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A Study of Estimation of Sea Level Variations using GNSS Technology and GPS Observations

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Abstract—*Anthropogenic sources added a large number of green house gases in the atmosphere which have changed the thermal structure of the atmosphere and hence the climate resulting global warming. Sea level rise due to global warming cause long term loses. Also mankind is intimately connected to oceans, which form 80% of the surface of the Earth. Tides affect the lives of large population living near the coasts all around the globe. Tides sometimes cause devastation resulting in loss of lives and property. In order to minimize the effect of disasters caused by oceanic tides and global warming, Coastal maps, GPS survey and GIS are important tools to effectively manage and mitigate disaster along coasts. This paper critically review some study undertaken to estimate sea level rise using tide records and GPS observations in India and in Egypt using GNSS technology. It has been observed that the absolute estimation of sea level variation needs accurate determination of any vertical land movements at tide gauge.*

Keywords*: Ocean, Tides, Global warming, GPS. GNSS.*

1. INTRODUCTION

The Earth's climate is continuously changing. For more than a hundred years, scientists have been suggesting that slight changes in chemical composition of the atmosphere could bring about major climatic variations. The possibility of global warming due to increasing concentration of greenhouse gases is now well established. General Circulation Model (GCM) simulation of climate change expected from increase of green house gases that have occurred since the industrial revolution began, predicted a steady state global average surface temperature increase of about 4^{o}C or a heating of 2 Wm^{-2} by decreasing infrared radiation emitted to space [1,2,3]. An important consequence of this is that glaciers and ice sheets are shrinking and global mean sea level is rising. Thus measurements of sea level are crucial for increasing our understanding of the processes that cause sea-level change. Sea levels have been measured for many hundreds of years. Early measurements consisted mainly of the heights and times of tide only [4,5]. However, only after the first automatic tide gauge was developed, it became possible to record the full tidal curve. This innovation led to important developments in studies of tides, storm surges and mean or extreme sea levels [6]. A revolution in sea-level measurements occur when satellite altimetry was introduced. The project starting in 1992 with the launch of the TOPEX/Poseidon radar altimeter satellite and this enabled to increase the spatial resolution and coverage of sea-level measurements. In 2002, the Gravity Recovery and Climate Experiment (GRACE) satellite and, complementary to GRACE, the Gravity field and steady-state Ocean Circulation Explorer (GOCE) satellite in 2009 were launched. At present-day sea-level change is determined mostly by both in situ -tide gauge as well as remote sensing measurements. Data are available for over 1750 tide gauge stations worldwide. In 1933 the Permanent Service for Mean Sea Level (PSMSL) was established and operates under the auspices of the International Council for Science (ICS). The advantage of the tide gauge measurements is that they provide relatively long time series. On the other hand, the spatial coverage of the satellite altimetry missions is much higher. Using remote sensing measurements eliminates the problem that tide gauges are mainly biased towards coastal areas in the northern hemisphere. For this reason both data are needed to complete each other. There are several studies combining the methods for shorter and longer time periods [7, 8]. It is well known, tide gauges measure the sea level relative to a benchmark. This provides the additional problem with the tide gauges - the vertical movements. Movements of the benchmarks and thus movements of tide gauges have been conventionally observed by leveling. Because leveling is not very fast or accurate method. To solve this problem GNSS technology can be used. GNSS offers better temporal coverage and continuous tracking in real time. Additionally, the benchmark stability data collection and analysis can be automated.

The aim of this paper was to present a review of recent efforts made on observing sea level variations using data from a GNSS receivers. GNSS technology was shortly described and some examples of ways how it was applied to sea-level monitoring in India and in Egypt were also discussed and analyzed. Presented results show that the GNSS based Tide Gauge system can be very useful for the determination of sea level changes and accurate Vertical land movements at a tide gauge.

