Absolute Sea Level Rise Estimation at Alexandria Using Tide Records and GPS Observations

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Abstract

Globally, research studies revealed that the sea level is rising in the last decade, with different rates for different regions of the Earth. Nationally, the issue of re-defining the Egyptian vertical geodetic datum and the existing problem of sea level rising has attained a great attention in the geodetic community.

In 2001, the Survey Research Institute (SRI) of the National Water Research Center (NWRC) has installed a stat-of-the-art sea level observing system at Alexandria. The new installed system consists of three devices integrated together in a unified scheme: a tide gauge, a meteorological unit, and a satellite-based GPS geodetic receiver.

Analyzing the GPS continuous time series and estimating the rate of ground deformation at the tide gauge station's site is an important issue to obtain absolute rate of MSL rise. Hence, this research concentrates on estimating the absolute rate of MSL rise at Alexandria tide gauge station using continuous tide and GPS observations.

1- Introduction

Recent geodetic and oceanographic MSL studies have shown that neither the sea levels nor the land are permanent with respect to time variations. The data analysis of tide gauges produces 'relative' sea level changes. However, using tide gauge data alone, it is impossible to distinguish between any true sea level variation and any changes in ground level at a tide gauge site. GPS monitoring can be used to decouple vertical land movements from change in relative MSL, so that tide gauge can provide estimates of changes in absolute MSL. For the purpose of monitoring and understanding long term variations in sea level, the contribution of land motion should be precisely determined. That means that in order to monitor "absolute" changes in sea level, the rates of any vertical land movements at a tide gauge must be determined and subtracted from the resulting rate of tide records [e.g. IPCC, 2001 and Bingley et al, 2000]. Consequently, a sea level monitoring system has been installed at Alexandria tide gauge site containing a GPS receiver as a geodetic monitoring technique to perform this task.

2- The Followed Methodology for Investigating the Problem

Teferle [2000] and Bingley et al [2001] provide a processing approach for GPS data processing and analysis for similar situations. The computational procedures consist of the following steps:

▪ Obtaining GPS raw data of some stations of the International Geodynamic Service (IGS) global high-precision GPS network.

- Processing the dual-frequency GPS data of the TG GPS station with the IGS stations on a 24-hour basis to produce ionospherically-free double difference observables with integer ambiguities not fixed.
- The tropospheric delays are mitigated by using Saastamoinen model.
- Constraining the IGS stations to their precise coordinates relative to the most recent International Terrestrial Reference Frame (ITRF) definition.
- The obtained height time series of the TG GPS station is firstly fitted to a linear regression model in a least squares sense.
- From this regression model, an estimate of the linear velocity is obtained.
- The daily height estimates are differenced from the linear velocity estimates to obtain a residual time series.
- A de-trended height time series is then obtained by computing the weighted root mean square (WRMS) of the height residuals weighted by the standard errors of the daily height estimates.
- Then, any height residual that is found to be greater than three times the WRMS is defined as an outlier and removed from the height time series.
- Another linear regression model is fitted to the clean height time series in order to obtain a revised linear velocity estimate of the TG GPS station height.

This processing approach has been utilized in the current research study to estimate a preliminary land movement measure of the Alexandria Tide Gauge station.

