narrow individual beams provides very high angular resolution and accuracy. In general, the wide swath, which is depth dependent, allows a boat to map more seafloor in less time by making fewer passes. The beams update many times per second (typically 1-40 Hz depending on water depth), allowing faster boat speed while maintaining 100% coverage of the seafloor (*NOAA/NGDC*, 2006). The Global Positioning System can also be coupled to the sounder enabling accurate measurement of location of depth in terms of geographic location and specifies where the survey work actually is. Sound velocity profiles (speed of sound in water) of the water column correct for refraction or "ray-bending" of the sound waves owing to non-uniform water column characteristics such as temperature, conductivity, and pressure. A computer system processes all the data, correcting for all of the above factors as well as for the angle of each individual beam. In the end, a map is semi-automatically generated from this massive trove of data.

3. Scope of Study

3.1. Description of study Area

The Ethiopian highland and rift valley consists of over 81 Lakes and reservoirs with surface areas ranging from less than a kilometre to thousands of square kilometres (*Lehner* and *Doll*, 2004). The Ethiopian rift valley lakes are habitats for migratory birds from around the world and are widely known mainly for their tourist attractions. It consist the northern most lakes of the African Rift Valley. A brief description of the lakes covered in this thesis is given below.

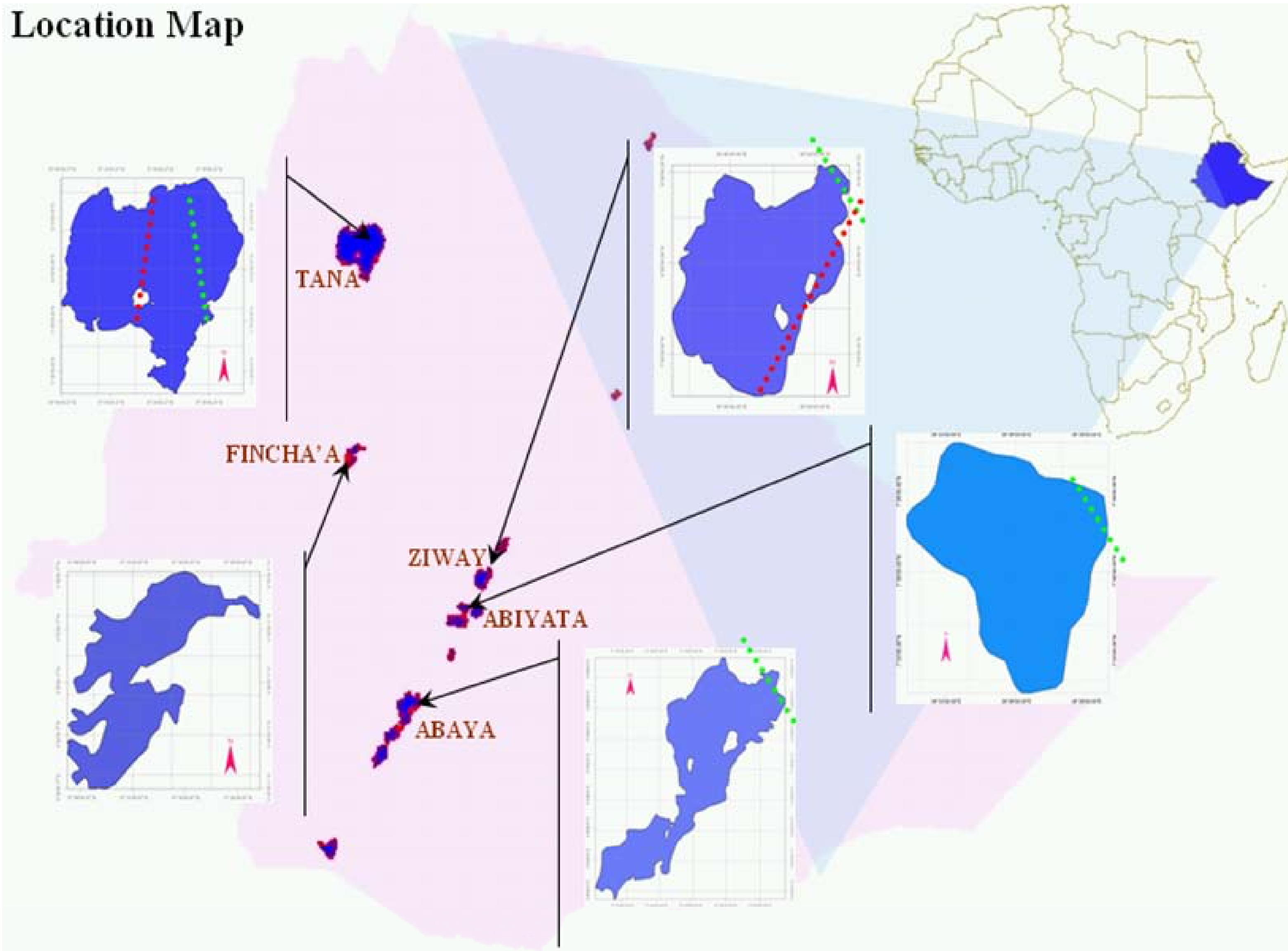
3.1.1. Lake Tana

Lake Tana with an estimated volume of 28 BMC is home for ancient monasteries on its islands, dated back to 15th century and is the source of the Blue Nile, supplying the water for the Tis Issat fall and serving as a natural reservoir for two micro hydropower stations. Tana is situated in a 'tropical highland monsoon' region with one rainy season between June and September. Though more than 40 rivers and streams are feeding the lake 93% of the water comes from four rivers with extremely low stream flow reliability.

In such a region where the stream flow reliability for 50% of the time of the year for example is as low as 18.1% of the mean annual flow large storage facilities are required to over come the strong stream flow variability (*Admasu*, 2004). The most pronounced advantage of Lake Tana is thus its storage characteristics in that it accommodates a live storage which amounts to more than two times that of the remaining five large reservoirs[†] rendering a relatively low cost per unit of utilizable water. The Lake is regulated by a 635 m long and 6m high weir[‡] aiming at a controllable storage of 9.1 BMC between elevations 1784.00 and 1787.00 meters a.m.s.l. (*Tesfaye.*, 2000), which represents approximately 2.4 times the average annual out flow of the lake (*Admasu*, 2004). About seven irrigation schemes have been proposed within the watershed of Lake Tana with an overall annual water demand of more than 600 Mm^3. In view of the estimated 33.3 Bm^3 of useable storage requirement to meet the water demand by the year 2025 the control structure built at Lake Tana is an important milestone for future integrated water resource management activities of the proposed projects.

[†] Gilgel Ghibe, Koka, Finchaa, Amerti, and Melka Wakena, provides an aggregate storage capacity of about 4.4 billion m^3

[‡] Construction cost of weir was 47 million Birr (approx. 4.7 million €uro)


Location Map
TANA
FINCHA'A
ZIWAY
ABIYATA
ABAYA

Lake Tana is also well recognized for its potential for fishing and navigation, as the result number of rural towns had established their economic activities at the lake shore. The northern and eastern side of the lake is characterized by a range of flat land which is often inundated during the rainy season displacing large number of people and massive livestock to elevated areas. The 1997 El-Niño had raised the lake level to an unprecedented level that endangers ancient monasteries on the islands. On the contrary a time serious plot of level for 1992-2006 time span (fig. 3.1) shows a considerable reduction of lake level in 2003 at which time a successive two years of drought were experienced. On the same development the lake level is still recovering from the then depletion in the mean time.

Large reservoirs are often characterized by their complexity of operation than small reservoirs in that large reservoir operations cannot be responsive to individual demand. The flexibility of large reservoirs is further reduced when they are multipurpose and potentially conflicting demands (for example, hydropower generation, irrigation, and flood mitigation) exist. Thus while offering the cost advantage per storage they pose the need for a reliable volume management technique.

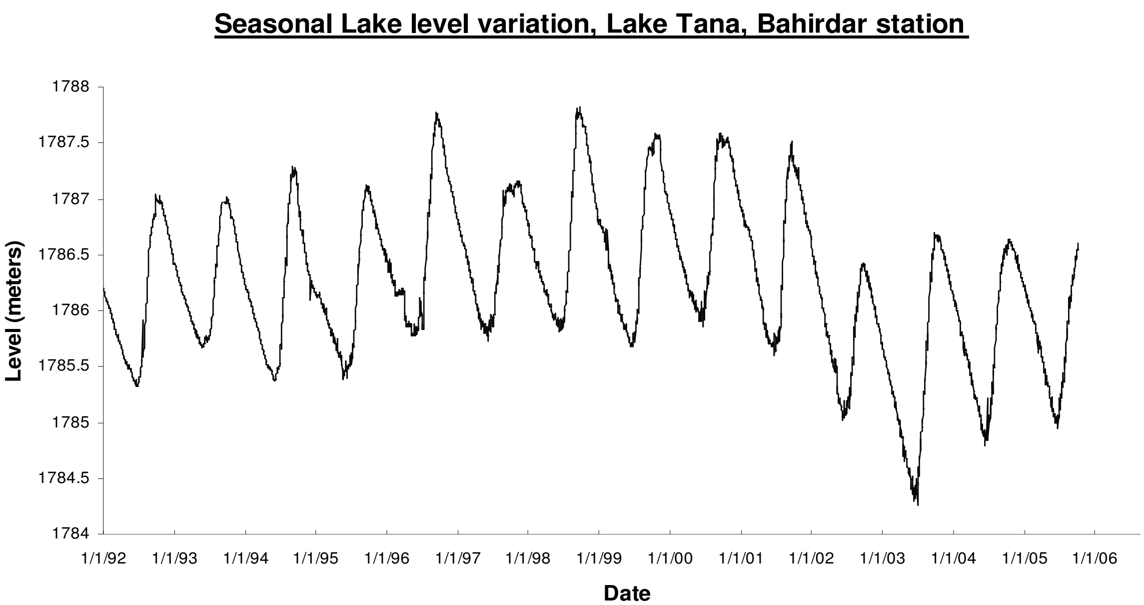


Figure 3.1 Seasonal variation of Lake Tana as observed at Bahirdar gauging station

The annual water budget of Lake Tana is determined from estimates of runoff, rainfall on the lake, measured outflow and empirically determined evaporation. In their preliminary analysis Kebede et al. had shown that despite a 20% rainfall variation in the Blue Nile basin in the last 50 years, the lake level remained regular, and sustained (7–8 years) rainfall reduction is required to cause cessation of outflow. However, the outflow from the lake shows significant variation responding to the rainfall variations. Based on 32 years hydrologic data analysis the same study had shown that the lake level and outflow can be functionally related as $R_{out}=0.0156H^{3.25}$ (*Kebede et al.*, 2005). The higher b-value means that at high lake level a small change in lake level would cause a significant change in outflow. More precisely a small change in net basin supply would result in only a small change in lake level but a significant change in outflow. A deeper understanding of Lake Tana is thus important from the perspective of three interdependent interests, namely developing hydrological models for water resources utilization, evaluating the impacts of the natural climate fluctuation such as the El Niño and effect of human induced climate changes (such as global warming) on lake hydrology.

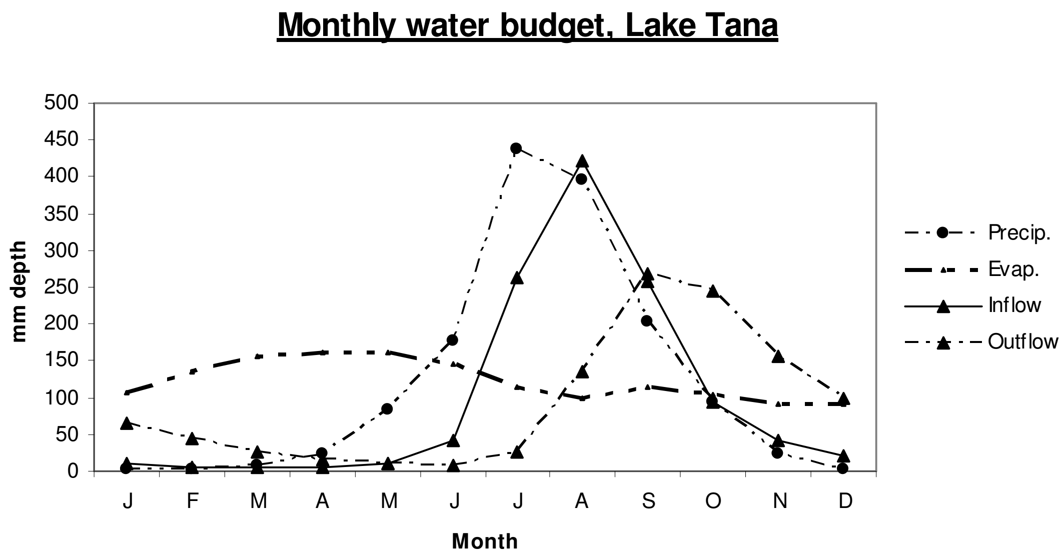


Figure 3.2 Monthly water budget of Lake Tana (1960–1992) (*Kebede et al.*, 2005)

3.1.2. Rift valley lakes

Most of the Ethiopian Rift Valley lakes are not fresh lakes. The largest of these lakes is Lake Abaya; other major lakes include Chamo, Awassa, Ziway, Abiyata, and Koka an artificial lake used for hydropower generation. The total irrigation potential of these lakes is estimated to 790, 000 ha out of which only 160,000 ha is irrigated to date (*FAO*, 1997).

Table 3.1 Characteristics of selected Lakes

Lake	Alt. (m)	Area (km^2)	Max. Depth (m)	Length of shoreline (km)	Vol. (Mm^3)	Catch. Area (km^2)
Tana	1,788	3600	14.9	385	28000	15319
Abiyata	1640	162.1	-	79.6	-	1600
Abaya	1249	1083.7	-	279.9	-	5300
Fincha'a	2232	302.5	25	154.4	-	700
Ziway	1643	410.5	-	112.5	-	9900

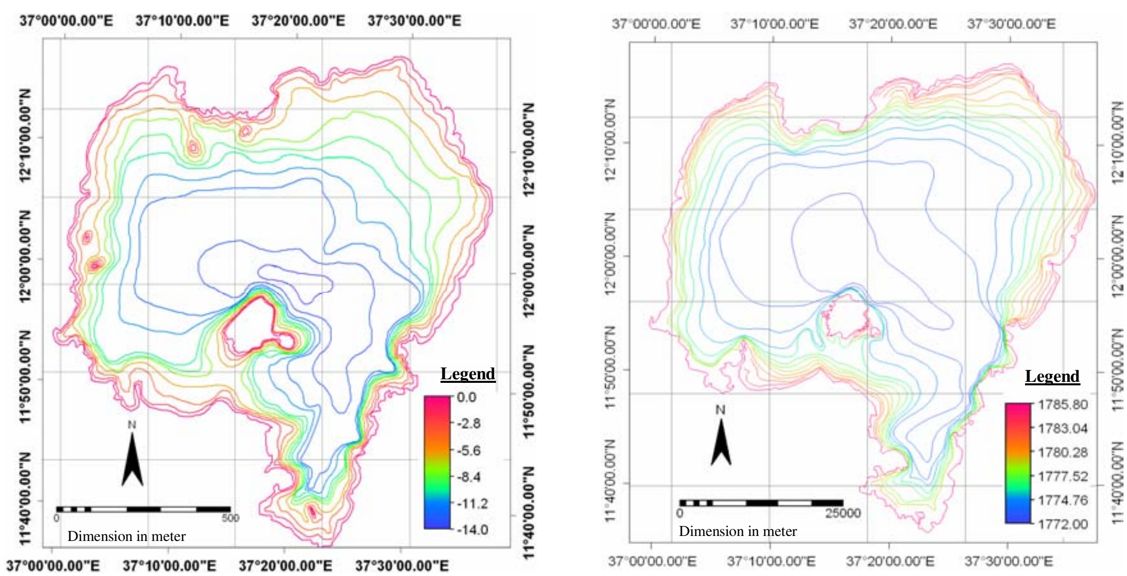
Source: International Lake Environment Committee, World lakes database

A validated altimetry lake level over these lakes thus adds to the capacity of the lake management system by providing additional modern data acquisition tool. However, altimetry data will be so scarce for these lakes due to their small size. Possibility of altimetry lake level retracking will be explored for Lakes Abaya, Ziway, Abiyata, and Fincha'a will be considered in this thesis. The lakes are selected in a way that they represent both natural as well as artificial reservoirs of varied size and shape. The fifth lake included in this study, Fincha'a, is an artificial reservoir not situated in the Rift Valley, but is considered for its multipurpose applications in irrigation and hydropower generation.

3.2. Previous studies

In 2002 the European Space Agency (ESA) had launched the River and Lake Project which aims at the provision of an easy-to-use and accurate product to monitor River and lake level. Wave forms retracked from ERS 2 altimeter for lakes in Africa including Lake Tana are used to plot a time series for the year 1995 to 2004 (*Berry et al.*, 2004). Since then The US Department of Agriculture's Foreign Agricultural Service (USDA-FAS) and LEGOS's Hydrological Database (Hydrologie Spatiale, France) are continuously updating the freely available online lake level database. However these databases do not include small sized lakes and hence data for small lakes will be made available upon request only.