2. GLOBAL NAVIGATION SATELLITE SYSTEMS (GNSS) TECHNOLOGY

Global Navigation Satellite Systems (GNSS) technology has become vital to many applications that range from city planning engineering and zoning to military applications. It has proved to be a versatile technology for estimation of sea level variations and has been widely accepted globally by governments and organizations. That is why we expect to have very soon in full operation at least three GNSS systems: the USA GPS, European Galileo, and the Russian GlONASS systems. There is a multibillion dollar investment in this field and intensive worldwide research activities. The impressive progress in wireless communications and networks has played a great role in increasing interest in GNSS and providing enabling methodologies and mechanisms. It is expected that all 4G and future generations of cellular phones will be equipped with GNSS chips. GNSS technology dominates the outdoor navigation, which provides accuracy to the range of few meters to 10 m in single point positioning technique or sub-meter to a few meter levels in differential GNSS technique (DGNSS). Different techniques have been developed recently for indoor positioning. They offer either absolute or relative positioning capabilities with acceptable precision [9]. Combining these technologies with GNSS allows to provide a more reliable and robust location solution. Most common implementation of Hybrid technology for Global System for Mobile Communication (GSM), General Packet Radio Services (GPRS) and Wide Band Code Division Multiple Access (WCDMA) is to combine A-GNSS with Cell-ID. A basic principle for the study of sea level variations using GNSS technology is illustrated in Figure 1

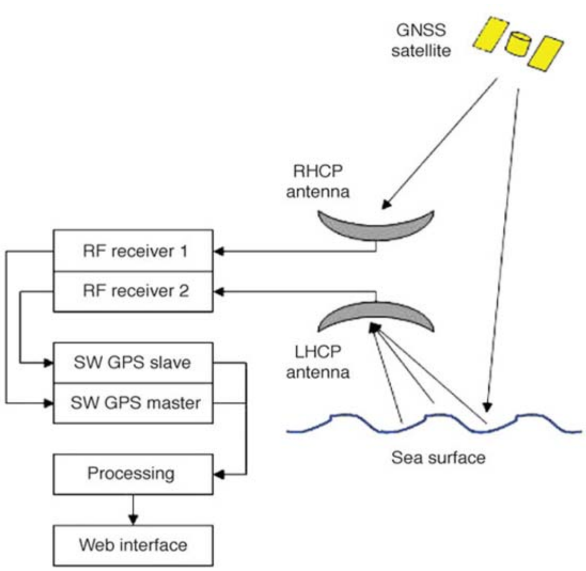

Fig. 1: Basic Principal of GNSS Technology for Studying Sea surface Variations

GNSS techniques can be used to determine the motion of the Earth's crust in relation to the center of gravity [10, 11]. By observing reflected GNSS-signals from the sea surface, information of both relative and absolute sea level change can be obtained. This formed the basis of the concept of a GNSS-based tide gauge.

3. OBSERVATION TECHNIQUES

The establishment of a long-term stable global reference frame is important for studying sea level. GNSS stations connected to the tide gauge benchmarks provide the necessary technique. The ideal tool for providing accurate and continuous measurements of land movement at tide gauge locations are GNSS Continuously Operating Reference Stations (CORS) [12]. Recent studies have shown that GNSS is able to provide vertical land motion monitoring with an accuracy of better than 1 mm/yr. So it is a perfect tool to improve the estimation of sea level rates both regionally [13] and globally [14]. Compared to traditional monitoring methods, the use of GNSS technology offers significant improvements in the measurement of land movements at tide gauges. A brief comparison of Terrestrial and GNSS CORS approaches is provided in Table 1.

Table 1: Land movement monitoring using traditional methods & GNSS CORS (based on: Janssen et al. 2013)[15]

Issue	Terrestrial Methods	GNNS CORS Techniques
Monitoring	Episodic/sporadic	Continuous
Reference Frame	Local	Global
Land Motion	Relative	Absolute
Data	Internal/Validated in-house	Shared/Validated by others
Precision	Generally Fixed	Improving with time/Algorithms
Accuracy	Survey Specific	Homogeneous across all sites
Data Archiving	Manual & Centralized	Electronic & Distributed
Labor	Intensive	Automated
Intent & Outcome	Defined/Limited	Multi-user/ Infrastructure
Alarm	n/a	Near-real time, variable thresholds

4. METHODOLOGY

The computational procedures adopted at Alexandria Tide Gauge station, Egypt [16, 17, 18] 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 iono-spherically-free double difference observables with integer ambiguities not fixed. The effect of ionosphere on GNSS measurement is of special interest in solving the ambiguity number [19]. Having multiple frequency can give more advantages from ionosphere models to estimate the first and second order effect of the ionosphere. Moreover, it allows more possibilities in ambiguity resolution process [20].