3- The Data Used and Their Processing and Implementation

A new Sea Level Observing System (SLOS) installed at the Tide Gauge station in Alexandria consists of three devices integrated together in a unified scheme: a tide gauge, a meteorological unit, and a satellite-based GPS geodetic receiver, Figure 1. The three components will be presented in details in the following sub-sections.
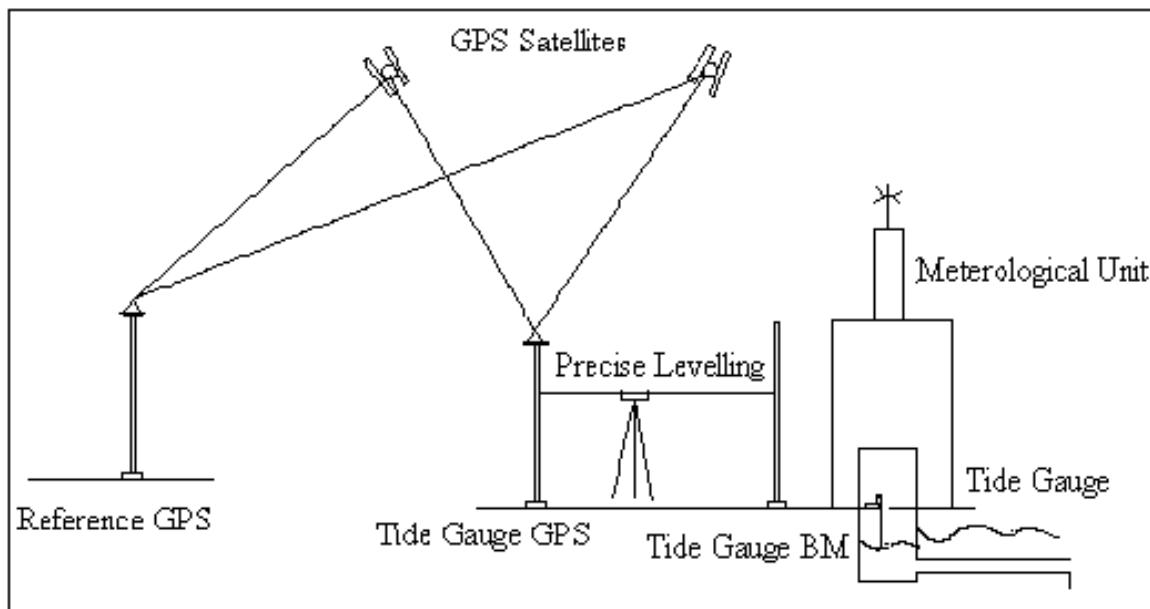
Figure 1: Modern Sea-Level Observing System

3-1- Utilized Tide Gauge Instrument

The utilized tide gauge is a high-accuracy temperature-compensated self-contained instrument for measuring and recording tide and wave data. The employed technology in this state-of-the-art device is based on the Silicon-On-Sapphire semi-conductor strain gauge pressure type. The instrument, which is called Wave and Tide Gauge WTG904 Series 3, measures instantaneously the water column pressure, and converts it to height of water with respect to a specific user-defined location. The pressure sensor output is digitized at a 2 Hz sampling rate via a 14-bit A/D converter controlled by a 32-bit CMOS microprocessor. The tide is calculated continuously and recorded automatically every 10 minutes. The measuring depth range of the gauge is from 0 to 35 meters, with a precision of ± 0.15 % of the measuring range, and a resolution of 0.006 % of the measuring range. Knowing that the depth of the water in the steeling well in Alexandria is approximately 1.5 meter, it can be expected that the accuracy of the measurements is 0.2 cm. The apparatus has a built-in battery-backed 64KB RAM memory that can record measurements up to 90 days. A communication interface (RS485 or RS232C) is used to download the recorded data to an attached computer. There are two ASCII output files, for both tide and wave recorded data, which could be used for further analysis and plotting procedures. The device works in operating temperature from -5 ^{o}C to 35 ^{o}C. The equipment uses internal alkaline batteries that can provide the required power up to 90 days in normal conditions [InterOcean, 1999].

The WTG904 Series 3 instrument measures instantaneously the water column pressure, and converts it to height of water with respect to a specific user-defined location. The instrument has been installed and calibrated so that its zero coincides with the zero of the staff rod fixed inside the tide well. Hence, its recorded readings represent the water level above the Egyptian vertical datum of 1906.

3-2- Utilized Meteorological Device

The utilized device, WMS-14 from Omega Inc., is a state-of-the-art microprocessor-based weather station. The Model WMS-14 features a combination wind vane and three-cup anemometer with 40 feet of interconnecting cable (which may be extended to 300 feet), a temperature and relative humidity sensor with sun shield, a solid state barometric pressure sensor, and, a self-emptying rain gauge. Hence, measurements of wind speed, wind direction, temperature, humidity, and precipitation are collected and processed by the control module of the station. Build-in memory can store measured data up to 32 days for later retrieval. The time interval between recordings is user-defined ranging from one to sixty minutes. The device is powered by an external 12V source from a standard 220V outlet. A 12V battery can be plugged into the auxiliary power jack to provide emergency backup power in the event of a loss of main power. A fully charged battery will run the device for five days.