A bathymetric survey is conducted on the lake by an Italian team in 1940 (*Morandini.*, 1938) and most recent survey was made in 1987 by Studio Pietrangeli SP, Italy, for use in the design of water conveyance structures for the then proposed Tana-Beles irrigation project in North-western Ethiopia. The vertical datum for the 1940 bathymetric map is not available and hence depth contours are given relative to the water level during the bathymetric work was undertaken.



a) b)

Figure 3.3 Bathymetric maps of (a) 1940 bathymetric map (School of Geography and Geosciences, University of St Andrews) (b) 1987 bathymetric map (MoWR)

An integrated flood management case study made in cooperation with WMO and Global Water Partnership had indicated the effect of the newly constructed weir at the outlet of Lake Tana in flooding the plain land in the eastern side of the lake (*Kefyalew A.*, December 2002). Other notable work is a resistivity model of Lake Tana basin prepared by a team of scientists from University of Edinburgh, UK and Ministry of mines, Ethiopia (*Sophie et al.*, 2002). The Blue Nile Basin master plan document contains important details of the lake basin as well. The output of this research could be a valuable source of information for Lake Tana resource management centre, EEPCo and MoWR.

4. Materials and methods

4.1. Data Requirement and Acquisition

4.1.1. Lake level data

a) *Altimetry data*

There are two ways of acquiring altimetry data. The first is a completely processed and corrected sea surface height anomaly which the user can directly use for the intended application. This is available for the continental ocean surface and can be obtained directly. ERS (ENVISAT), JASON-1, and TOPEX/POSEIDON (T/P) missions are the most common data sources that provide data on sea level anomalies, dynamic topography, and surface wind speed. Various data downloading mechanisms are devised by data providers operating these missions. However, altimetry data for inland lakes are neither available ready made nor the extraction is straight forward. Two separate data sets namely the Geophysical Data Record (GDR) and the Error Budget should be retrieved via a *live access server* (LAS) which is also a highly configurable Web server designed to provide flexible access to altimetry data. The lake level can be derived by deducting the error budget from the GDR.

The along track sea surface height data is organized in "passes" and "cycles". A *pass* is half a revolution of the earth by the satellite from extreme latitude to the opposite extreme latitude. For example for Topex/Poseidon an ascending (odd numbered passes) pass begins at -66 degrees and ends at +66 degrees (*CIT*, 2006). A descending (even numbered passes) pass has the opposite sense. A CYCLE contains collection of consecutive passes (up to 254 for Topex/Poseidon) and represents a collection of data where the ground track of the satellite repeats itself (10 days for Topex/Poseidon and 35 days for ENVISAT). After the provision of the bounding box coordinates for a number of lakes in Ethiopia NASA/PODACC data centre had identified satellite paths available over the lakes and reservoirs listed above. The time coverage of this data is since 1992 to date for both Topex/Poseidon and ENVISAT. For the sake of getting an understanding about the impact of reduction in surface area of the lake surface on accuracy of retracked radar signals a range of lake areas need to be considered.

b) *Gauge data*

Lake level data from gauging stations should fulfil certain requirements. First, the gauging station should be with in a very short distance from the satellite ground track. This helps in minimizing measurement errors due to location. These errors may be due to back water curve or tide waves or both. Secondly dates of gauge and altimetry measurement should match in order to make comparisons. This is practically impossible unless daily lake level data is available in which case the user will screen the gauge lake level data that corresponds to the altimetry passes that corresponds to the lake under study. To ensure data reliability gauge readings for a given lake should be retrieved from more than one stations and used for data checking where this is possible. However not all lakes have more than one gauging station and hence cross checking is restricted. Other techniques as visual inspection and simple data plots can be applied to identify outliers.

Lake level data are collected from MoWR and EEPCo (Ethiopia) for the lakes under consideration. For Tana and Abaya Lakes data is acquired from two gauging stations. However a well defined reference level (extended from the national triangulation network) is available only for the gauging station situated at Bahirdar. This is mainly because the data is used for operation planning of Tis Abay II power station situated downstream of the lake. As the result lake level measured at Bahirdar gauging station is used for analysis in this thesis. All other stations measure lake level variation to an arbitrarily fixed reference on the gauging staff.

Table 4.1 Selected validation sites

Lake	Altimetry data		Gauge data		REMARK
	source	Temporal resolution	source	Temporal resolution	
Tana	ENVISAT T/P, JASON-1	35 days 10 days	MoWR	1 day	Two gauging stations
Abaya	T/P, JASON-1	10 days	MoWR	1 day	Two gauging stations
Ziway	T/P, JASON-1	10 days	MoWR	1 day	One gauging station
Abiyata	GFO	17 days	MoWR	1 day	One gauging station
Fincha'a	T/P, JASON-1	10 days	EEPCo	1 day	One gauging station

4.1.2. Bathymetric data

Based on the pertaining lake characteristics, resource constraints (time and financial), and existing experience a 5 km wide traversing route is assumed to be adequate. The morphometric characteristics of the lake based on the 1940 bathymetric map had indicated that the lake was about 12 meters deep and 62 km wide. The boundary of Lake Tana corresponding to the SRTM DEM level 1786 m above mean sea level (a.m.s.l) is manually digitized and is used in planning the bathymetry survey route. The SRTM lake level had shown a considerably high level of agreement when compared with the lake level data recorded for the whole days of the mission. As a limit to the traverse path across the lake a 1 kilometre buffer is arbitrarily fixed from the coast line beyond which no sounding had taken place. This is because of the shallow depth at the lake periphery observed from the 1940 bathymetric map at which the sounder can not be operational. The proposed route plan is dumped to a hand held GPS which is connected with the echo sounder during the bathymetric work. A slight adjustment is made during the actual field work to pass round small islands and in areas where the depth drastically reduces.

A dual frequency echo sounder coupled with a GPS is used to collect lake depth. The sounder operates by transmitting sound waves toward the bottom of the lake in a cone-shaped pattern. The transmitted sound wave reflected back to the transducer after striking the lake bed. The transducer collects the reflected sound waves and sends to the data processing unit after which a resulting plot is displayed on the graphical user interface (GUI). The foot print of the transmitted sound waves is determined by the cone angle of the transducer and the water depth. The cone angle is dependent on the frequency used by the transducer. The one used in this case transmits 50 kHz (in which case the cone angle is 40^0 and approximately 6m diameter at 9m depth) and 200 kHz (in which case the cone angle is 10^0 and approximately 1.8m diameter at 9m depth) signals and combines the information. This helps to cover large area while retaining good bottom resolution (*GARMIN*, 2005). The GPS is synchronized with the sounder in such a way that it records the geographic coordinate at location of depth recording. To avoid excessive data points the depth recording interval is set to record depth at every 30 seconds interval. The data collected on every working day is dumped to an external storage and plotted to a point map using ILWIS. The variation in boat speed had resulted in a variable data point interval which actually reduces the bias of the depth sample points. A total of 835 km path is traversed on the survey and about 4424 depth readings are taken along the path of traverse. The occurrences of large waves were minimal except on the third day of the survey where the work is temporarily halted and the effect of which can be seen in the lower left side of the lake (fig. 4.1b). The effect of tide was minimized by temporarily halting sounding during such an event.

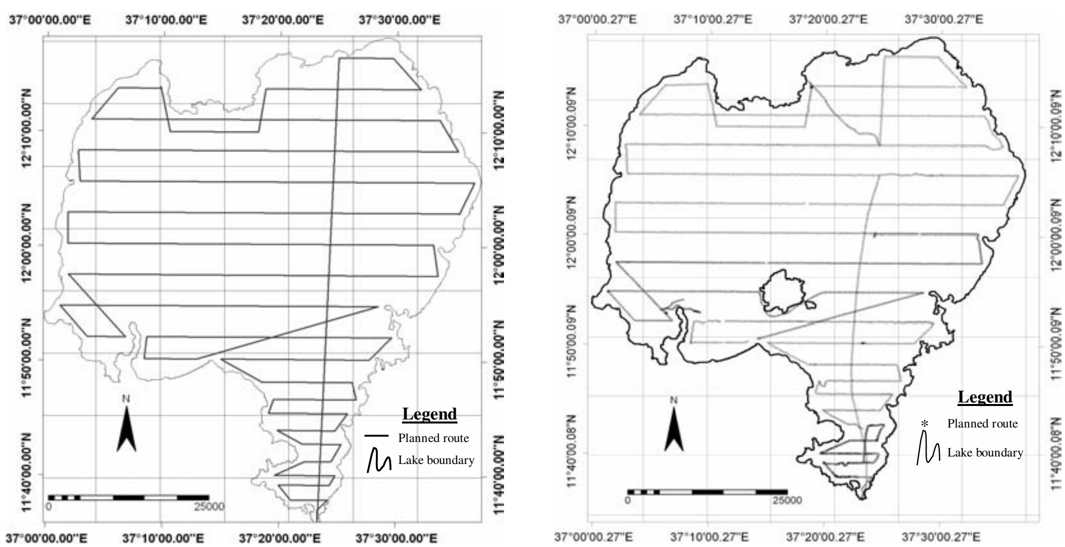


Figure 4.1 Proposed and actual path of traverse for bathymetric survey

4.1.3. High resolution images

High resolution images helps in mapping the aerial extent of the lake. Various criteria may be applied in selecting the images. Within the context of this research however, suitability and cost of availability are used to select the images. Suitability refers to the data quality in relation to the proposed application. This may include spatial resolution and availability of a single scene image that covers the whole lake. This avoids the need of mosaicing images of different days. Mosaicing should be avoided to the extent possible as it will introduce error in estimating aerial extent due to the fact that scenes of different days couldn't logically be correlated to a single lake level.

The area determined after delineating the Lake boundary using applicable classification methods will be used in combination with the Elevation-Storage-Area characteristic to estimate the lake level. Landsat images related to known events such as the 1987 El Niño or the 2003 extreme drought and corresponding to altimetry pass dates are retrieved and processed.

4.2. Data Analysis

4.2.1. Lake level comparison

The two aspects of precision of a measurement examined in this thesis are validity and reliability. Validity refers to the agreement between the value of a measurement and its true value. Validity can be quantified by comparing measurements with true values or values that are as close to the true values as possible. Poor validity degrades the precision of a single measurement, and it reduces the ability to characterize relationships between variables. Time series of surface water levels from gauging stations are used to validate radar altimeter lake level data.

Reliability refers to the reproducibility of a measurement. Similar wave forms along the track of the satellite are used to generate height data as these represents more or less a reflecting surface with similar surface characteristics. The crossing by ERS-2 and Jason-1 altimeters over Lake Tana is shown below to illustrate this (*River and Lake*, 2004). It is evident that signals reflected from the island (for ERS-2 altimeter) are contaminated by the land topography and hence should be excluded in the retracking process. Random samples of returned signals are taken repeatedly for the retracking process. Standard deviation of these retracked levels is often displayed along with the lake level data as an indication of relative accuracy of estimate. For Lake Tana the standard deviation of lake level estimate for Topex/Poseidon and ENVISAT measurements were respectively 0.064 (Error range was 0.042 to 0.275) and 0.091(Error range was 0.004 to 0.474).

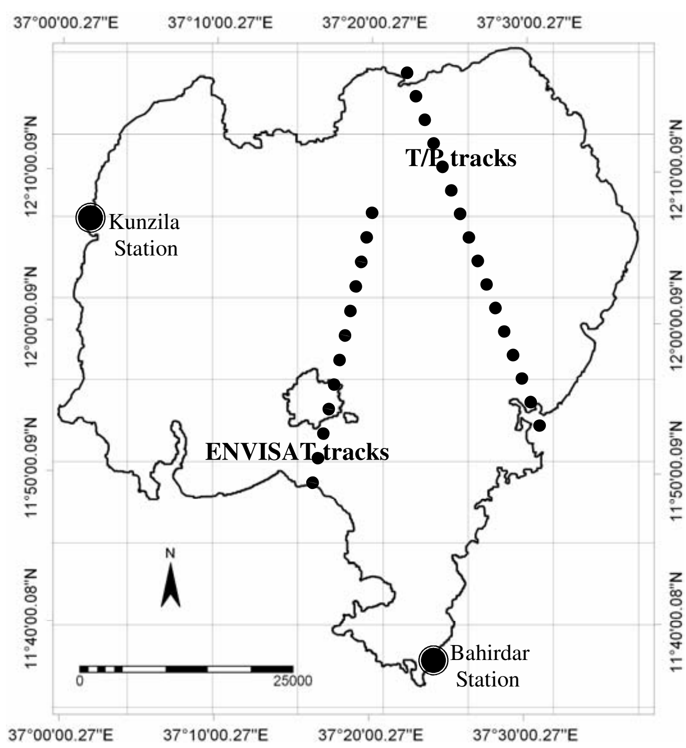


Figure 4.2Altimetry missions ground track over Lake Tana

Altimetry height time series data derived from satellite tracks near gauging stations are ideal for comparison of the two data sets as minimizes errors due to slight spatial variation of the lake surface. However as gauges are situated at the shore of the lake reflected radar signals near such a location are susceptible to contamination by shore topography. A satellite path crossing islands (as the one shown above) also results in a contaminated signal and hence avoided in the retracking process. Comparison of altimetry measurements for Lake Tana (Topex/Poseidon and ENVISAT) and gauge level readings is given below. Gauge data from Bahirdar station is compared with Topex/Poseidon and ENVISAT altimetry datasets.

The National Standard for Spatial Data Accuracy (NSSDA, US) implements a *statistical methodology* for estimating the positional accuracy of *points* on maps and in digital geospatial data, with respect to geo-referenced ground positions of higher accuracy. As a means of measuring the quality of geospatial data the US Federal Geodetic Control Subcommittee (FGDC) recommends the use of Root-Mean-Square-Error (RMSE) (*FGDC.*, 1998).

$$RMSE_z = \sqrt{\frac{(z_{data_i} - z_{check_i})^2}{n}}$$

Where

$z_{data\ i}$ is the vertical coordinate of the i^{th} check point in the dataset

$z_{check\ i}$ is the vertical coordinate of the i^{th} check point in the independent source of higher accuracy

n = the number of points being checked

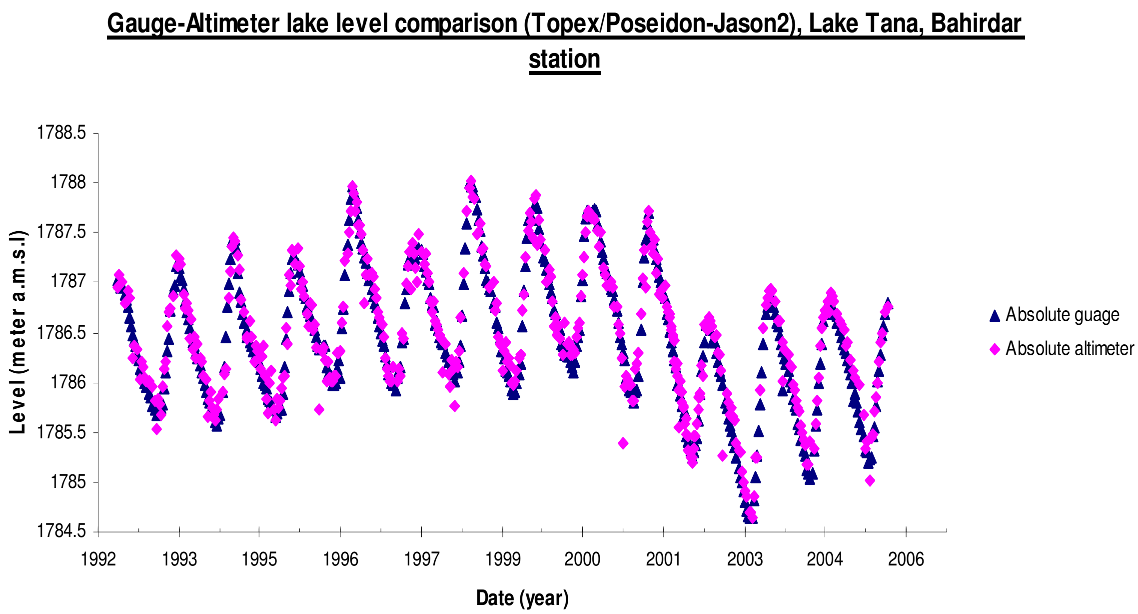
i=integer from 1 to n

Under these procedures vertical accuracy shall be tested by comparing the elevations in the dataset with elevations of the same points as determined from an independent source of higher accuracy. Assuming the vertical error to be distributed normally and systematic errors have been eliminated as best as possible the factor 1.9600 is applied to compute linear error at the 95% confidence level (*FGDC.*, 1998). Therefore, vertical accuracy may be computed as:

$$Accuracy_z = 1.9600 * RMSE_z$$

In this research the data set from gauge measurements are considered as 'independent source of high accuracy' for making comparison with altimetry data sets. These data sets are produced from averages of four measurements taken daily at the gauging site. But it is anticipated that the lake level might change between successive intervals due to an inflow of a flash flood into the lake and this variation is disregarded due to the large lake size. It is also practically difficult to make sure that the satellite pass time and gauge level measurement time coincide. Hence the average of those four level readings is assumed to represent the day lake level and this is compared to the lake level from altimetry.

Observation on correlation of altimetry and gauge data is made to formulate a functional relation between the two which will be used as a calibration tool for future applications. This functional relation can be used to determine the achievable accuracy of lake level measurement using radar altimetry data. The relation can also be used in regions where gauge data is not archived or to fill data gaps for dates with no data due to malfunctioning gauges. Simple trend functional relations are easy to interpret and hence are preferred over complex functions provided that the former resulted in a reasonable goodness of fit.