- Troposphere causes a delay in both the code and carrier observations. Since it is not frequency dependent, it cannot be canceled out by using dual frequency measurements but it can, however, be successfully modeled. Tropospheric models depend on empirical models by considering all values of temperature, pressure, relative humidity and mapping function. Examples of such models are the Hopfield and Saastamoninen models. So the tropospheric delays are mitigated by using Hopfield and 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 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 study to estimate a preliminary land movement measure.

The relevant detail of Alexanderia Tide Gauge Station is given in Figure 2

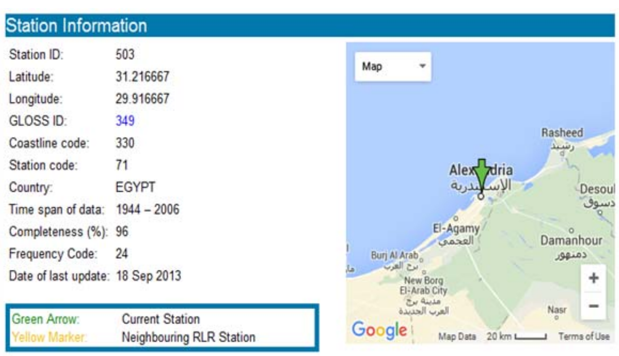

Fig. 2. The relevant detail of Alexanderia Tide Gauge Station

While in India, the methodology adopted is as follow [21]:

- The monthly tide gauge data set of the Permanent Service for Mean Sea Level (PSMSL), [22] is used in this study. Fig. 3 shows the location of seven tide gauges that are present in the PSMSL data base with more than 30 years of data and which have a GNSS station installed at the site [23, 24]. At Goa a continuous GNSS station was recently installed and the first two months of observations were processed with the GIPSY-OASIS II software [25] using the PPP method [26] to produce daily solutions that were subsequently mapped into ITRF2008[27]. This Figure also shows the location of the GNSS stations in Hyderabad and Bangalore. These two inland stations were used as a proxy of the noise properties which one expects at the coastal sites.
- It is assumed that both the secular relative sea level rise and the vertical land motion can be described by a linear trend. These trends in the tide gauge data and GNSS position time-series were estimated using the Hector software. This software uses weighted least squares to estimate the trend together with a yearly, twice yearly periodic signal.
- The covariance matrix in the estimation process is based on a noise model and the values of its parameters are estimated using the Maximum likelihood method.
- For the tide gauge data, the most reliable Generalized Gauss Markov noise model [28] was used.
- For the GNSS data, a power-law plus white noise model was used [29]. The most important feature of these two noise models is that they are able to represent the temporal correlations that are present in the data. Knowing the values of the parameters used in the noise models of the GNSS time-series, one can predict the obtainable accuracy of the estimated vertical land motion at the tide gauge locations.
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The Indian Tide Gauge Network along with National GPS and Tidal Data Centers are given in Figure 4.

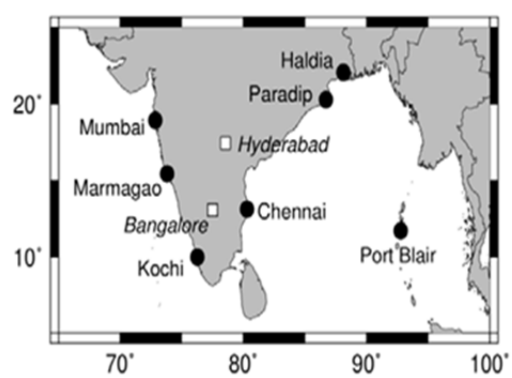

Fig. 3: The Tide Gauge stations along with GNSS station used in the present study.

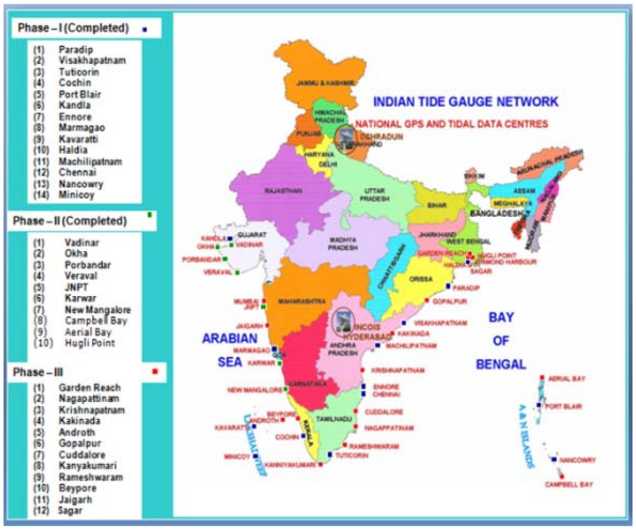

Fig. 4: The Indian Tide Gauge Network along with National GPS and Tidal Data Centers