The WMS-14 instrument has five accurate and reliable sensors for collecting different types of meteorological data. A wind speed sensor combines a three-cup anemometer and a wind vane on a single axis. This sensor measures, computes, and stores wind speed and wind direction. Barometric pressure is sensed using a piezoresistive sensing element, which responds to changes in pressure with a corresponding change in resistance. The resistance is converted to a voltage form, which the microprocessor calculates the pressure at the elevation at which the barometer is located. Temperature is sensed using a thermistor element whose resistance changes in response to temperature fluctuations. Relative humidity is sensed by

changes in capacitance of a thin polymer film as it absorbs moisture, or sheds it to, the surrounding air. The rain gauge used with the WMS-14 is a traditional tipping bucket design. The accuracy measures of the five sensors are [Omega, 1999]:

For barometric pressure:	± 5 mb
For Wind Speed:	± 3 mph
For Wind Direction: $\pm 2^o$	
For Rain precipitation:	± 1 %
For Temperature:	$\pm 2^o$ F
For Relative Humidity:	$\pm 3\%$

The detailed processing of the above mentioned tide and meteorological data is done in [Faisel, H., 2005] , and the reliable estimate of the relative sea rise rate has been computed as 1.7 mm/year. For more details refer to Faisel, H., [2005]

3-3- GPS Data at the Tide Gauge Station

Lieca GPS system 500 comprises GPS receiver, terminal and post-processing software are used. The SR520 dual-frequency GPS receiver has 12 L1 and 12 L2 continuous data tracking channels that track both codes and carrier phases of the transmitted satellite signals. It tracks up to 12 simultaneously satellites. The collected data is stored on a standard PCMCIA cards that has storage capacity up to 85MB (i.e., up to three months of measurements). An alphanumeric TR500 terminal is connected to the receiver, either via a connection cable or directly to a certain port, in order to configure and control the receiver options. A high-precision AT504 choke-ring type antenna is utilized in the GPS project configuration. The normal accuracy of the obtained baseline length, in a static mode, is 5 mm ± 1 ppm (part per million) [Lieca 1999]. In other words, this means that for a baseline of 10 km, the expected mean square error is 15 mm. It worth mentioning that this accuracy limits could be improved using several items, e.g. using precise satellite orbits instead of the normal ones broadcasted in real-time from the GPS satellites.

The available 24-hour data sets of the GPS receiver located at Alexandria, depicted in Table 1, consist of almost-continuous 477 days of raw data from November 2000 to July 2002. The existed few gaps in the time series are due to some minor operating problems in the installed GPS receiver.

Table 1: Available GPS observations at the installed Tide Gauge station

Year	Month											
	1	2	3	4	5	6	7	8	9	10	11	12
2000												
2001												
2002												