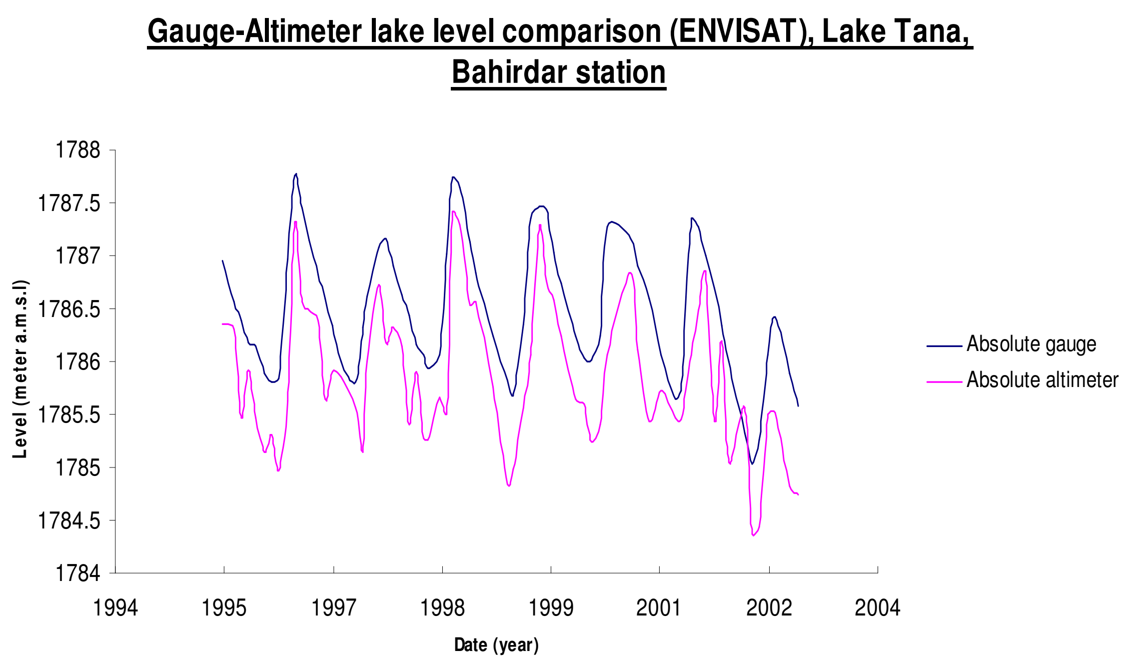


Figure 4.3 Graphical visualization of altimeter-gauge data sets

4.2.2. Hybrid data sets

One of the flaws of the present day altimetry missions is the temporal resolution. The shortest possible time gap achieved to date is that of Topex/Poseidon mission with 10 days revisit time. Successive measurements of shorter interval could be achieved by hybridizing data sets from different missions. However, this procedure introduces a varying error attributed to the specific mission from which the data is brought. As the result an improved temporal resolution will be achieved only through a compromise on accuracy.

Based on such a rationale, datasets from Topex/Poseidon and ENVISAT missions of 7 years time span (1995-2001) are used. This is because ENVISAT data sets are available since 1995 to 2001. Topex/Poseidon datasets are then supplemented by ENVISAT datasets to achieve an improved temporal resolution. In events where both missions provide altimetry readings the Topex/Poseidon measurement is retained. This is basically because of the fact that datasets from the Topex/Poseidon mission had exhibited a much better agreement with gauge readings as shown in figure 4.3.

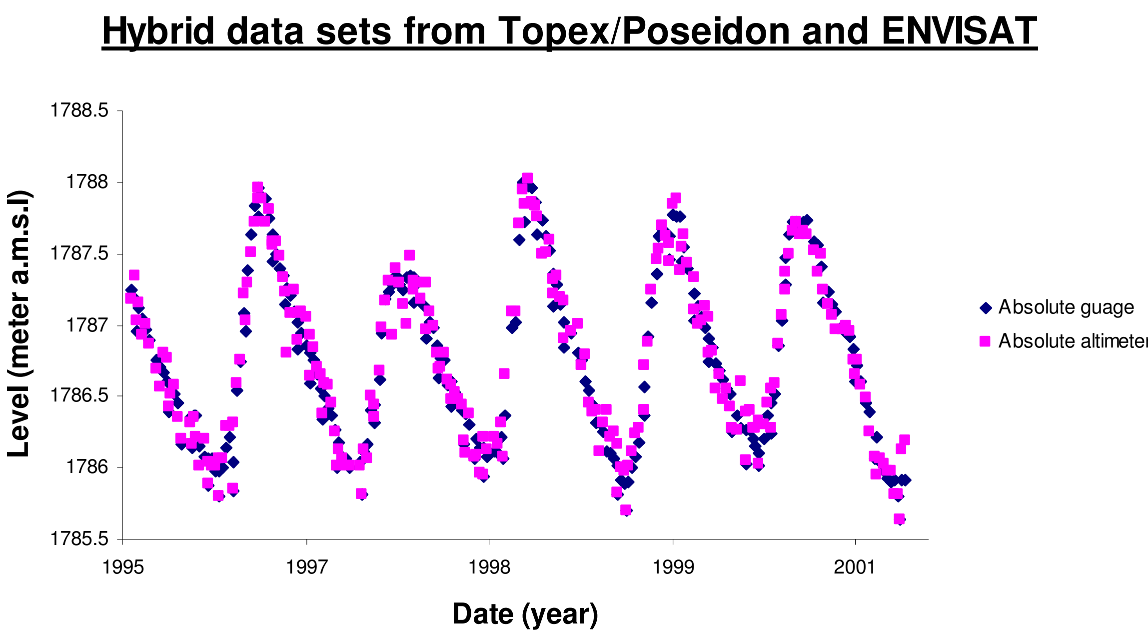


Figure 4.4 Calibrated Hybrid data from Topex/Poseidon and ENVISAT

In this procedure ENVISAT data sets are calibrated using the Gauge-altimeter correlation. The mean error calculated for the initial dataset and each single lake level is compared to the mean error. Lake level values greater than the mean error are considered outliers and hence excluded in the analysis. A plot of the hybrid dataset (fig. 4.4) accurately replicates the trend in lake level variation but only with a reduced accuracy as indicated on chapter 5 of this thesis.

Retracking signals for the other lakes (Abaya, Ziway, Abiyata, and Finchaa') is difficult due to the smaller size of the lakes and the spatial resolution of the altimeters. Level retracked from GFO mission for Lake Abiyata is plotted in figure 4.5 in which retracked levels could not even replicate the trend in level variation.

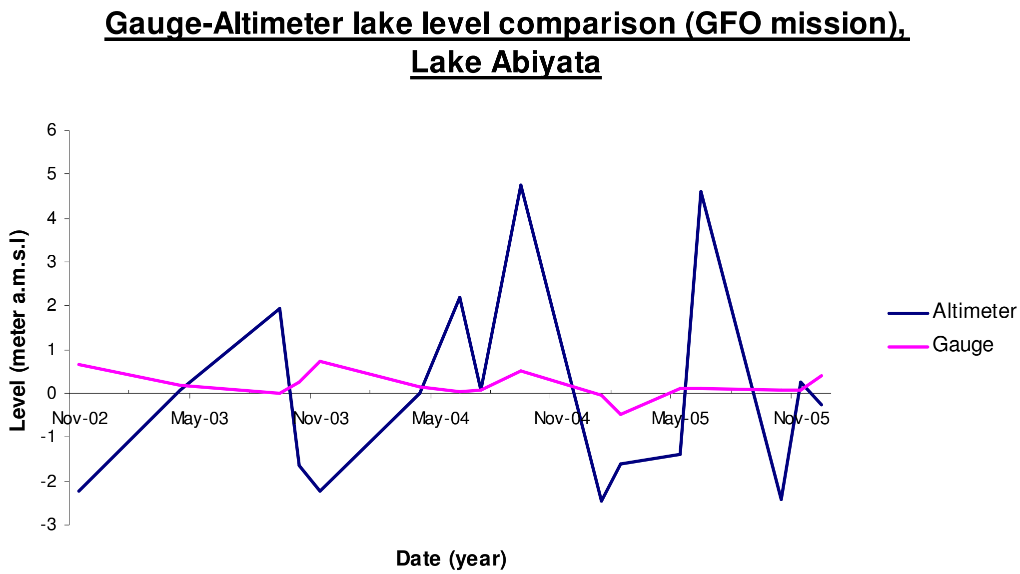


Figure 4.5 Lake Abiyata level estimates based on GFO altimeter

4.2.3. Bathymetric map generation

This involves bathymetry acquisition, interpolating and verification of mapping accuracy (*Dost* and *Mannaerts*, 2004). Various interpolation methods are applied to estimate a spatial variable based on measured values at defined locations. All these methods are based on the basic principle of spatial autocorrelation that states points close to one another are more alike than points farther away. However, how far will this alikeness exist? The answer to this question leads towards establishing a search radius beyond which points are no more relevant in telling the characteristics of the point in question. This can simply be put as the farther the neighbourhood the lesser the spatial autocorrelation of the measured values with the values to be estimated. Thus, points farther away can be eliminated with little influence on the accuracy of the interpolated value.

In the bathymetric map generation process of Lake Tana two methods, Inverse Distance Weighted (IDW) and Kriging are used and comparative advantage of one method over the other is explored. Inverse Distance Weighted (IDW) is a method of interpolation that estimates point values by averaging the values of sample data points in the neighbourhood of each processing cell. The closer a point is to the centre of the cell being estimated, the more influence, or weight it has in the averaging process. This method assumes that the variable being mapped decreases in influence with distance from its sampled location.

The simplest form of inverse distance weighted interpolation can be put as follows (*EMS*, 2006):

$$F(x, y) = \sum_{i=1}^{n} w_i f_i$$

Where

n: number of scatter points in the set

f_i: prescribed function values at the scatter points (i.e. the data set values), and

w_i: weight functions assigned to each scatter point (controls the significance of each point)

The weight function can also be described as:

$$w_i = \frac{d_i^{-p}}{\sum_{j=1}^{n} d_j^{-p}}$$

Where:

p: an arbitrary positive real number called the weighting exponent and most adopted value is 2.

d_i: distance from the scatter point to the interpolation point and is calculated as

$$d_i = \sqrt{(x - x_i)^2 + (y - y_i)^2}$$

Where

(x, y) are the coordinates of the interpolation point

(x_i, y_i) are the coordinates of each scatter point.

The weight functions are normalized so that the weights sum to unity.

The significance of known points (weight) on the interpolated values can thus be controlled by their distance from the output point. Thus introducing a higher power mean more emphasis on the nearest points, and the resulting surface will be less smooth. Specifying a lower power on the other hand put more influence to the points that are farther away, resulting in a smoother surface. A power of 2 is most commonly used with IDW. Very high power values tend to resemble the Thiessen polygon approximation. The characteristics of the interpolated surface can also be controlled by applying a fixed or variable search radius, which limits the number of input points that can be used for calculating each interpolated cell.

A fixed search radius requires a neighbourhood distance in map units and a minimum number of points. For each interpolated cell the radius of the circle used to find input points is the same. When there are fewer measured points in the neighbourhood than the specified minimum, the search radius will increase until it can encompass the minimum number of points. The minimum number of points indicates the minimum number of measured points to use within the neighbourhood. All the measured points that fall within the radius will be used in the calculation of the value to be determined.

With a variable search radius, the number of points used in calculating the value of the interpolated point is specified, which makes the radius distance vary for each interpolated point, depending on how far it has to search around each interpolated value to reach the specified number of input points. Thus, the number of points used in the calculation depends on the density of the measured points near the interpolated value. A maximum distance can be specified in map units such that the search radius cannot exceed this maximum distance. Hence if the radius for a particular neighbourhood reaches the maximum distance before obtaining the specified number of points, the prediction for that location will be performed on the number of measured points within the maximum distance. For a highly variable phenomena smaller neighbourhoods or a minimum number of points are generally adopted.

The most pronounced problem with IDW interpolation is the edge effect. In order to fully cover the surface of an interpolated area, some unknown points around the edges of the dataset will have to be extrapolated. It is always recommended to have known data points covering an area larger than the area of interest to avoid extrapolation, and always interpolate. To avoid such a problem some interpolation algorithms provides an option to introduce a 'barrier'. A barrier is a polyline dataset that is used as a break line to limit the search for input sample points. It represents an interruption in the surface which may be caused by forcing of existing features, in this case too shallow depth all around the periphery of the lake. A barrier introduced in the interpolation limits the calculation process to use points which are in the same side of the barrier.

The other interpolation method used to generate the bathymetric surface is Kriging. Kriging is an optimal interpolation method in the way that it decides the maximum correlated distance and the distance weighting. Besides, it *gives the estimated error in the interpolation to measure the goodness of the process (Burrough and McDonnel, 1998)*. The basic assumption in kriging is that the parameter being interpolated can be treated as a regionalized variable. Based on the regionalized variable theory, kriging assumes that the spatial variation of any variable such as elevation of the land surface is neither totally random nor deterministic. Instead, the spatial variation can be expressed as the sum of three major components:

- a structural component, having a constant mean or trend;
- a random, and locally varying but spatially correlated component, known as the variation of the regionalized variable; and
- a spatially uncorrelated random noise or residual error term.

The kriging method can be described as follows:

$$Z(x) = \xi(x) + \zeta(x) + \varsigma(x)$$

Where:

x: a position in 1,2, or 3 dimension

Z(x): the value of a random variable

$\xi(x)$: a deterministic function describing the structural component

$\zeta(x)$: the regionalized variables

$\varsigma(x)$: a residual, spatially independent Gaussian noise term having zero mean and variance σ^2.

Kriging consist a set of linear regression routines which minimize estimation variance from a predefined covariance model. Thus the first step in kriging is to construct a variogram from the scatter point set to be interpolated.

A variogram consists of two parts, an experimental variogram and a model variogram. Once the experimental variogram is computed, the next step is to define a model variogram. A model variogram is a simple mathematical function that models the trend in the experimental variogram. Each point inside the range has the weight that is determined by the distance from the curve to sill. The further the distance, the bigger the weight is. Interpolated value of an unknown point is the sum of the weighted value of known points within a radius or certain number of the nearest known points. The variogram characterizes the spatial continuity or roughness of a data set. Ordinary one dimensional statistics for two data sets may be nearly identical, but the spatial continuity may be quite different. Variogram analysis consists of the experimental variogram calculated from the data and the variogram model fitted to the data.

Typical characteristics of a variogram includes: *Sill* which describes where the variogram develops a flat region (i.e. where the variance no longer increases), *Range* that shows the distance between locations beyond which observations appear independent (i.e. the variance no longer increases) and *Nugget* the amount by which the variance differs from zero is known.

The appropriate model is chosen by matching the shape of the curve of the experimental variogram to the shape of the curve of the mathematical function. This is a trial and error procedure applied on available variogram models (spherical, exponential, Gaussian, Rational quadratic, circular and wave models) and hence requires checking the accuracy of the model in estimating the required variable, depth in this case. Hence the depth data is partitioned in to two sets; one set is used for the interpolation purpose and the other for testing the applicability of the variogram model used. Thus 20% of the data randomly selected from the whole data is excluded from interpolation process.

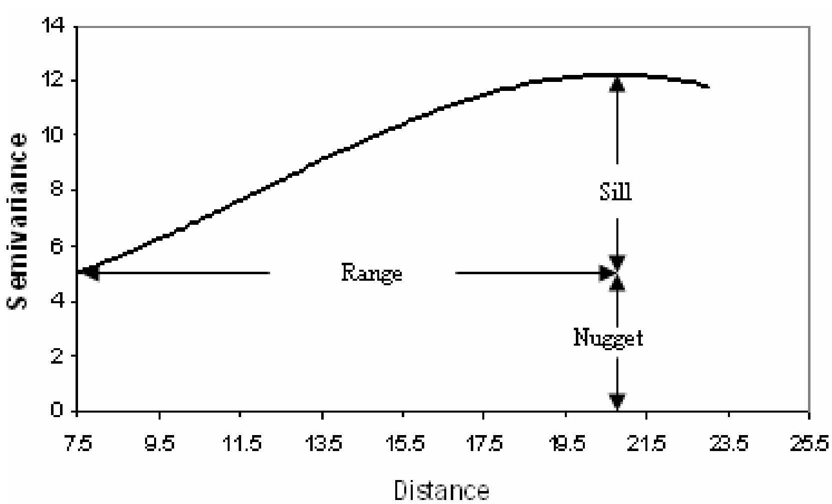
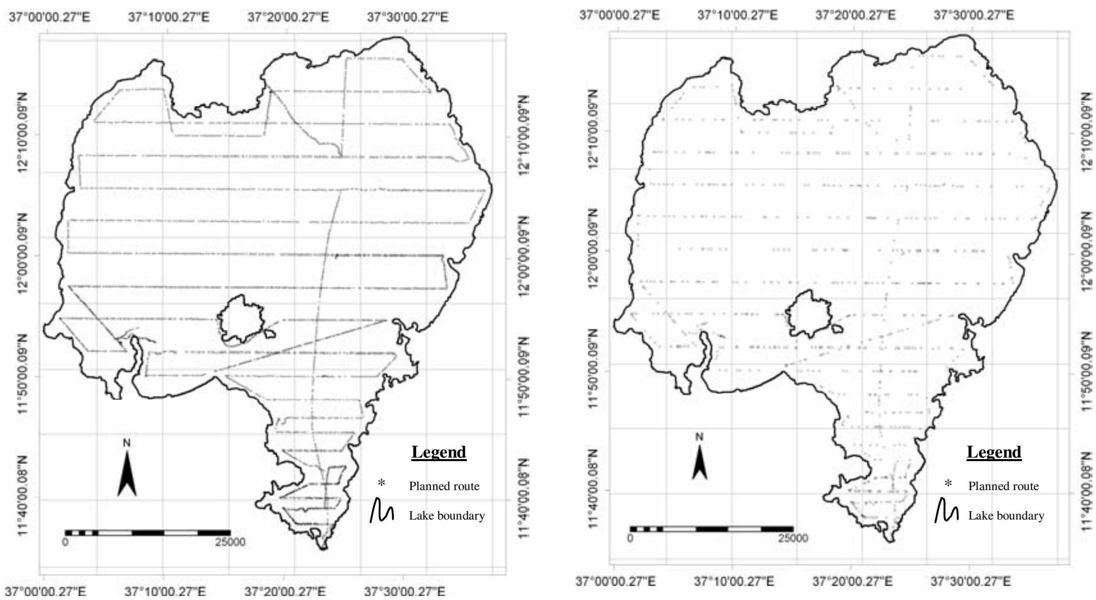


Figure 4.6 Typical characteristic features of a variogram

The relative merits in using kriging is that it gives direct estimates of the quality of the predictions made in terms of an estimation variance for the predicted value (*Burrough* and *McDonnel*, 1998). Consequently, the technique developed by ITC (*Dost* and *Mannaerts*, 2004) for the generation of lake bathymetry using geo-referenced sonar sounding and satellite imagery is used to generate bathymetric map of Lake Tana.