5. OBSERVING SYSTEM USING GNSS TECHNOLOGY

A modern Sea Level Observing System (SLOS) using GNSS technology 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 is shown in Figure 5

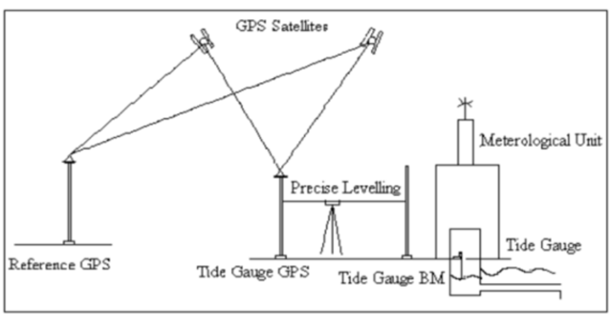

Fig. 5 Modern Sea Level Observing System using GNSS (Google Image)

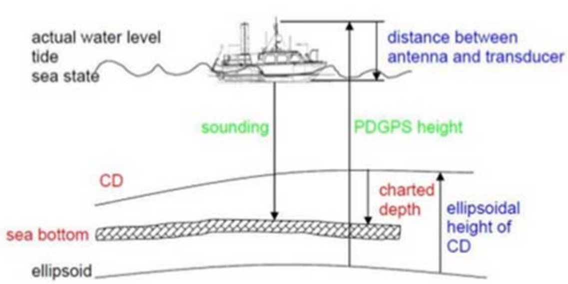

Fig. 5A Quantities to be corrected when GNSS is used for Tide correction

6. RESULTS AND DISCUSSION

The data obtained from above mentioned three units at Alexandria (Egypt) has been processed in accordance to procedure laid down in methodology to estimate the relative sea level rise rate. The detailed processing of the above mentioned tide and meteorological data is done. 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. 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. 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.

Having estimating the height trend, the reliable estimate of the relative sea rise rate has been computed as 1.7 mm/year [30]. 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. The results are presented in Figure 5 & 6 respectively.

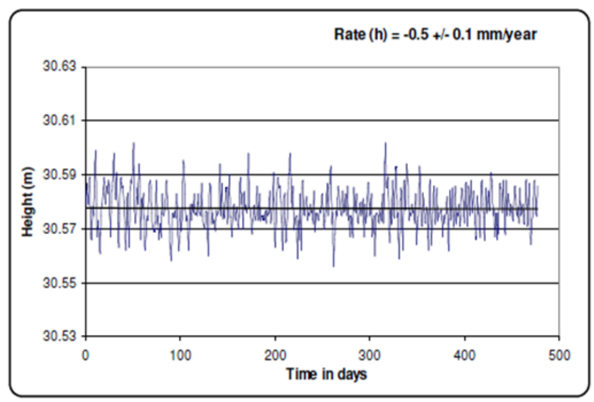

Fig. 6 Revised GPS height time series and Velocity estimates (based on Shaker et al, 2011) [31]

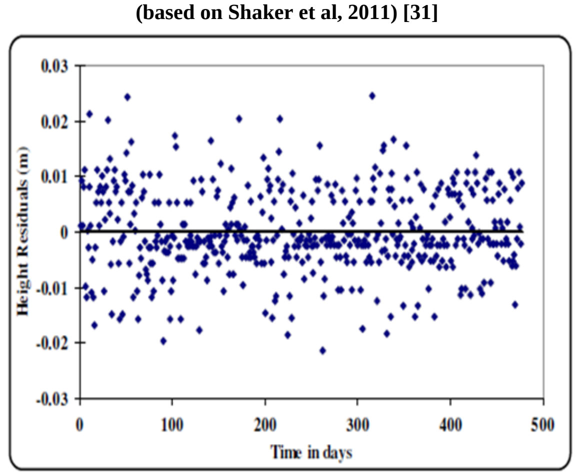

Fig. 7: Residual of revised height time series(based on: Shaker et al, 2011)

The Estimated sea level rise values with their standard deviation in mm/year in India [21, 32] are given in Table 2 and the vertical land motion observed with GNSS at Goa (India) is given in Figure 7. Also the predicted accuracy of the estimated vertical land motion using the observed noise in GNSS time Series at Hyderabad and Bangalore is shown in Figure 8

Table 2: Estimated sea level rise values with their standard deviation (based on: Unnnikrishan et al, 2007 & Bos et al 2013).