3-4- IGS GPS Data

Consequently, raw 24-hour data of three IGS stations have been downloaded in the Rinex format. Those stations, as depicted in Figure 2, named DRAG, RAMO, and NICO, have been selected to be the most nearest IGS stations to Alexandria in order to minimize the baseline lengths as possible. It is a matter of fact that most error sources in GPS networks, especially the tropospheric and ionospheric delays, are baseline dependant errors [e.g. Sorour, 2004].
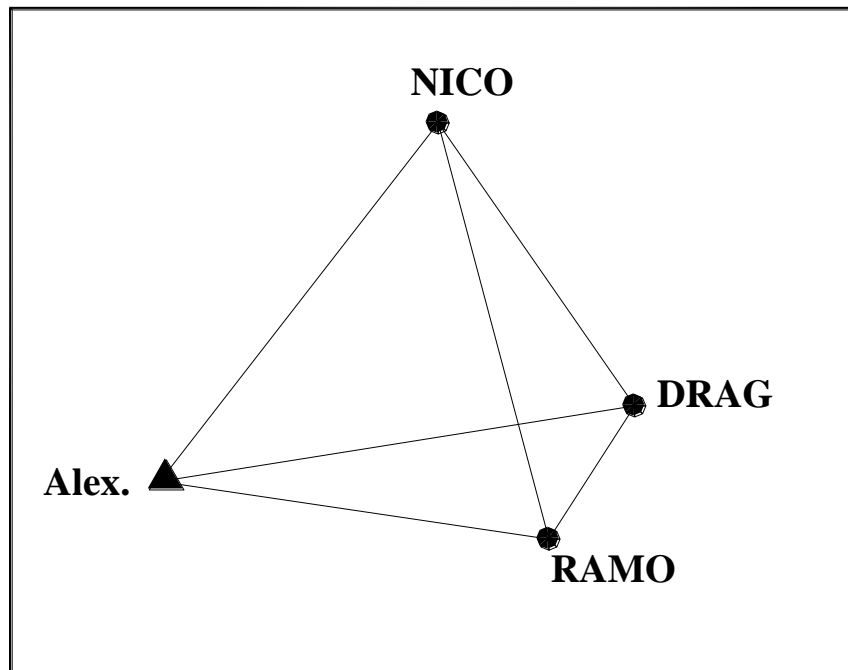
Figure 2: Utilized IGS global GPS stations

3-5- ITRF and its Role

The ITRF is realized through the global Cartesian coordinates and linear velocities of a global set of sites equipped with various space geodetic observing systems, and it is maintained by participating agencies. It is assembled by combining sets of results from independent techniques as analyzed by a number of separate groups organized under the International Earth Rotation Service (IERS) and cooperating services. The space geodetic techniques used at present are lunar and satellite laser ranging (LLR, SLR), VLBI, GPS, and Doppler Orbit determination and Radio positioning Integrated on Satellites (DORIS). In addition to these observations, the frame also depends on the surveyed tie vectors that relate collocated systems at a subset of the ITRF sites. Unlike some of the older terrestrial reference frames, the ITRF allows for the relative motions of sites on the Earth's surface, due to plate tectonics as well as other local effects. These observations of contemporary motions can be compared to plate motion models, which are based on geological data spanning the past 3 million years. Outside of plate boundary deformation zones, the rates generally agree very well.

The first ITRF realization was prepared shortly after the founding of IERS in 1988. In the past decade, a new ITRF has been prepared approximately every 2 years. In March of 2001, ITRF2000 was released. ITRF2000 is the most extensive and accurate terrestrial reference frame ever developed and includes positions and velocities for about 800 stations located at

about 500 sites. Based on the internal consistency of the independent solutions included in ITRF2000, the global frame scale and origin stability over 10 years is estimated to be accurate in scale to better than 0.5 parts per billion [Altaminim, 2003, and Boucher et al, 2004]. Therefore, the ITRF2000 coordinates (X, Y, Z) and velocities (R_X, R_Y, R_Z) at epoch 1997.0 of the utilized three utilized IGS stations have been obtained [http://large.ensg.ign.fr/ITRF/ITRF2000]. Those figures are shown in Table 2 and Table 3.

Table 2: Coordinates of utilized ITRF2000 stations (m)

Station	X $\pm$ σX	Y $\pm$ σY	Z $\pm$ σZ
NICO	4359415.849 ±0.004	2874116.974 ±0.003	3650777.712 ±0.003
RAMO	4514722.017 ±0.008	3133507.725 ±0.006	3228024.574 ±0.006
DRAG	4432980.874 ±0.128	3149431.992 ±0.110	3322110.339 ±0.099

Table 3: Rate of velocities of utilized ITRF2000 stations (m)

Station	RX $\pm$ σRX	RY $\pm$ σRY	RZ $\pm$ σRZ
NICO	-0.1350 $\pm$ 0.0017	0.0139 $\pm$ 0.0012	0.0138 $\pm$ 0.0014
RAMO	-0.0179 $\pm$ 0.0032	0.0161 $\pm$ 0.0024	0.0148 $\pm$ 0.0023
DRAG	-0.0369 $\pm$ 0.0354	0.0104 $\pm$ 0.0305	0.0074 $\pm$ 0.0275