Interpolation depth points **Test depth points**



a) b)

Figure 4.7 Depth data partitioned for (a) interpolation and (b) accuracy assessment

Point depth values collected from bathymetric survey are interpolated to generate the bathymetric surface map which is used in combination with SRTM generated DEM to establish the Elevation-Storage-Area relationship of the lake. Bathymetric maps produced in 1940 and 1987 are used for comparison of change in lake storage characteristics due to sedimentation and other geophysical phenomenon. The parameters used in the variogram models and their corresponding goodness of fit are listed on the table below. It is estimated based on the standard deviation of depths along the relatively flat part of the lake.

Table 4.2 Variogram parameters used in Lake floor profile interpolation

Model	Nugget	Sill	Range	RMSE	R^2
Spherical	0.5	9.5	27000	0.0138	0.9810
Circular	0.5	9.5	30000	0.0142	0.9797
Exponential	0.5	10	12500	0.0132	*0.9823*
Gaussian	0.5	9.5	12500	0.0234	0.9471
Wave	0.5	9	8900	0.0285	0.9206
Rational Quadratic	0.5	9.5	7750	0.01963	0.9611

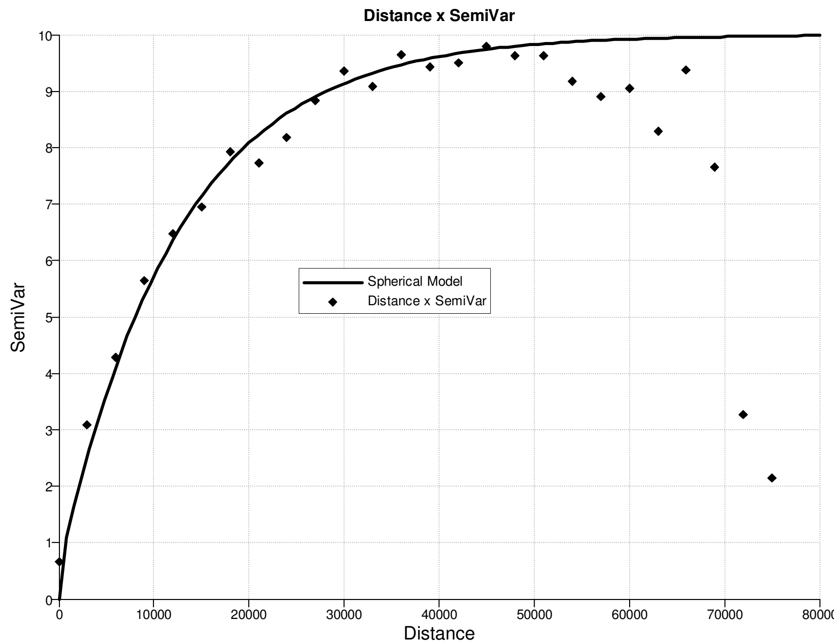


Figure 4.8 Variogram models as applied to the depth data

The interpolated depth value corresponding to the location of test points is extracted by applying cross map operation in ILWIS. These points are plotted for all variogram models to identify the best model that reproduces the test points using. A trend line fitted to the scatter plot for interpolation using exponential variogram model yields the highest goodness of fit. In all cases the outliers are kept during plotting in order to avoid bias. Consequently the result obtained using the exponential model is adopted to generate isobaths and determine the storage characteristic of Lake Tana.

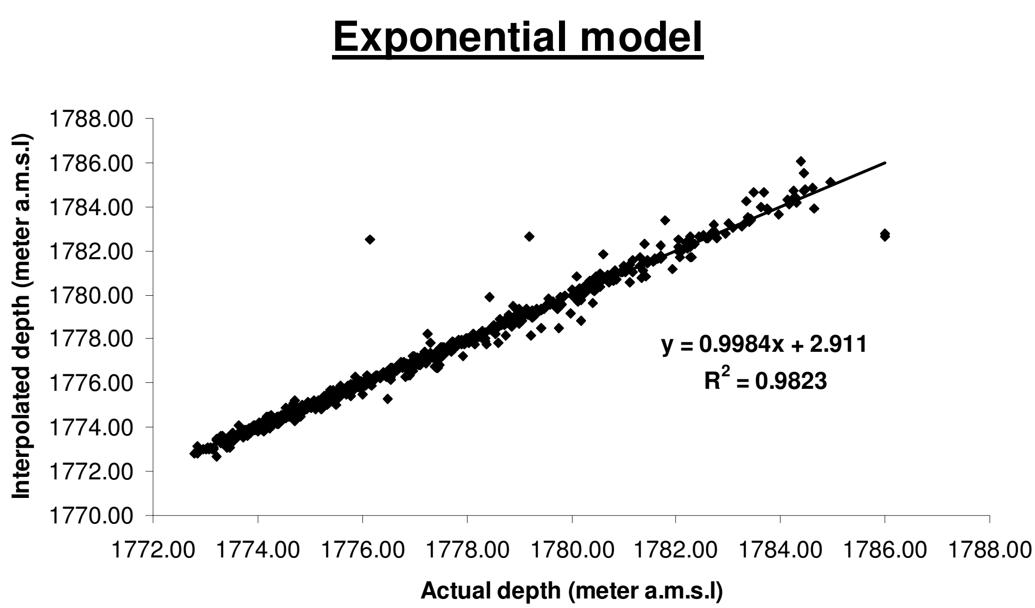


Figure 4.9 Correlation between interpolated and test points, maximum goodness of fit is observed with exponential model parameters

As the lake is characterized by its large surface area a small variation in water level represents a considerable change of storage volume. To account for such a characteristic a 0.05 m height interval is adopted in developing Elevation- storage-area relationship of the lake. This also results in a dense scatter plot and as the result a smooth trend line.

The error map created contains the standard error of the estimate, i.e. the square root of the error variance. The error variance in each estimated output pixel depends on:

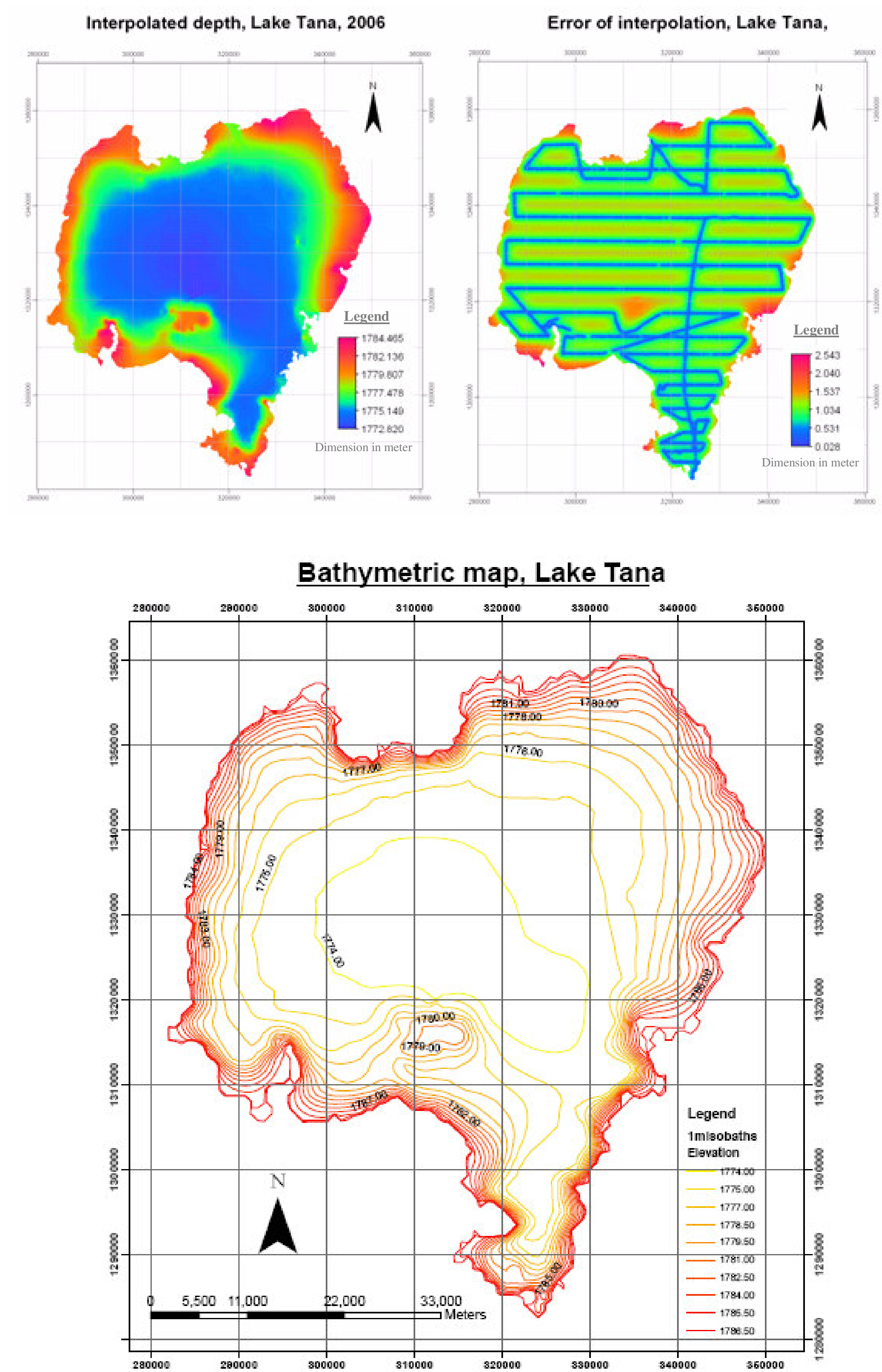
- the semi-variogram model including its parameters,
- the spatial distribution of the input sample points,
- the position of an output pixel with respect to the position of the input sample points.

A standard error which is larger than the original sample standard deviation denotes a rather unreliable prediction. The maximum error is observed in the periphery of the lake which may be due to the 1 km buffer used while undertaking the bathymetry survey.

Important morphometric characteristics of the lake are summarized below.

Table 4.3 Morphometric characteristics of Lake Tana

Parameter	
Altitude (m a.m.s.l)	1786
Catchment area, (km^2)	15319
A, including islands (km^2)	3024
L_{me} (km)	73.89 between $11^0$36'00N, $37^0$23' 19.07"E and $12^0$16'04.97"N, $37^0$23'19.07"E
W_{me}(km)	64.548
D_{max}(m)	14.9 at $12^0$00'13.34"N, $37^0$16'47.39"E
D_{avg}(m)	10.46
Length of shore line (km)	412.315
Volume (m^3)	28.372124×10^9



a)

b)

Figure 4.10 a) Interpolated Lake floor profile and error of interpolation b) Extracted isobaths

4.3. Alternative validation technique

Lake level validation is a continuous procedure. However, since the ultimatum of radar altimetry is to find a reliable, cost effective means of water level measurement in lieu of gauging stations, a corresponding GIS method of validation that will rule out the necessity of in-situ gauging stations should be developed. As such it is possible to reproduce lake levels from satellite imagery and the storage characteristics of the lake. These reproduced lake levels could then be used for validation of radar altimeter data sets where gauge data is not available. This approach can be applied in monitoring lakes that are inaccessible to gauge but have significant ecological relevance. The procedures used to develop the technique can be outlined as:

- Deriving Elevation-Storage-Area relationship using the bathymetric characteristics of the lake;
  The bathymetric map generated in the procedure above will be used to calculate the change in storage volume for a change in lake level and the corresponding lake surface area. Thus the lake level will be mathematically described as a function of storage volume and lake surface area.

- Selection of suitable image classification algorithm and estimation of lake area from classified image;
  Single scene satellite images of high resolution are always preferred. However this is not always be possible and hence a compromise should be made. Among the various classification methods available selection will be made based on ease of use and relative accuracy.

- Correlating area estimates from image classification and Elevation-Storage-Area characteristic curves;
  Lake surface area will be retrieved from the histogram of the classified images and will be used to estimate lake level using the functional relationship of area and elevation explained above.

4.3.1. Storage characteristics

Being a natural reservoir the boundary surface of the lake exhibits a complex degree of irregularity. Thus in calculating the volume an infinitesimally small level difference (dh) has to be adopted in order to minimize error. The total storage capacity is the integral of the volumes contained the applied small level difference, which mathematically can be expressed as,

$$V = \int_{h_1}^{h_2} A dh$$

Where

h_1 and h_2 are elevation of successive contours ($h_2>h_1$) and A is the mean area

GIS provides the capability to handle such complex operations with ease and very high accuracy. The Elevation-Storage-Area characteristic of the lake in this study is derived by using the 3DAnalyst tool of ArcGIS. The lake floor profile (DEM) resulted from the interpolation of depth points is exported to ESRI grid format and used as an input surface in the Area-Volume statistics calculation. The *volume*, *2D area* and *surface area* for a range of reference surfaces are calculated at the same interface which appends the results of the calculation to an output text file which could be easily imported to a spreadsheet for plotting. A 0.05 meter interval is adopted in the calculation to produce a smooth plot.

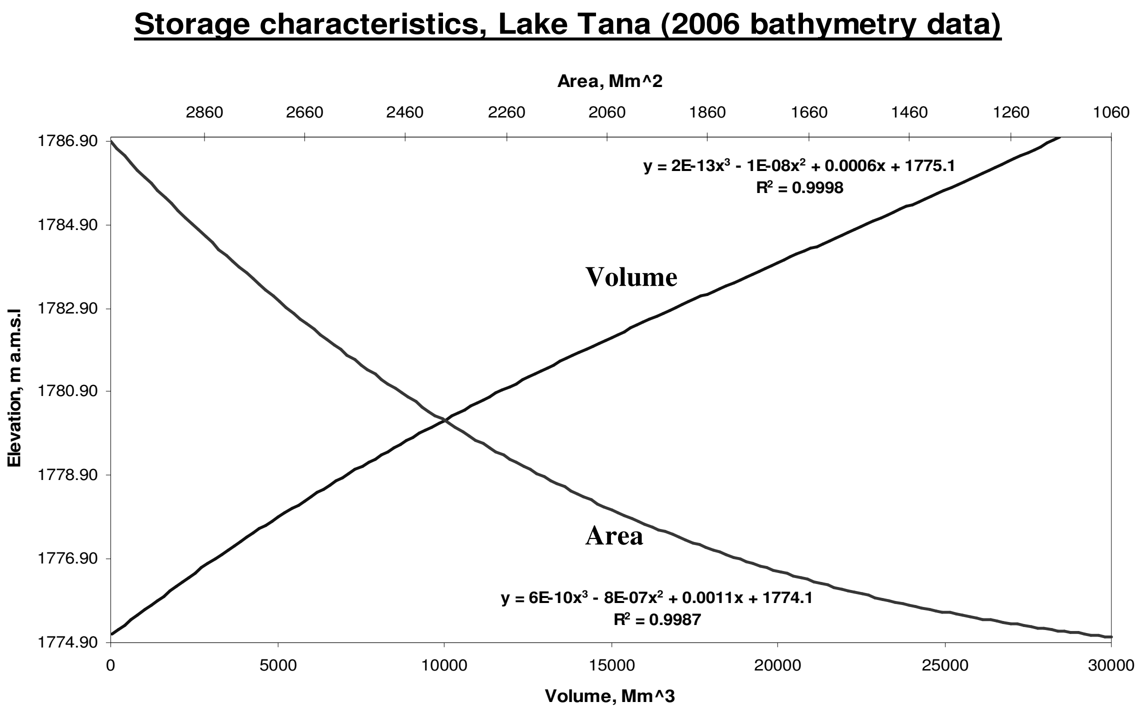


Figure 4.11 Elevation-Storage characteristics, Lake Tana

Two bathymetric maps of 1940 and 1987 are used for a rough check on the accuracy of the constructed characteristic curve which shows a good agreement with the interpolation result shown in figure 4.11. A slight reduction in storage capacity of the lake is observed during the comparison which is mainly attributed to sediment inflow into the lake. A cubic polynomial trend line fitted to both the elevation-storage and elevation-area characteristic curves gives a goodness of fit (R^2) value of 0.999 in both cases.

4.3.2. Lake area estimation from satellite image

The stage curve (shown in figure 4.11) is used to estimate the lake level elevation using the lake surface area estimated from a classified satellite image. For this purpose suitable satellite images of the lake are used to map the aerial extent of the lake. However factors affecting the choice of satellite images come in to play at this step. Aster and Landsat images are taken in to consideration at this stage due to availability of images and good spatial resolution.

Even though Aster images of Lake Tana are readily available through ITC's geo database facility they are not found to be suitable for the purpose. This is because ASTER images do not fully cover the lake on single date. Instead free archived Landsat ETM+/Landsat 4-5 images are used for these provides a complete coverage of the lake for the same date . Five images of the years 1986, 1999, 2001, 2002 and 2003 are downloaded from the Global Land Cover Facility (GLCF) website and imported to ILWIS. Some of these images need to be georeferenced.