Tide Gauge Station	Unni. & Shankar result (mm/year)	Bos et al. Results (mm/year)
Mumbai	0.77±0.08	0.80±0.13
Marrnugao (Goa)		1.00±0.36
Kochi	1.31±0.23	1.60±0.35
Chennai		0.32±0.20
Paradip		1.15±0.70
Haldia		2.66±0.64
Port Blair		2.03±0.39

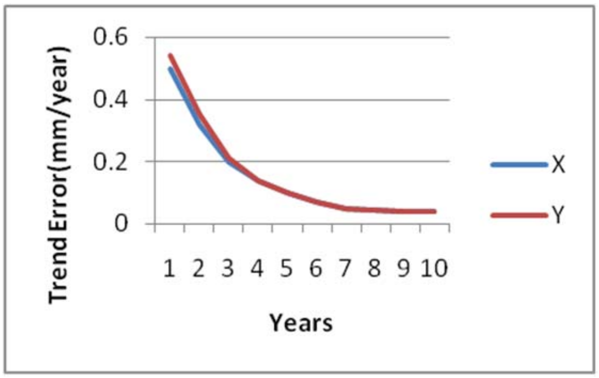

Fig. 8: The predicted accuracy of the estimated vertical land motion using the observed noise in GNSS time Series at Hyderabad(X) and Bangalore(Y).

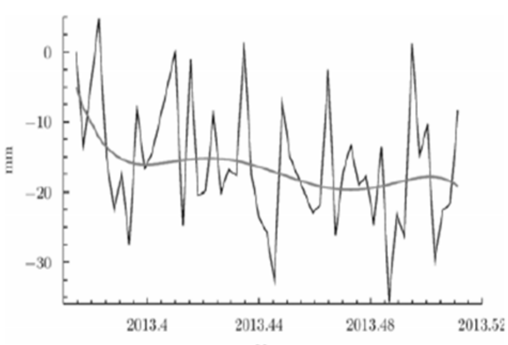

Fig. 9: The vertical Land motion observed with GNSS at Goa.

It can be seen that with 10 years of observations, the trend error at these two stations is currently around 0.05mm/year. At Mumbai continuous GNSS observations started in January 2002. Assuming similar noise properties, the error of vertical land motion is currently around 0.04 mm/year' together with the uncertainty of the estimated trend in the tide gauge data of 0.08 mm/year, this produces an error of the absolute sea level rise uncertainty of 0.09 mm/year. Without using the GNSS information, one is left using the uncertainty of 0.1 mm/year in the post- glacial rebound models, which would give an absolute sea level rise uncertainty of 0.13 mm/year showing the advantage of using GNSS observations. At Marmugao (Goa), where recently a new GNSS station was Installed, the uncertainty in sea level rise is currently around 0.36 mm/year. Using Figure 9, it is expected that the vertical land motion can be determined with the same accuracy within two years from now. The corresponding absolute sea level obtain a value of 0.51 mm/year. Therefore longer period of GNSS observations are desirable to reduce the error of the absolute sea level rise.

7. CONCLUSION

In the present paper, a critical analysis has been done by comparing the studies undertaken at Alexandria Tide gauge station Egypt and seven tide gauge stations in India in reference to measurement of sea level rise and accuracy. It has been found that GNSS Technology in tide gauge monitoring is versatile to calculate movements of absolute sea level rise. Combining three devices; a tide gauge, a meteorological unit and GNSS stations integrated together in a unified scheme, maximize the accuracy and would give a significant contribution to the sea level monitoring. GNSS sea level measurements for a longer period can provide absolute sea level measurements over spatial and temporal scales that are impossible to achieve with satellite altimetry. It has been observed that the absolute estimation of sea level variation needs determination of any vertical land movements at tide gauge which is possible using GNSS technology. The GNSS tide gauge has better performance in high wind conditions and allows simultaneous and permanent determination of sea level and position with respect to the International Terrestrial Reference Frame system.

8. ACKNOWLEDGEMENTS

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