3-6- GPS Data Processing

It is a fact that processing GPS long baselines is affected by three main sources of errors, namely the orbital errors, tropospheric errors, and ionospheric errors. Hence, a processing strategy has been developed to account for each type of errors in order to come up with the most reliable coordinates of the GPS tide gauge station. This methodology consists of the following criteria:

(a) The daily final IGS precise orbit (SP3 format) is obtained, e.g. from ftp://igscb.jpl.nasa.gov/pub/product/, which is available at 12 days latency. This orbit is computed based on the analysis of all available IGS network stations, hence it estimates and gets ride of orbital errors of GPS satellites.

(b) The daily ionospheric estimated file is obtained from one of the IGS processing data processing centers, e.g. the CODE center of Bern University (ftp://aiub.unibe.ch). Such a daily solution estimates the ionospheric effects covering the area from latitude -88.32^o to latitude 87.46^o through the analysis of data collected from 139 global IGS stations. Thus, incorporating these ionospheric models in the processing stage for each GPS day enables the generating of iono-free double difference solutions for almost all processed GPS baselines.

(c) For the tropospheric errors, apply the Saastamoinen tropospheric model with a 1-hour interval for the estimation of the zenith delay. This global model, with such computation interval, produces accurate estimate of the long baselines components [Rabah, 2004].

(d) Since the installed GPS at the tide gauge station at Alexandria is surrounded with many obstructions especially the communication radio towers, it is preferable to increase the cut-of angle to 25°. Even though this criterion reduces the number of the processed GPS data, it gets ride of near-ground multipath reflected signals. In the case in hand, the data processed for each event contain 24-hour continuous series, which produce a high degree of freedom even with such cut-of angle. Saad and Al-Tokhy [2001] have concluded that up to 30° musk angle is suitable in most geodetic and surveying works.

(e) Since the ITRF2000 coordinates of the utilized IGS stations are referenced to epoch 1997.0, a fundamental step was to compute the corresponding coordinates for each station at each processed day of the available time series. That step has been performed utilizing the next formulas [Boucher et al, 2004]:

$$X (t) = X_o + R_X * (t - 1997)$$
$$Y (t) = Y_0 + R_Y * (t - 1997)$$
$$Z (t) = Z_0 + R_Z * (t - 1997)$$

where,

t	is the date, in years, of the processing day
X_o, Y_o, Z_o	are the given ITRF2000 coordinates at epoch 1997.0

4- The Obtained Results

Hence, the computed coordinates of the IGS stations are used as fixed values in order to estimate the corresponding coordinates of the GPS station at the tide gauge.

This strategy has been applied for each day of the available 477-day GPS data set. Therefore, a time series of the Alexandria tide gauge GPS station has been attained.

The raw height time series range from 30.562 m to 30.613 m with an average of 30.575 m and a standard deviation equals 0.010 m. The previously mentioned analysis scheme

proposed by Teferle [2000] and Bingley et al [2001] has been obeyed. Fitting a linear regression to those values produces an estimate of the height velocity of -0.52 mm/year. The resulted residual values vary between -0.028 m and 0.030 m, with a mean equals zero