All image data acquired by the Landsat 7 (ETM+) from July 2003 onwards has been collected in Scan Line Corrector (SLC)-off mode due to a failure in the Scan Line Corrector (SLC), which compensates for the forward motion of the satellite. Approximately 22 percent of image data is lost for every given scene. The data gap is filled using histogram-matched data values derived from one or more alternate acquisition dates (*USGS.*, 2006). However those images will incorporate greater uncertainties in that it is not far different from mosaicing images of different dates, which is the reason to disregard ASTER images. Therefore Landsat images taken prior to July 2003 are used in developing the method.

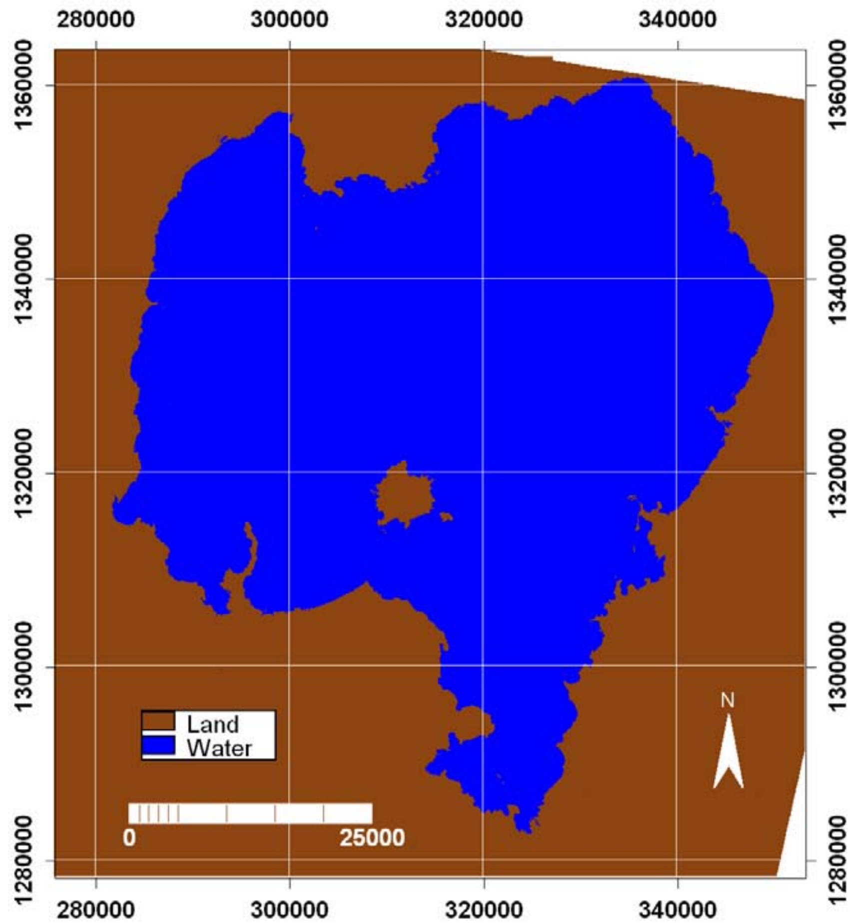
Various image classification techniques can be used to map the aerial extent of the lake. In this research two methods, band rationing and supervised image classifications are applied in estimating the lake area for their applicability and ease of use. Band rationing is a powerful technique for extracting spectral information from multi-spectral imagery, and is widely used for coastal area mapping (*Winasor* and *Budhiman*, 2001). Band ratio images enhance spectral differences between land and water and also suppress topographic effects. The ratio of VNIR to Red bands of Landsat images yields in a ratio value of less than 0.35 for water. The classification is confined to land-water classes for the details of objects on land are not point of interest.

The maximum likelihood classifier algorithm in supervised classification method is used in this study so as to exploit the assumption that spectral values of training pixels are statistically distributed according to a 'multivariate normal (Gaussian) probability density function' (*ITC*, 2001). Only two classes are to be identified, Land and Water with no need of detail on the land cover type. This gives the advantage of a well defined boundary between the feature spaces which is very important in this case as a satellite image of coarser spatial resolution is used. Adjacent water pixels which are not connected to the lakes are manually edited to improve the estimate of the area and render realistic lake extent.

Table 4.4 Comparison of classification methods using Landsat 7 (ETM+) images

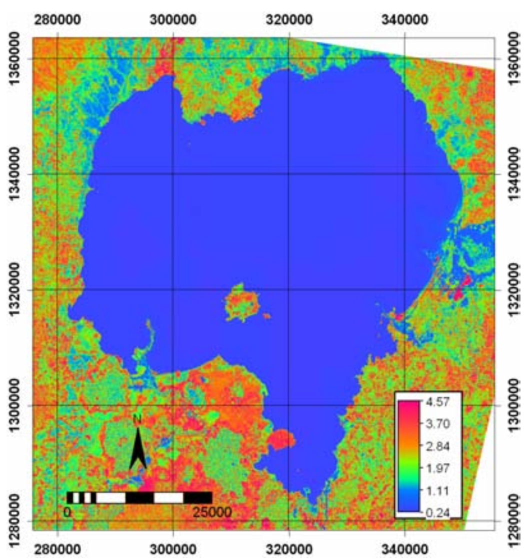
Image acquisition date	Area estimate from classified image (km^2)		Difference
	Band rationing method	Supervised method	/Δ/
1/3/1986	3041.82	3032.06	9.22
4/10/1998	3058.09	3029.48	26.61
9/12/1999	3067.83	3058.89	8.94
2/5/2001	3055.80	3059.38	3.58
7/2/2002	3031.39	3007.67	23.72
4/16/2003	2947.23	2954.83	7.6

Image Classification using supervised classification method, Lake Tana

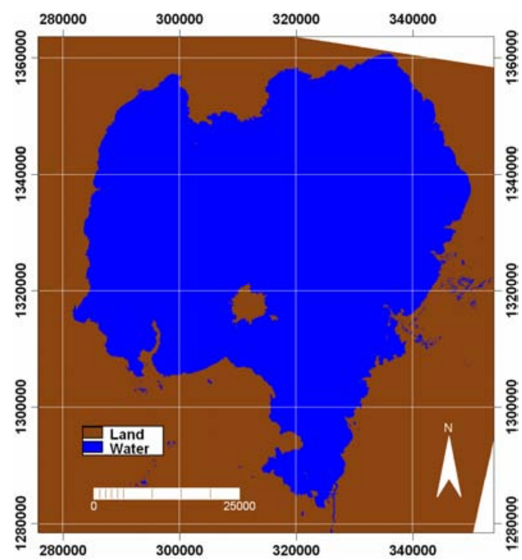


a)

Result of Band Rationing operation



Sliced image after band rationing operation



b)

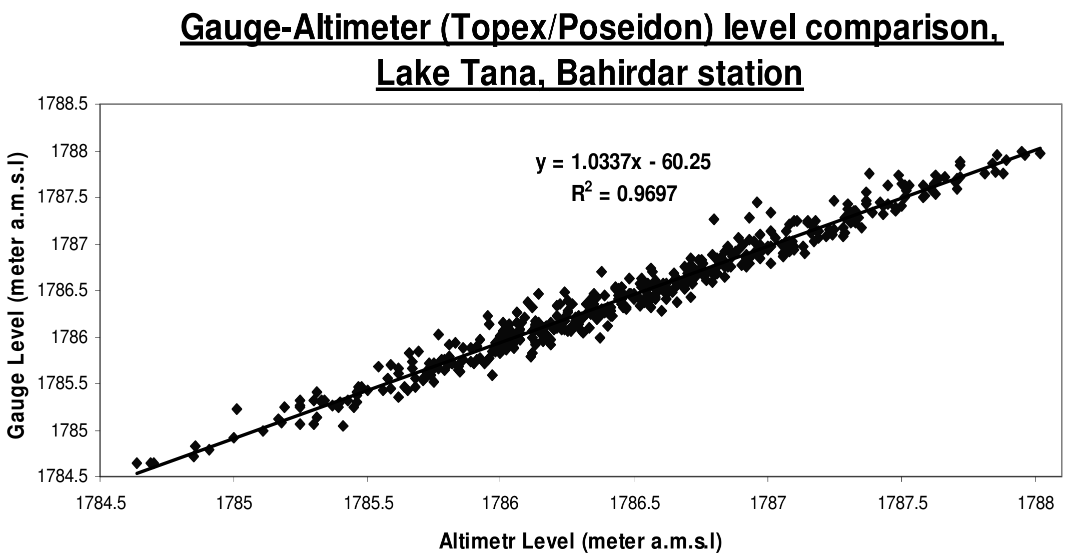
Figure 4.12 Classified images using a) Supervised classification and b) Band rationing method (September 1999 image)

The lake surface area determined from the above procedure is used to calculate the elevation of the lake using the relation obtained from the storage characteristic curve. This lake elevation value is compared to the gauge level values of the corresponding dates and a simple trend line correlation is established. The estimation capability of this correlation should however be validated using additional image classified in the same way mentioned above. This is done by using additional Landsat image of April 1998 (see shaded values in table above). The result of the classification work is shown in table 4.4.

5. Results and discussion

5.1. Comparison of altimeter and gauge data

Altimetry lake level data for Lake Tana from Topex/Poseidon and ENVISAT missions are compared with gauge level data for a time span of 1992 to 2005. However, the time span of the available data from the two missions doesn't fit exactly. Estimated regression coefficients that minimize the Sum of Squares for Error (SSE) are very sensitive to outliers and hence for both missions outliers are excluded from the datasets using the mean gauge-altimeter difference as a threshold. The RMSE calculated for Topex/Poseidon data is 0.019 and for that of ENVISAT is 0.091 (figure).



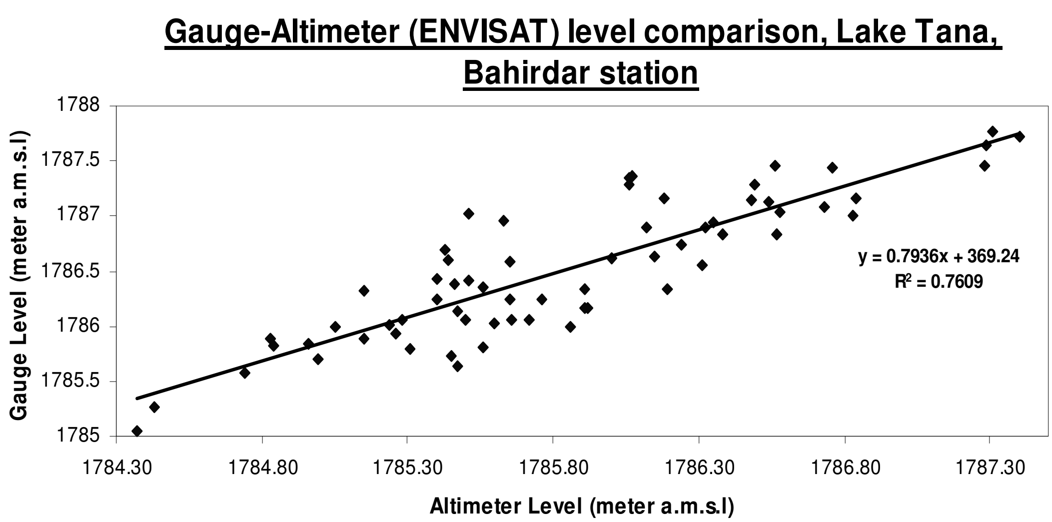


Figure 5.1 Gauge-Altimeter correlation for Topex/Poseidon and ENVISAT missions

The gauge-altimeter level correlation for Topex/Poseidon and ENVISAT yields in a goodness of fit value of 0.9697 and 0.7609 respectively (figure 5.1). A hybrid of the two data sets improves the temporal resolution but with a strong surge in RMSE amounting to 0.11.

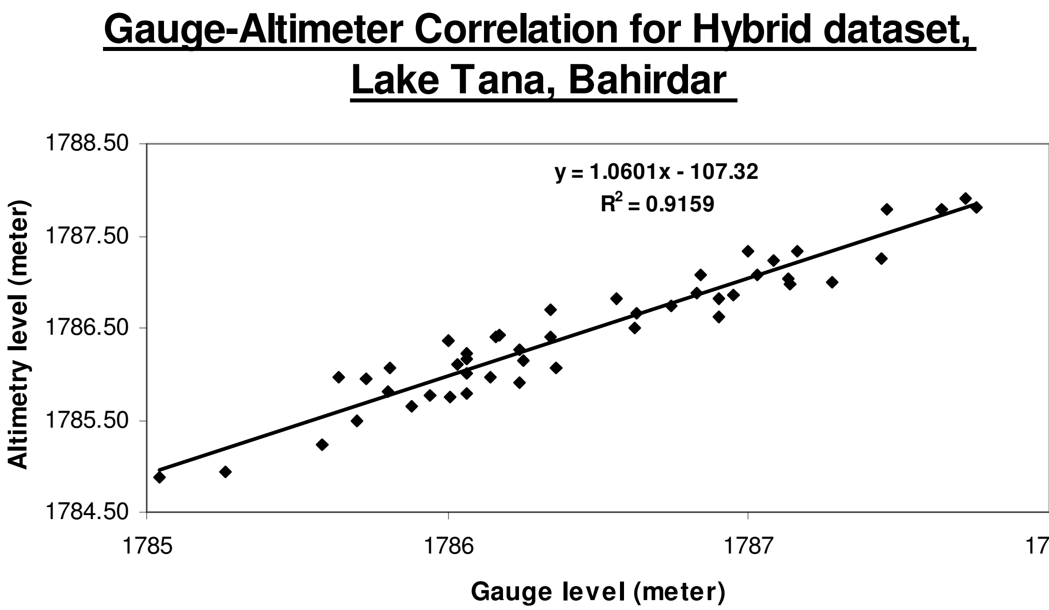


Figure 5.2 Hybrid dataset from Topex/Poseidon and ENVISAT compared to gauge data (Bahirdar)

Test has been made to check the normality of the error in data obtained from both Topex/Poseidon and ENVISAT altimeters and the resulting plot is shown below.

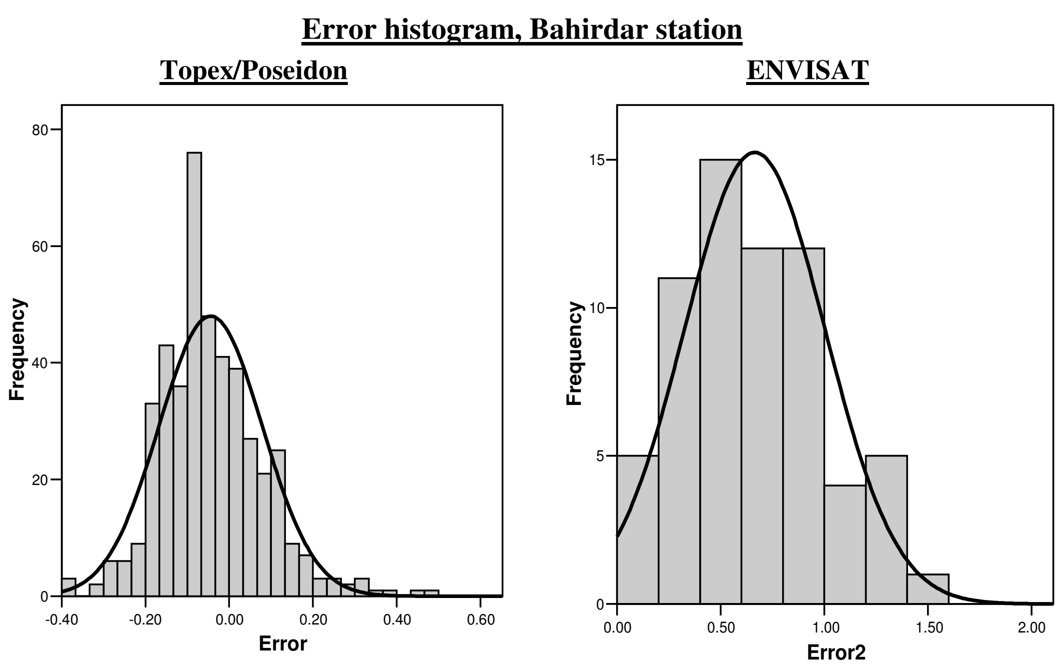


Figure 5.3 Histogram plots of error showing skewed distribution for both stations

The statistical analysis made on the error values for both data sets and tabulated below shows a Skewness coefficient of 0.688 (with standard error of Skewness 0.116) for Topex/Poseidon data and 0.414 (with standard error of Skewness 0.297) for ENVISAT data. As a rough guide, a skewness value more than twice it's standard error is taken to indicate a departure from symmetry. Hence the recommendations by FGDC for accuracy determination can not be applied in this case.

Table 5.1 Summary of statistical analysis

Parameter	Topex/Poseidon	ENVISAT
Std. Error of Mean	.00585	.04221
Std. Deviation	.12353	.34029
Skewness	.688	.414
Std. Error of Skewness	.116	.297
Range	.85	1.37

Lake level retracked from GFO mission for Lake Abiyata could not reproduce measured gauge levels accurately as shown in figure 4.5. The RMSE are found to be 2.44 which is considerably high. The level variation trend is also far from the observed and hence these data sets are not as such usable for monitoring purpose.