Then, weighted height residuals have been computed and the residuals that are found to be greater than three times the WRMS are defined as outliers and removed from the height time series. The clean set of heights range from 30.556 m to 30.602 m with an average of 30.578 m and a standard deviation equals 0.008 m. Another linear regression model is fitted to the clean height time series. This model produces a revised linear velocity estimate of the TG GPS station height that is equals -0.47 ± 0.08 mm/year. The results are tabulated in Table 4 and depicted in Figure 3 and Figure 4.
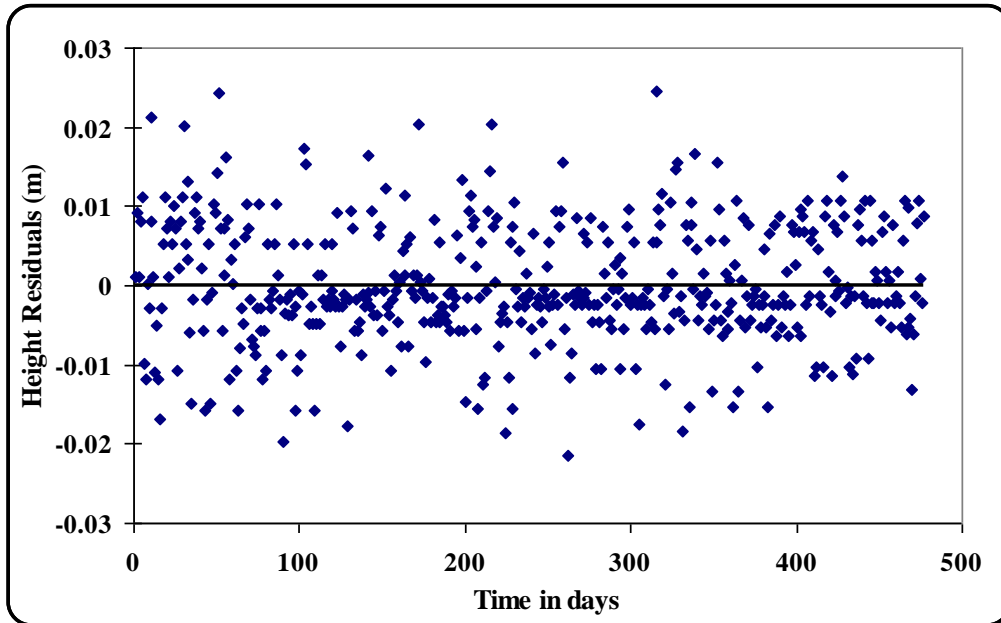
Table 4: Height and residuals time series (m)

	Minimum	Maximum	Mean
Height time series	30.556	30.602	30.578
Residuals time series	-0.022	0.025	0.000
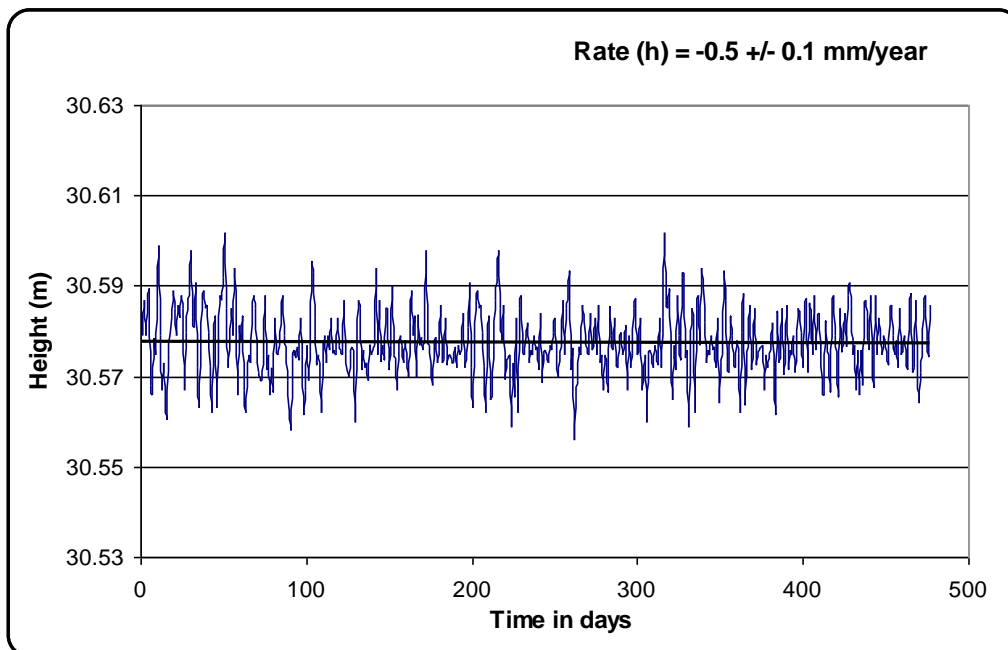
Figure 3: Revised GPS height time series and velocity estimates

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Figure 4: Residuals of revised height time series

## 5- Investigating the Horizontal Displacement

Even though the geodetic height of the GPS station in hand is the most important item in the context of this research, the horizontal coordinates of the station have been also analyzed.