5.2. Applicability of alternative validation technique

The methods for developing alternative validation techniques explained in chapter four resulted in a good estimate of lake level with a RMSE of 0.720. A statistical analysis in the error distribution had shown that the error is distributed normally (with Skewness of 0.463 and standard error of 0.845) and consequently the recommendations by FGDC for spatial data accuracy determination can be used. Hence, using the alternative validation method developed as above the level of Lake Tana can be determined with a 95% confidence interval as

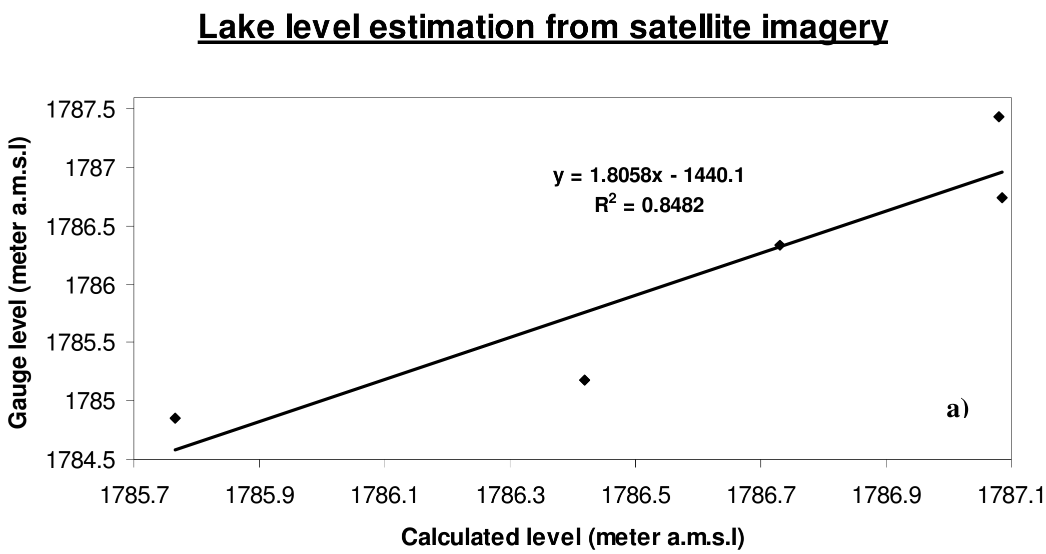
$$= \pm 1.96 * 0.72$$
$$= \pm 1.41$$

With respect to the surface area of the lake it is quite understandable that such a range represents a huge volume of water and the method may not be applicable for operational purposes. Nonetheless the accuracy can be improved by using increased number of images in establishing the 'actual gauge level to calculated gauge level' relationship.

Table 5.2 Level estimation using Lake surface area extracted from satellite images

Date	Area from image classification (A)	Gauge Level	Lake level from storage characteristics curve $6*10^{-6}A^3 - 8*10^{-7}A^2 + 1.1*10^{-3}*A + 1774.1$	Δ
1/3/1986	***3032.06***	1786.33	***1786.73***	-0.4006
9/12/1999	***3058.89***	1787.44	***1787.08***	0.3614
2/5/2001	***3059.38***	1786.74	***1787.09***	-0.3450
7/2/2002	***3007.67***	1785.18	***1786.42***	-1.2401
4/16/2003	***2954.83***	1784.86	***1785.77***	-0.9064

For example introducing a single Landsat image of April 1998 results in a 3.37% reduction (from 0.74 to 0.72) in RMSE. An interesting trend observed in correlating the gauge-altimeter data is that exclusion of extreme low lake levels (hence reduced surface area and increased exposure of lake vegetation and islands) tend to considerably improve the goodness of fit as illustrated by the plots below



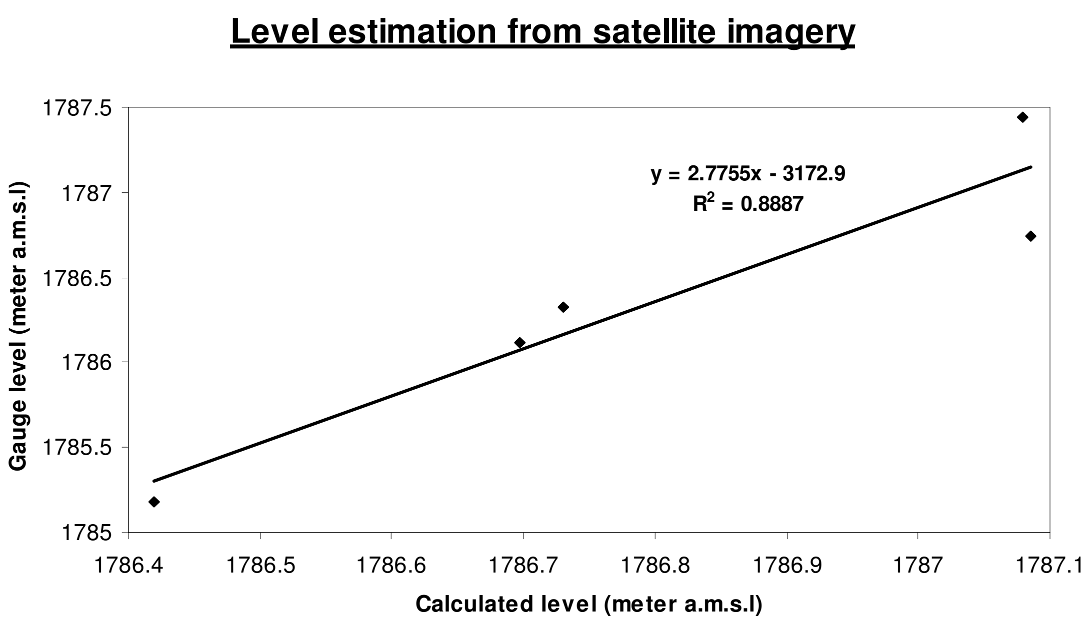


Figure 5.4 Correlation between measured and calculated a) including area estimates of low lake level and b) after excluding extreme low lake levels

5.3. Applications in lake level monitoring

Flood management is an integral part of integrated water resources management. Very little activities had been accomplished on flood management in most of the river basins in Ethiopia. Such is the case in Lake Tana as well. It is evident that extreme deforestation in the highlands of that drain to Lake Tana and expansion of farmlands has induced increased inflow of both water and sediment. Analysis on the 1987 and 2006 bathymetric maps had shown that a total volume of 200 Mm^3 is lost between elevations 1775 and 1783 meters. The increased sediment inflow had considerably reduced the capacity of the lake; the water being accommodated by the adjacent low lands in the eastern side of the lake causing damage to farm land and displacement.

Building flood defence structures (embankments, walls, weirs, sluices and pumping stations) in one place might cause more stress elsewhere, sometimes creating a bigger problem than the natural phenomena itself. As an alternative it might be best to increase flooding in one area to reduce it in other more sensitive area. This is just one of the many options to be considered in Catchment Flood Management Plan preparation. The land use across a larger area will be evaluated and possibilities of temporarily moving certain volume of water to areas where the flood could cause least harm to people and the environment will be weighed. Natural methods of dealing with flood such as providing space for flood water is more effective where climate change becomes the driving force. Such a method generally occupies larger area of land but require less investment and maintenance.

The storage-elevation-area relation established in this study is a typical tool for monitoring the lake level and preparing Catchment Flood Management Plans. The isobaths extracted from the merged DEM helps in assessing the physical extent of the lake surface area and thereby the extent of submerged land which can be used to identify potential areas of mitigation measures.

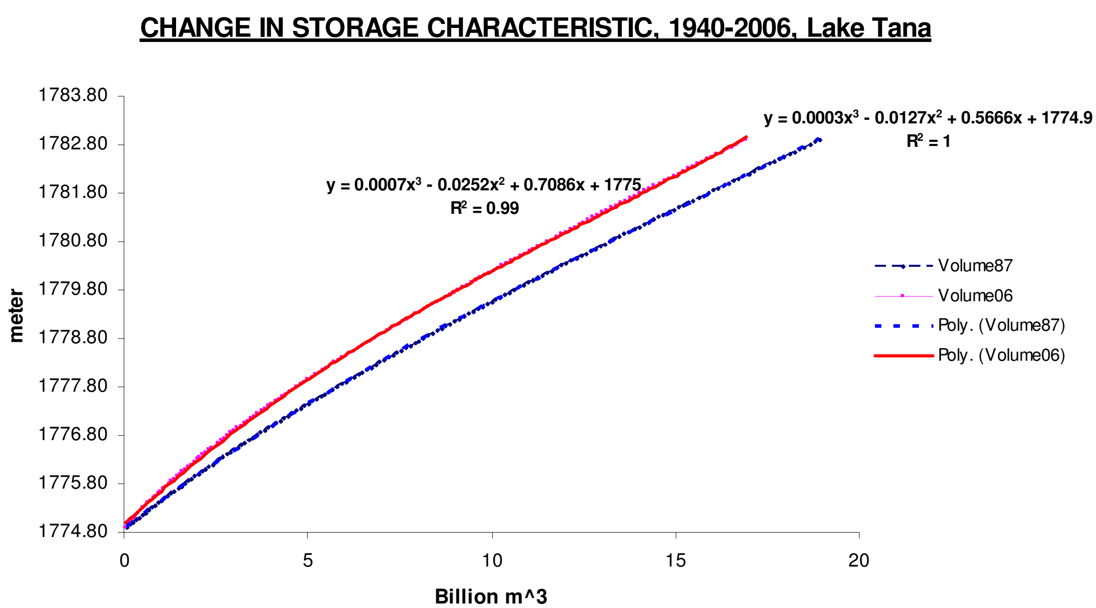
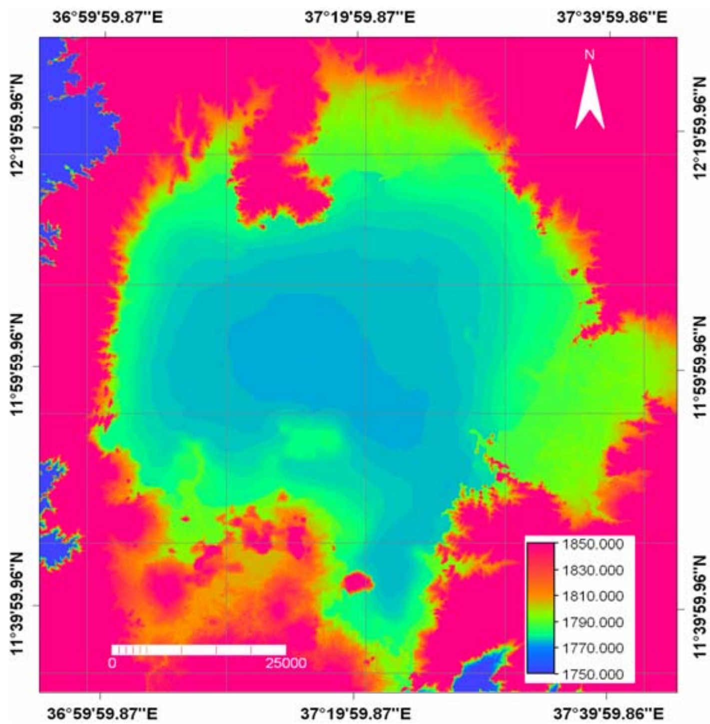


Figure 5.5 A reduction in storage capacity of Lake Tana mainly attributed to sediment inflow

<u>Bathymetry of Lake Tana fitted to SRTM DEM</u>



<u>Flood extent extracted from SRTM DEM</u>

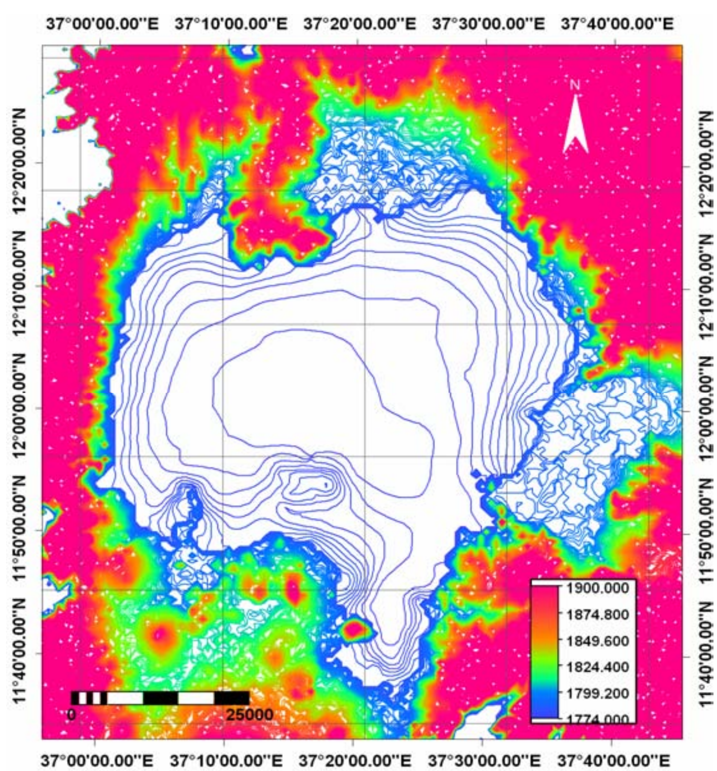


Figure 5.6 Interpolated lake profile fitted to SRTM DEM

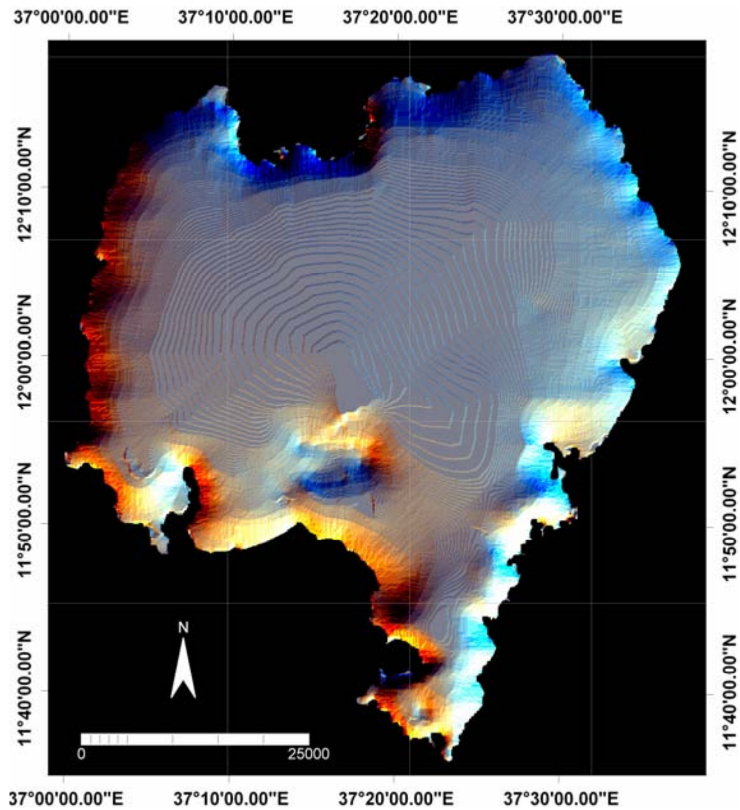


Figure 5.7 Lake Tana bottom relief developed for Visualization

The above analysis results can be used in conjunction with other GIS spatial analyst tools to plan disaster prevention measures (such as safest evacuation and relocation areas, locating suitable locations for rescue measures etc.), damage evaluation and flood zone mapping. Similarly the storage characteristics curve of the lake can be used in conjunction with satellite image to estimate the water volume, an important input for optimized use of the water to serve multi purpose projects of conflicting needs.

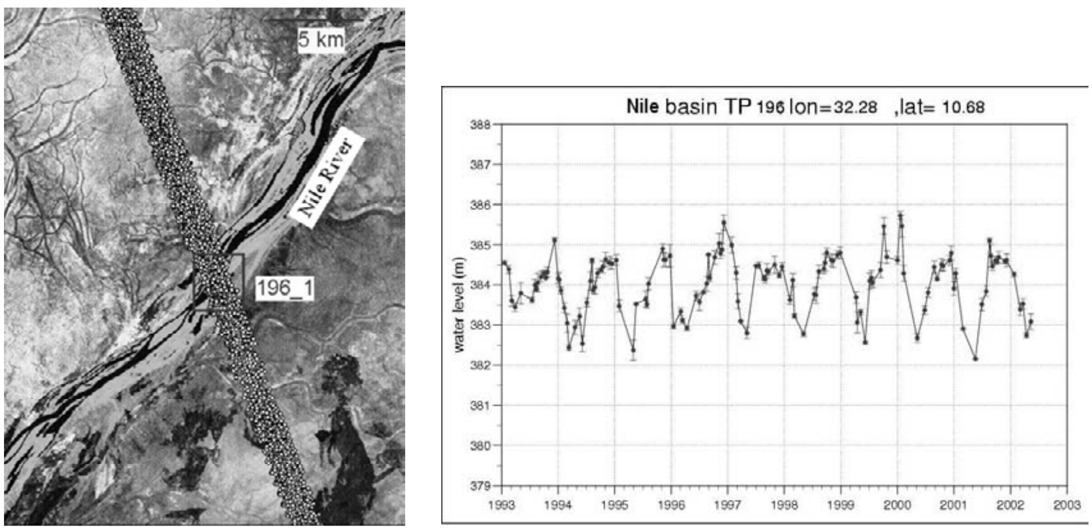
5.4. Applicability in Trans-boundary water resources management

Water is one of the most politicized natural resources feared to be a potential cause of coming major conflicts. More than two hundred river basins are currently shared by two or more sovereign nations while very few formal treaties exist among these countries for sharing the river waters in an equitable manner (*Elhance*, 2004). Given the accelerating water scarcities due to exploding population growth and increasing complexity of international politics sovereign nations should be persuaded to cooperate in the use and development of common water resources to avoid conflicts and maintain environmental balance.

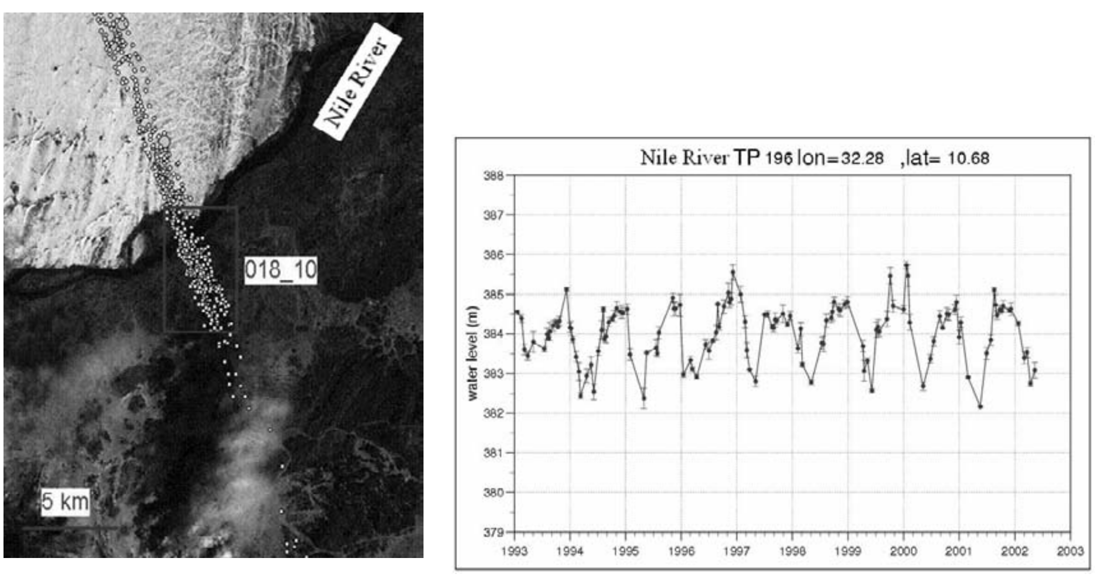
The most frequently mentioned of such a case is the Nile basin which is shared by ten countries. In recent years the basin countries establish a transitional institutional mechanism called the Nile Basin Initiative (NBI) to facilitate an equitable use of the water resource. The NBI action program constitute the Shared Vision Program (SVP) aiming at building an enabling environment for investment and the

Subsidiary Action Program (SAP) a vehicle to translate the Shared Vision into action. At the core of the SVP is Confidence Building and Stakeholder Involvement (CBSI) working to build confidence between basin countries and confidence that the development objectives of the NBI can be achieved. According to this plan the confidence building is "to be accomplished through *activities and exchanges across borders that build trust* and lead to the development of bilateral and regional partnerships" (*NBI*, 2002).

Most often data related to water resources, namely river discharges and lake levels are kept 'private' and are hardly shared easily. However, recent developments in remote sensing technologies seem to put an end to such mistrust enabling everyone to access data with no restrictions.



a)



b)

Figure 5.8 Altimetry paths over Nile River at a) downstream of Rosier dam and b) near Giza, Egypt (LAGOS)

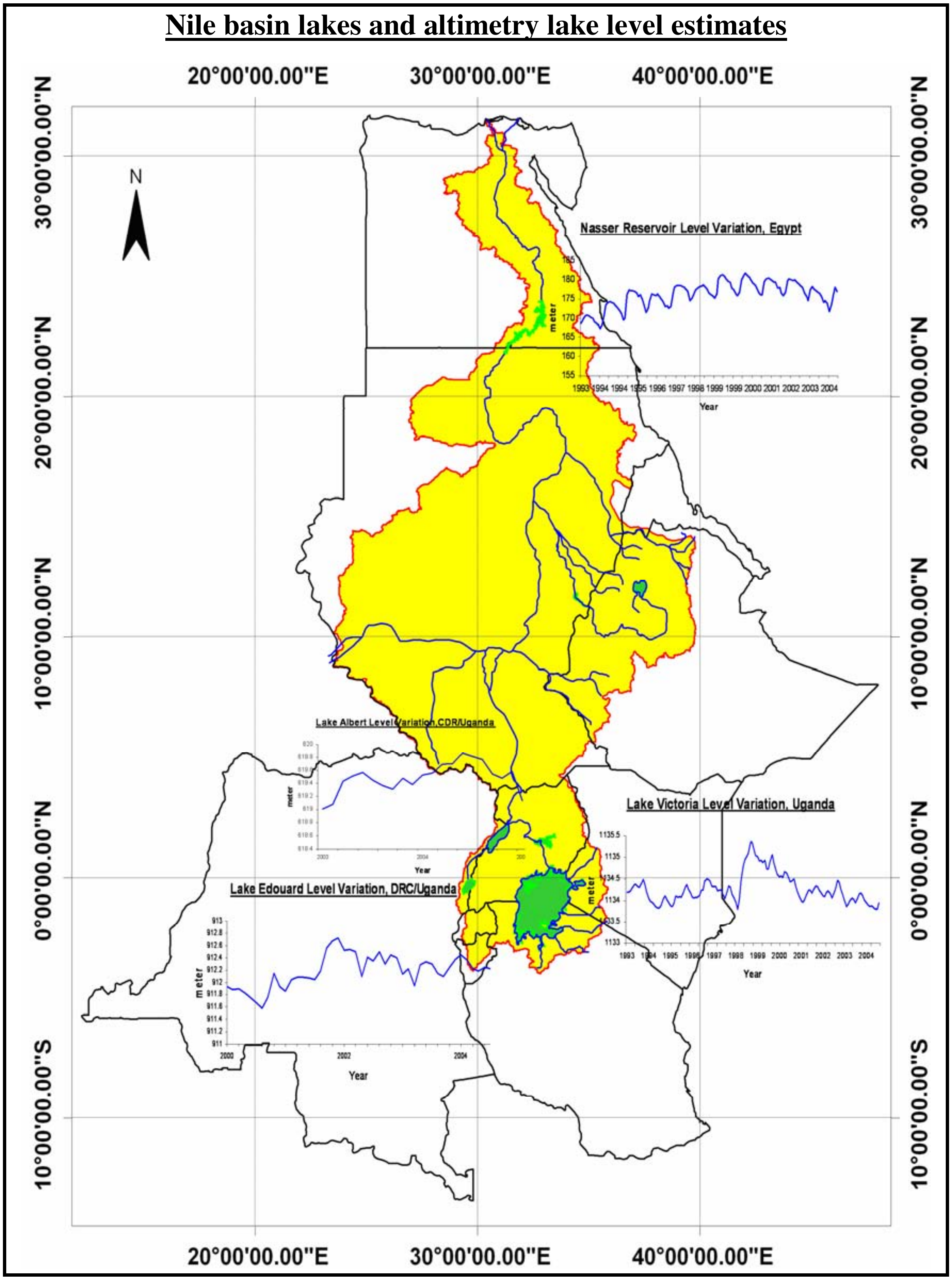


Figure 5.9 The Nile basin and water sources currently covered by altimeter observation

Nasser reservoir, Lake Albert, Lake Victoria, Lake Edouard, Lake Tana and Rosier reservoir are currently covered by Topex/Poseidon or ENVISAT missions and lake level data are made easily available on the web empowering decision makers to monitor the state of the water resources. Hydrological products from satellites are unaffected by political and logistical considerations and can provide accurate height measurements not only for lakes but also for large rivers. Studies on the Amazon and Rio Negro had revealed that river stage can be measured using radar altimetry techniques (*Rosmorduc et al.*, 2006). This enables water resources managers of riparian countries to monitor the state of the water in a trans-boundary river. Similarly river discharge measurements using an established gauge-discharge relation and altimetry measurement had proved to have a promising future as a tool River discharge measurement. Such measurements are currently available for the Nile River at Sudan and Egypt. Figures 5.10 show some of the lakes in the Nile River basin which are currently covered by Topex/Poseidon and ENVISAT missions (*François*, 2007).

6. Conclusions and recommendations

6.1. Conclusion

Altimeter measurements over Lake Tana showed a good agreement with gauge measurements exhibiting a strong capability for monitoring inland waters. Topex/Poseidon data sets have the merit over ENVISAT data sets due to the lower RMSE and higher temporal resolution. For the Topex/Poseidon data set a very good gauge-altimeter correlation is observed for Lake Tana, which may be used to supplement the gauges at Bahirdar station. A hybrid data set from Topex/Poseidon and ENVISAT missions after applying a correction to the datum shift observed in ENVISAT data sets. Altimetry lake level could not be retracked for other lakes of interest in the study area from any of the available missions mentioned or were of very poor accuracy. Altimeter signals could not be retracked from Finchaa', Koka, Ziway and Abaya lakes even though altimetry ground tracks are available over these lakes. The ground tracks over these lakes are adjacent to the lake shore and hence signals will be highly contaminated by land topography. Signals retracked for small lakes (Lake Abiyata in this case) are of very poor quality such that even the lake level variation trend couldn't be reproduced. Generally it can be concluded that the present status of the technology is not suitable to measure water level of small size inland lakes.

Data retrieval tools are limited to extract water elevation data from the open ocean. Retracking procedures are complicated and time consuming and hence could not be done by end users. Lake level for an inland lake is therefore processed and supplied up on request only. Lower error margins of lake level estimates could be achieved by repeated sampling of signals. The standard deviation of estimated lake level is provided with the data set and is an indication to the accuracy of the retracking work. The retracking can end up with erroneous results as can be seen from lake levels estimates from GFO altimeter for one of the lakes (figure 4.4) considered in the study.

A major achievement of this research is the development and implementation of a prototype validation technique that integrates remote sensing with reservoir characteristics derived from bathymetry. In situations where gauges become intermittently unfunctional or inaccessible due to damage or extreme meteorological events the method can be used to ensure data continuity. The accuracy of lake level estimates based on this method does have a wide margin of error. This reduces the reliability of the method with respect to volume estimation, especially in the case of lakes with larger surface area as in the case of Lake Tana ($R_{out}=0.0156H^{3.25}$) for example where the outflow is largely a function of the lake level (chapter 3).

One major draw back of this technique is that a single scene or single date mosaic image is required. High resolution satellite images of a single date are not easily available and hence lower resolutions images can be applied which actually affects the accuracy of the technique. The correlation between the measured and calculated levels can be improved by using set of images for a wide range of the lake level. For example in this study the RMSE of lake level estimation had improved considerably (figure 5.4b) by introducing one additional image to the analysis. It has to be noted however that introducing images of low lake levels tends to spoil the correlation. The image classification methods used in setting up this validation technique are made more so that water management professionals with an intermediate RS and GIS skill could apply it for practical use.

Water issues are not only technical in nature but also have certain political and national aspects which cannot be resolved without building mutual trust and confidence among riparian states. As part of the confidence building measures the riparian states may decide to share data at basin level. But this may not always be achievable especially in regions where long history of mistrust and prejudice prevails. The major foreseeable application of radar altimetry in water resources management is its use as a tool to monitor the state of the water beyond national boarders where such formal exchange of data is not working.

6.2. Recommendations

At present the temporal resolution of the system is one of the pronounced setbacks of the technology which needs a breakthrough. Efforts should be integrated towards providing repetitive accurate water level measurements to improve the understanding of storage dynamics of lakes, reservoirs and wetlands. Future missions such as CRYOSAT II and projects dedicated to monitoring water bodies from space such as WATER HM have the potential to add value to the capability of continuous monitoring of not only continental waters but also inland lakes and important rivers. The validation works may also be extended to river discharge estimation based in combination with the stage-discharge relationship of a river. Hydrological observations that have implications for water management often are closely guarded, and are only released many years after their practical use has become insignificant. Altimetry technology could be a valuable tool in the future enabling trans-boundary water resources monitoring and evaluation.

RS supported water resources monitoring has proved to be a powerful tool in water volume management. The accuracies achieved in this thesis can be further improved by applying more advance image classification methods. The use of dense bathymetric grid will also result in a more accurate characterization of the lake storage and hence improved accuracy. Moreover the effect of other hydrologic phenomenon that characterizes the catchment such as change in land cover and erosion could be incorporated to render a wholesome approach to the validation technique. As an example a comparison between the 1987 and 2006 bathymetric maps of Lake Tana had shown a change in storage characteristics of the lake which is basically due to the large volume of sediment flowing in to the lake. It is evident that this will result in a change of storage characteristics. Accuracy of the validation technique developed in this research is thus subject to variation in storage characteristics. The response of the lake for increased discharge and sediment inflow should thus be further studied from the perspective of a change in storage characteristics. In the future the validation work may also be extended to incorporate the effect of the distance between altimetry tracks and gauge locations.

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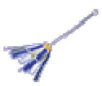
Annex

Appendix A: List of Acronyms

AVISO	Archiving, Validation and Interpretation of Satellite Data in Oceanography (France)
CEO	Committee on Earth Observation Satellite
CLS	Collecte Localisation Satellites (French firm for satellite based environmental data collection)
CNES	Centre National d'Etudes Spatiales (French space agency)
EEPCo	Ethiopian Electric Power Corporation
ERS	European Remote sensing Satellite
FGDC	Federal Geographic Data Committee
GDR	Geophysical Data record
GFO	Geosat Follow On (continuing mission of Geosat satellite)
GPS	Global Positioning System
GRDC	Global River Discharge Center
LEGOS	Laboratorie d'Etudes en Geophysique et Oceanographie Spatiales (France)
MoWR	Ministry of Water Resources
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
PODAAC	Physical Oceanography Distributed Active Archive Centre
RMSE	Root Mean Square Error
SRTM	Shuttle Radar Topographic Mission
SWH	Significant Wave Height
T/P	Topex/Poseidon
USDA-FAS	United States Department of Agriculture-Foreign Agricultural Service
USGS	United States Geological Survey
WatER HM	Water and Terrestrial Elevation Recovery Hydrosphere Mapper
WFP	World Food Program
WMO	World Meteorology Organization

Appendix B: Altimetry missions: Past, Current and Future

Satellite	Agency	Launch	Altitude	Altimeter	Frequency	Revisit	Inclination	Error
Skylab 	NASA	1973	435 km	S193		?	50°	R: 1 m; O: ~500 cm
GEOS 3 	NASA	1974	845 km	ALT			115°	R: 25 cm; O: ~500 cm
Seasat 	NASA	1978	800 km	ALT	Ku-band	17 days?	108°	R: 5 cm; O: ~100 cm
Geosat 	US Navy	1985	800 km		Ku-band	17 days	108	R: 4 cm; O: 30-50 cm
ERS-1 	ESA	1991	785 km	RA	Ku-band	35 days	98.5°	R: 3 cm; O: 8-15 cm
Topex/ Poseidon 	NASA / CNES	1992	1336 km	Topex Poseidon-1	Ku and C-band Ku-band	10 days	66°	R: 2 cm; O: 2-3 cm
ERS-2 	ESA	1995	785 km	RA	Ku-band	35 days	98.5°	R: 3 cm; O: 7-8 cm
GFO 	US Navy / NOAA	1998	800 km	GFO-RA	Ku-band	17 days	108°	R: 3.5 cm; O: ? cm
Jason-1 	CNES / NASA	2001	1336 km	Poseidon-2	Ku and C-band	10 days	66°	R: 2 cm; O: 2-3 cm
Envisat 	ESA	2002	800 km	RA-2	Ku and S-band	35 days	98.5°	R: <4.5 cm ; O: 2-3 cm
Jason-2 	*	2008	1336 km	Poseidon-3	Ku and C-band	10 days	66°	
Cryosat II 	ESA	2009	720 km	SIRAL	Ku-band	369 days	92°	

R: Range, O: Orbit, *: NASA /Eumetsat /NOAA
Source: http://www.altimetry.info/html/missions/welcome_en.html

Appendix C: Altimetry and corresponding Gauge data for Lake Tana

Topex/Poseidon mission			ENVISAT mission		
Date	Gage level	Alt. level	Date	Gage Level	Alt. level
9/26/92	1787.02	1786.95	10/18/95	1786.95	1786.35
10/6/92	1786.98	1787.07	12/10/95	1786.56	1786.31
10/26/92	1786.97	1787.01	1/14/96	1786.39	1785.46
11/5/92	1786.88	1786.79	2/18/96	1786.17	1785.92
11/15/92	1786.83	1786.81	3/18/96	1786.14	1785.47
11/25/92	1786.75	1786.92	4/28/96	1785.88	1785.15
12/5/92	1786.65	1786.84	5/29/96	1785.8	1785.31
12/25/92	1786.48	1786.24	7/7/96	1785.84	1784.96
1/3/93	1786.42	1786.36	8/11/96	1786.96	1785.63
1/13/93	1786.36	1778.12	9/15/96	1787.76	1787.31
1/23/93	1786.28	1786.34	10/20/96	1787.45	1786.56
2/12/93	1786.14	1786.03	11/24/96	1787.14	1786.48
2/22/93	1786.12	1786.2	12/29/96	1786.83	1786.38
3/4/93	1786.05	1786.15	2/2/97	1786.59	1785.65
3/14/93	1786	1786.05	3/8/97	1786.34	1785.91
3/24/93	1785.95	1786.01	4/13/97	1786	1785.86
4/3/93	1785.89	1786.02	6/22/97	1785.81	1785.56
4/13/93	1785.85	1785.97	7/25/97	1786.32	1785.15
4/23/93	1785.76	1785.95	8/11/97	1786.62	1786.00
5/12/93	1785.72	1785.81	10/5/97	1787.08	1786.73
5/22/93	1785.68	1785.54	11/9/97	1787.16	1786.18
6/1/93	1785.7	1785.84	12/14/97	1786.9	1786.32
6/11/93	1785.75	1785.78	1/18/98	1786.63	1786.15
6/21/93	1785.74	1785.67	2/22/98	1786.43	1785.40
7/1/93	1785.78	1785.96	3/26/98	1786.16	1785.91
7/11/93	1785.94	1786.13	4/27/98	1786.06	1785.28
7/21/93	1786.1	1786.21	5/22/98	1785.94	1785.26
7/31/93	1786.31	1786.56	7/11/98	1786.06	1785.66
8/10/93	1786.43	1786.71	8/16/98	1787.02	1785.51
8/20/93	1786.72	1786.74	9/10/98	1787.72	1787.40
8/30/93	1786.91	1786.86	10/13/98	1787.64	1787.29
9/18/93	1787.17	1787.28	11/29/98	1787.13	1786.54
9/28/93	1787.18	1787.17	12/26/98	1786.84	1786.57
10/8/93	1787.15	1787.23	3/14/99	1786.24	1785.76
10/18/93	1787.06	1787.19	5/23/99	1785.82	1784.84
11/7/93	1786.93	1786.89	6/15/99	1785.7	1784.99
11/17/93	1786.82	1786.74	8/1/99	1786.36	1785.56
11/27/93	1786.71	1786.79	9/5/99	1787.36	1786.07
12/7/93	1786.64	1786.73	10/10/99	1787.46	1787.28
12/17/93	1786.54	1786.43	11/12/99	1787.44	1786.76
12/26/93	1786.48	1786.64	12/19/99	1787.03	1786.58
1/5/94	1786.4	1786.34	1/23/00	1786.74	1786.24
1/15/94	1786.36	1786.45	3/30/00	1786.25	1785.65
1/25/94	1786.29	1786.25	5/7/00	1786.03	1785.60
2/4/94	1786.24	1786.38	6/11/00	1786.01	1785.24
2/14/94	1786.17	1786.24	7/16/00	1786.24	1785.40
2/24/94	1786.1	1786.2	8/20/00	1787.28	1786.06
3/6/94	1786.04	1786.07	12/3/00	1787.16	1786.84