The same analysis strategy has been applied to the horizontal coordinates of the GPS at the tide gauge station. The Cartesian coordinates time series and the horizontal coordinates time series (Northing and Easting) have been obtained. Figure 5 and Figure 6 show the horizontal coordinate time series and velocity estimates. The revised trends for the Northing and Easting components have been estimated as 4.2 ± 0.9 mm/year and 6.3 ± 1.1 mm/year respectively. Similar results have been reported by El-Fiky [2000], where the analysis of GPS observations collected at Helwan revealed that it moves northward, relative to the Eurasian plate, at a rate of 6 mm/year.

6- Conclusions and Recommendations

Having estimating the height trend, the absolute sea level rise rate may be determined. Refereeing to [Faisel, H., 2005], the reliable estimate of the relative sea rise rate has been computed as 1.7 mm/year. Taking out the land deformation rate at the tide gauge station, which is -0.47 mm/year, the absolute sea level rise at Alexandria becomes 2.17 mm/year.

However, because of the relatively short time span of the utilized data sets, it is recommended to continue collecting continuous GPS measurements at the Alexandria tide gauge station and performing further analysis in order to be able to estimate a precise land movement measure and, then, be capable of determining the absolute sea level rise in Egypt. Tide Gauge stations should be established at other will distributed places at the Egyptian shores. Similar investigations should be also done at those proposed stations to assure the obtained results.
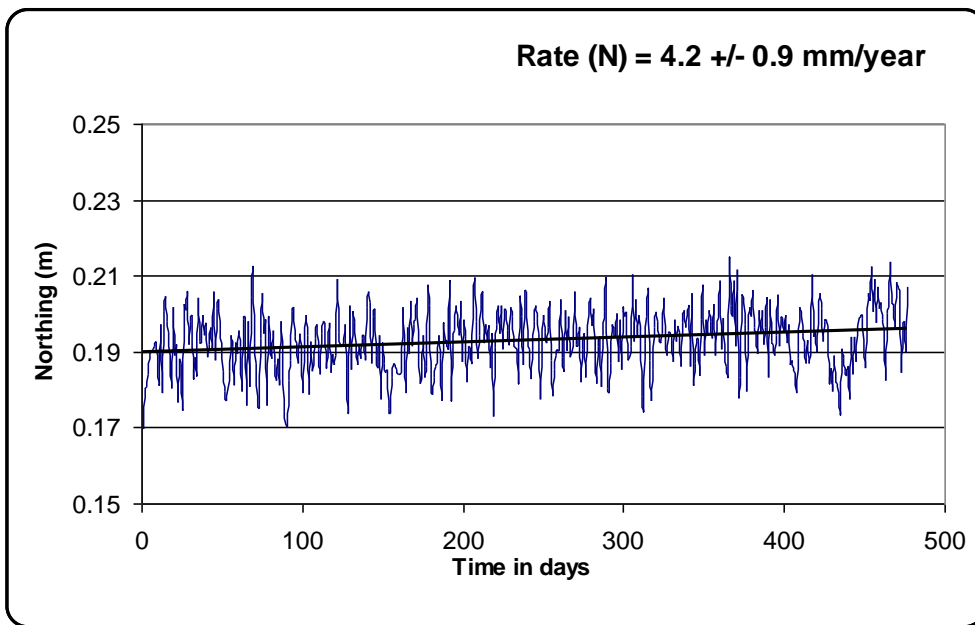
Figure 5: The horizontal coordinate time series (Northing) and velocity estimates
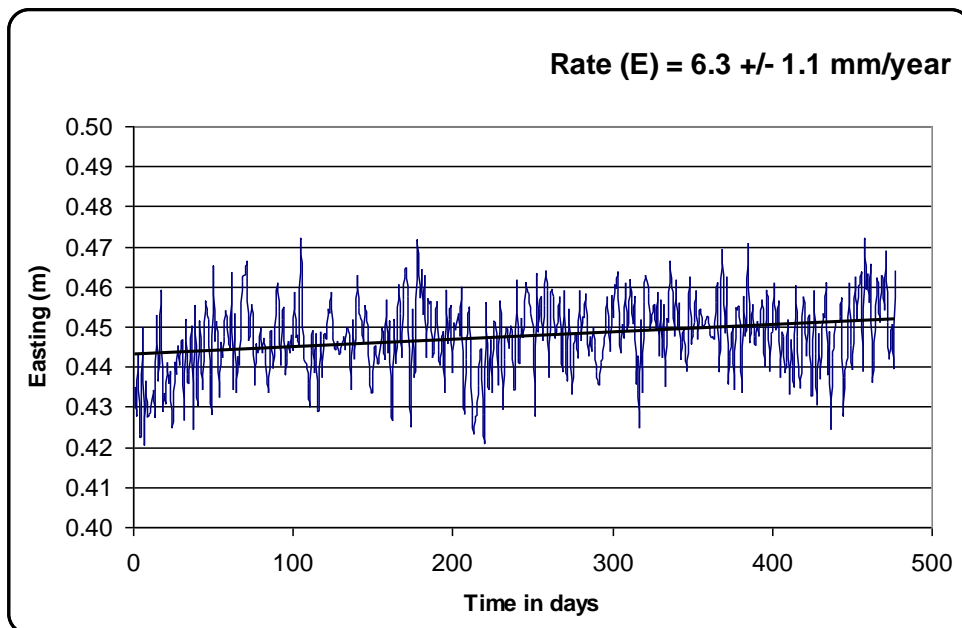
Figure 6: The horizontal coordinate time series (Easting) and velocity estimates

References

Altaminim, Z., 2003, ITRF, GPS Permanent stations and the AFREF project, Proceedings of the Second FIG Regional Conference, Morocco, December 2-5.

Bingley, R., Dodson, A., Penna, N., and Booth, S., 2000, Using a combination of continuous and episodic GPS data to separate crustal movements and sea level changes at tide gauges in the UK., Proceedings of the tenth general assembly of the WEGENER project, San Fernando, Spain, Sept. 18-20.

Bingley, R., Dodson, A., Penna, N., Teferle, N., and Baker, T., 2001, Monitoring the vertical land movement component of changes in mean sea level using GPS: Results from tide gauges in the UK, Journal of Geospatial Engineering, V. 3, No. 1, pp. 9-20.

Boucher, C., Altaminim, Z., Sillard, P., and Feissel-Vernier, M., 2004, The ITRF2000, The International Earth Rotation and Reference Systems Service (IERS), Technical Note No. 31, 289 pp.

El-Fiky, G., 2000, Crustal strains in the eastern Mediterranean and middle east as derived from GPS observations, Bull. Eartq. Res. Inst., Univ. Tokyo, Volume 75, pp.105-125.

Faisel, H., 2005, Realization and Redefinition of the Egyptian Vertical Datum Based on Recent Heterogeneous Observations., PhD thesis, Shoubra Faculty of Eng.

InterOcean Systems, Inc., 1999, User manual of model WTG904 Series 3 wave and tide gauge, Revision E., California, USA.

IPCC (Intergovernmental Panel on Climate Change), 2001, Climate change 2001: The scientific basis, UN Technical report.

Leica Inc., 1999, GPS System 500 User Manual, Heerbrugg, Switzerland.

Omega, Inc., 1999, WMS-14 Weather station Operator's Manual, Stamford, CT, USA.

Rabah, M., 2004, Personal communication.

Saad, A., and Al-Tokhy, M., 2001, Precision investigation of the GPS results based on practical observations, CERM, V. 23, No. 2, pp. 719-754.

Sorour, T., 2004, Accuracy study of GPS surveying operations involving long baselines, Ph.D. Dissertation, Ain Shams university, Cairo.

Teferle, N., 2000, Continuous GPS measurements at UK tide gauge sites, 1997-2000, Proceedings of the 13th International Technical Meeting of the Satellite Division of the Institute of Navigation ION-GPS 2000, Utah, USA, September 19-22.

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