3/26/94	1785.91	1786.03
4/5/94	1785.83	1785.66
4/14/94	1785.79	1785.81
4/24/94	1785.72	1785.9
5/4/94	1785.68	1785.74
5/14/94	1785.67	1785.67
5/24/94	1785.61	1785.62
6/3/94	1785.57	1785.72
6/13/94	1785.64	1785.84
7/3/94	1785.9	1785.91
7/13/94	1786.16	1786.08
7/23/94	1786.46	1786.14
8/11/94	1786.98	1786.85
8/21/94	1787.24	1787.11
8/31/94	1787.42	1787.37
9/10/94	1787.42	1787.45
9/20/94	1787.44	1787.42
10/10/94	1787.09	1787.28
10/20/94	1786.9	1787.14
10/30/94	1786.82	1786.83
11/19/94	1786.6	1786.7
11/29/94	1786.52	1786.44
12/8/94	1786.46	1786.46
12/18/94	1786.4	1786.62
12/28/94	1786.36	1786.45
1/17/95	1786.342	1786.21
1/27/95	1786.27	1786.37
2/6/95	1786.24	1786.32
2/16/95	1786.2	1786.24
2/26/95	1786.14	1786.13
3/8/95	1786.06	1786.26
3/18/95	1786	1786.37
3/28/95	1785.98	1786.06
4/6/95	1785.94	1785.83
4/16/95	1785.84	1785.69
4/26/95	1785.82	1786
5/6/95	1785.79	1786.11
5/16/95	1785.72	1785.73
5/26/95	1785.66	1785.62
6/5/95	1785.69	1785.84
6/15/95	1785.72	1785.75
6/25/95	1785.72	1785.82
7/5/95	1785.72	1785.94
7/15/95	1785.88	1786.05
7/25/95	1786.16	1786.06
8/3/95	1786.44	1786.55
8/13/95	1786.7	1786.38
8/23/95	1786.91	1787.08
9/2/95	1787.1	1786.97
9/12/95	1787.24	1787.32
9/22/95	1787.28	1787.31
10/2/95	1787.24	1787.18
10/12/95	1787.18	1787.35

1/7/01	1786.9	1786.12
3/2/01	1786.6	1785.44
4/22/01	1786.06	1785.72
7/1/01	1785.64	1785.47
7/22/01	1785.73	1785.45
9/9/01	1787.34	1786.06
10/14/01	1787.28	1786.49
11/15/01	1787	1786.83
12/23/01	1786.7	1785.43
1/27/02	1786.34	1786.19
3/3/02	1786	1785.05
5/12/02	1785.33	1785.56
6/16/02	1785.04	1784.37
7/21/02	1785.26	1784.43
8/25/02	1786.06	1785.50
9/29/02	1786.42	1785.51
12/8/02	1785.88	1784.83
1/12/03	1785.58	1784.74

10/22/95	1787.12	1787.16
11/1/95	1787.04	1786.93
11/11/95	1786.97	1787.01
11/21/95	1786.89	1786.87
12/10/95	1786.76	1786.69
12/20/95	1786.7	1786.57
12/30/95	1786.67	1786.8
1/9/96	1786.61	1786.77
1/19/96	1786.58	1786.52
1/29/96	1786.52	1786.58
2/8/96	1786.46	1786.35
2/28/96	1786.33	1785.73
3/9/96	1786.35	1786.32
3/19/96	1786.36	1786.35
3/28/96	1786.36	1786.22
4/7/96	1786.15	1786.01
4/17/96	1786.08	1786.2
4/27/96	1786.06	1786.04
5/7/96	1786.06	1786.01
5/17/96	1785.98	1786.02
5/27/96	1785.98	1786.07
6/6/96	1786	1786.06
6/16/96	1786.14	1786.29
6/26/96	1786.22	1786.29
7/6/96	1786.04	1786.31
7/15/96	1786.54	1786.59
7/25/96	1786.74	1786.75
8/4/96	1787.08	1787.22
8/14/96	1787.38	1787.3
8/24/96	1787.63	1787.51
9/3/96	1787.84	1787.72
9/13/96	1787.96	1787.96
9/23/96	1787.9	1787.89
10/3/96	1787.88	1787.72
10/13/96	1787.75	1787.81
10/23/96	1787.63	1787.58
11/2/96	1787.5	1787.58
11/11/96	1787.39	1787.48
11/21/96	1787.35	1787.33
12/1/96	1787.26	1786.8
12/11/96	1787.21	1787.08
12/21/96	1787.1	1787.24
12/31/96	1787.02	1787.08
1/10/97	1786.94	1787.1
1/20/97	1786.86	1787.06
1/30/97	1786.8	1786.93
2/9/97	1786.76	1786.84
2/19/97	1786.65	1786.7
3/1/97	1786.56	1786.66
3/10/97	1786.5	1786.59
3/20/97	1786.42	1786.58
3/30/97	1786.36	1786.45
4/9/97	1786.26	1786.25

4/19/97	1786.18	1786.13
4/29/97	1786.08	1786.07
5/9/97	1786.06	1786.02
5/19/97	1786	1786.02
5/29/97	1785.98	1786.16
6/18/97	1786.04	1786.02
6/28/97	1786.12	1786.13
7/7/97	1786.16	1786.06
7/17/97	1786.41	1786.5
7/27/97	1786.44	1786.44
8/16/97	1786.94	1786.98
8/26/97	1787.18	1787.17
9/5/97	1787.23	1787.31
9/15/97	1787.28	1786.93
9/25/97	1787.34	1787.39
10/5/97	1787.28	1787.29
10/15/97	1787.24	1787.15
10/25/97	1787.33	1787.01
11/3/97	1787.35	1787.48
11/13/97	1787.33	1787.31
11/23/97	1787.3	1787.3
12/3/97	1787.16	1787.18
12/13/97	1787.12	1787.29
12/23/97	1787.02	1787.09
1/2/98	1786.98	1787
1/12/98	1786.85	1786.81
1/22/98	1786.77	1786.71
2/1/98	1786.76	1786.81
2/11/98	1786.58	1786.62
2/21/98	1786.61	1786.58
3/2/98	1786.53	1786.53
3/12/98	1786.46	1786.48
3/22/98	1786.4	1786.44
4/1/98	1786.38	1786.1
4/11/98	1786.3	1786.38
5/1/98	1786.2	1786.09
5/11/98	1786.14	1785.96
5/21/98	1786.14	1786.22
5/31/98	1786.08	1786.13
6/10/98	1786.02	1785.77
6/19/98	1786.12	1786.21
6/29/98	1786.1	1786.16
7/9/98	1786.21	1786.31
7/19/98	1786.37	1786.66
8/8/98	1786.98	1787.1
8/28/98	1787.59	1787.71
9/7/98	1788	1787.95
9/17/98	1787.97	1788.02
9/27/98	1787.96	1787.86
10/7/98	1787.86	1787.84
10/26/98	1787.74	1787.49
11/5/98	1787.62	1787.51
11/15/98	1787.52	1787.59

11/25/98	1787.36	1787.32
12/5/98	1787.28	1787.34
12/15/98	1787.14	1787.19
12/25/98	1787.02	1787.17
1/14/99	1786.94	1786.96
2/3/99	1786.8	1787.01
2/12/99	1786.75	1786.72
2/22/99	1786.6	1786.79
3/4/99	1786.54	1786.45
3/14/99	1786.44	1786.39
3/24/99	1786.32	1786.41
4/3/99	1786.31	1786.12
4/13/99	1786.25	1786.32
4/23/99	1786.12	1786.4
5/3/99	1786.1	1786.21
5/13/99	1786.06	1786.25
5/23/99	1786.02	1786.17
6/2/99	1785.92	1786
6/11/99	1785.89	1785.98
6/21/99	1785.9	1786.01
7/1/99	1786	1786.12
7/11/99	1786.08	1786.24
7/21/99	1786.18	1786.28
7/31/99	1786.57	1786.72
8/10/99	1786.92	1786.88
8/20/99	1787.16	1787.25
9/9/99	1787.62	1787.53
9/19/99	1787.67	1787.7
9/29/99	1787.65	1787.62
10/8/99	1787.62	1787.45
10/18/99	1787.77	1787.85
10/28/99	1787.76	1787.88
11/7/99	1787.76	1787.38
11/17/99	1787.54	1787.63
11/27/99	1787.4	1787.43
12/17/99	1787.22	1787.33
12/27/99	1787.13	1787.01
1/6/00	1787.06	1787.03
1/16/00	1786.98	1787.13
1/26/00	1786.9	1787.06
2/4/00	1786.84	1786.82
2/14/00	1786.73	1786.56
2/24/00	1786.68	1786.65
3/5/00	1786.62	1786.48
3/15/00	1786.55	1786.56
3/25/00	1786.52	1786.43
4/14/00	1786.36	1786.27
4/24/00	1786.28	1786.6
5/4/00	1786.26	1786.39
5/14/00	1786.26	1786.4
5/24/00	1786.2	1786.28
6/2/00	1786.15	1786.28
6/12/00	1786.1	1786.33

6/22/00	1786.2	1786.3
7/2/00	1786.36	1786.46
7/12/00	1786.46	1786.55
7/22/00	1786.52	1786.59
8/1/00	1786.86	1786.87
8/11/00	1787.03	1787.07
8/21/00	1787.47	1787.25
8/31/00	1787.64	1787.5
9/10/00	1787.72	1787.66
9/20/00	1787.72	1787.72
9/30/00	1787.7	1787.64
10/10/00	1787.72	1787.66
10/19/00	1787.73	1787.63
11/8/00	1787.58	1787.52
11/18/00	1787.56	1787.37
11/28/00	1787.41	1787.5
12/18/00	1787.23	1787.15
12/28/00	1787.14	1787.07
1/7/01	1787.1	1786.97
1/26/01	1787	1786.97
2/5/01	1786.94	1787
2/15/01	1786.92	1786.96
2/25/01	1786.83	1786.75
3/7/01	1786.72	1786.75
3/17/01	1786.6	1786.58
3/27/01	1786.46	1786.49
4/6/01	1786.39	1786.25
4/16/01	1786.3	1785.39
4/26/01	1786.22	1785.95
5/6/01	1786.04	1786.06
5/15/01	1785.98	1786.03
5/25/01	1785.93	1785.98
6/4/01	1785.9	1785.98
6/14/01	1785.91	1785.81
6/24/01	1785.8	1785.81
7/4/01	1785.91	1786.13
7/14/01	1785.92	1786.19
7/24/01	1786.06	1786.3
8/3/01	1786.52	1786.69
8/13/01	1787	1787.05
8/23/01	1787.26	1787.33
9/2/01	1787.44	1786.96
9/11/01	1787.59	1787.61
9/21/01	1787.7	1787.71
10/1/01	1787.5	1787.51
10/11/01	1787.46	1787.37
10/21/01	1787.43	1787.3
10/31/01	1787.32	1787.43
11/10/01	1787.24	1787.1
11/20/01	1787.16	1787.23
11/30/01	1787.06	1786.89
12/10/01	1787	1786.91
12/20/01	1786.91	1786.84

12/30/01	1786.84	1786.97
1/8/02	1786.68	1786.75
1/18/02	1786.64	1786.71
1/28/02	1786.51	1786.65
2/7/02	1786.41	1786.52
2/17/02	1786.32	1786.47
2/27/02	1786.22	1786.21
3/9/02	1786.15	1786.14
3/19/02	1785.98	1786.07
3/29/02	1785.98	1785.92
4/8/02	1785.87	1786.01
4/18/02	1785.76	1785.79
4/28/02	1785.66	1785.75
5/17/02	1785.46	1785.64
5/27/02	1785.4	1785.31
6/6/02	1785.31	1785.25
6/16/02	1785.24	1785.25
6/26/02	1785.3	1785.46
7/26/02	1785.62	1785.85
8/5/02	1785.88	1785.89
1/28/02	1786.51	1786.69
2/7/02	1786.41	1786.56
2/17/02	1786.32	1786.46
2/27/02	1786.22	1786.42
3/9/02	1786.15	1786.19
3/19/02	1785.98	1786.19
3/29/02	1785.98	1785.55
4/8/02	1785.87	1786.02
4/18/02	1785.76	1785.91
4/28/02	1785.66	1785.77
5/7/02	1785.7	1785.59
5/17/02	1785.46	1785.48
5/27/02	1785.4	1785.46
6/6/02	1785.31	1785.3
6/16/02	1785.24	1785.19
6/26/02	1785.3	1785.33
7/6/02	1785.37	1785.46
7/16/02	1785.44	1785.59
7/26/02	1785.62	1785.72
8/5/02	1785.88	1785.86
8/15/02	1786.12	1786.17
8/25/02	1786.26	1786.06
9/3/02	1786.41	1786.58
9/13/02	1786.58	1786.55
9/23/02	1786.62	1786.53
10/3/02	1786.61	1786.65
10/13/02	1786.53	1786.62
10/23/02	1786.41	1786.56
11/2/02	1786.4	1786.45
11/12/02	1786.3	1786.47
11/22/02	1786.21	1786.29
12/2/02	1786.12	1786.28
12/12/02	1786.06	1786.12

12/21/02	1785.98	1785.27
12/31/03	1785.92	1786.01
1/20/03	1785.74	1785.89
1/30/03	1785.64	1785.79
2/9/03	1785.56	1785.68
2/19/03	1785.51	1785.75
3/1/03	1785.43	1785.65
3/11/03	1785.36	1785.62
3/21/03	1785.24	1785.39
3/31/03	1785.14	1785.31
4/10/03	1785.06	1785.3
4/19/03	1785	1785.11
4/29/03	1784.91	1785
5/9/03	1784.8	1784.91
5/19/03	1784.72	1784.85
6/8/03	1784.64	1784.7
6/18/03	1784.64	1784.69
6/28/03	1784.65	1784.64
7/8/03	1784.82	1784.86
7/18/03	1785.06	1785.25
7/28/03	1785.27	1785.25
8/16/03	1785.78	1785.92
9/5/03	1786.39	1786.54
9/15/03	1786.68	1786.77
9/25/03	1786.75	1786.85
10/5/03	1786.88	1786.92
10/15/03	1786.88	1786.94
10/25/03	1786.85	1786.92
11/14/03	1786.68	1786.81
12/4/03	1786.57	1786.61
12/13/03	1786.47	1786.62
1/2/04	1786.32	1786.4
1/12/04	1786.24	1786.34
2/1/04	1786.12	1786.27
2/11/04	1786.01	1786.17
2/21/04	1785.96	1786.16
3/2/04	1785.84	1785.98
3/12/04	1785.77	1785.92
3/22/04	1785.72	1785.82
4/1/04	1785.59	1785.74
4/10/04	1785.54	1785.71
4/20/04	1785.43	1785.56
4/30/04	1785.42	1785.5
5/10/04	1785.32	1785.43
5/20/04	1785.26	1785.37
5/30/04	1785.12	1785.17
6/9/04	1785.09	1785.18
6/19/04	1785.04	1785.41
7/9/04	1785.32	1785.34
7/19/04	1785.56	1785.58
7/29/04	1785.72	1785.82
8/7/04	1786	1786.05
8/17/04	1786.19	1786.36

8/27/04	1786.38	1786.54
9/6/04	1786.62	1786.66
9/16/04	1786.68	1786.72
10/6/04	1786.76	1786.81
10/16/04	1786.84	1786.71
10/26/04	1786.78	1786.9
11/5/04	1786.76	1786.86
11/15/04	1786.68	1786.81
12/4/04	1786.59	1786.69
12/14/04	1786.52	1786.61
12/24/04	1786.46	1786.58
1/13/05	1786.34	1786.52
1/23/05	1786.29	1786.37
2/2/05	1786.22	1786.41
2/22/05	1786.08	1786.23
3/14/05	1785.82	1786.12
3/24/05	1785.88	1786.05
4/22/05	1785.6	1785.97
5/12/05	1785.46	1785.68
5/22/05	1785.32	1785.33
6/1/05	1785.3	1785.4
6/21/05	1785.22	1785.01
7/1/05	1785.25	1785.45
7/11/05	1785.46	1785.47
7/20/05	1785.55	1785.71
7/30/05	1785.76	1785.86
8/9/05	1786.01	1786
8/19/05	1786.12	1786.2
8/29/05	1786.28	1786.41
9/8/05	1786.47	1786.5
9/28/05	1786.68	1786.7
10/8/05	1786.8	1786.76