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PRELIMINARY OCEAN TIDE MODEL INFERRED BY SATELLITE ALTIMETRY FOR A TEST SECTION OF THE ASEAN REGION

Mr. Muhammad Nur Jason Philip Vella (email: nur_vella@yahoo.com)*
Dr. Shahrum Ses (email: shahrum@fksg.utm.my)*
Dr. Majid Kadir (email: majid@fksg.utm.my)*
***Centre for Geodetic and Geodynamic Studies (CGGS)**
Faculty of Geoinformation Science and Engineering
Universiti Teknologi Malaysia
81310, UTM Skudai, Johor
Tel:+607-5502866/Fax:+607-5566163
Dr Ole B. Andersen
National survey and Cadastre (KMS)
DK-2400 Copenhagen, Denmark (email: oa@kms.dk)

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ABSTRACT

During the recent years the availability of accurate ocean tide models have become more and more important as tides are the main contributor to disposal and movements of sediments, tracers, pollutants and a whole range of offshore applications in engineering, environmental observations, exploration and oceanography. Tides are the largest contributor to sea level variations and the TOPEX/POSEIDON science working team has urged the development of regional models to be used for the correction of altimetry for future satellite missions like JASON-2 and ENVISAT-2. An empirical satellite altimeter derived tide model for the Straits of Malacca has been produced using cycles 11 to 200, a time span of up to 4-5 years of altimeter data. The model entails the establishment and maintenance of a data centre for altimetric observations for the ASEAN region. This database will be of vital importance to users of satellite altimetry (i.e. off-shore, fisheries, oceanographers), and will contain both low level unprocessed altimetric observations, but also high-level processed altimetric observations for the direct benefit of users. This model is only an empirical model in that it contains only in situ altimeter measurements and no extra modelling. However it will be discussed how the inclusion of extra hydrodynamical modelling techniques can greatly improve the workability of such a model in this region.

INTRODUCTION

Current ocean tide models allow an unambiguous observation of deep ocean surface dynamic topography using satellite altimetry. Other significant contributions include their applications in an improved orbit computation for TOPEX/POSEIDON and other geodetic satellites, to yield accurate predictions of Earth rotation excitations and improved estimates of ocean loading corrections. This also applies for geodetic observations and to allow potential separation of astronomical tides from phenomena with meteorological and geophysical origins.

Since the launch of TOPEX/POSEIDON (T/P) in August 1992 and, to a lesser extent, since the launch of ERS-1 a year earlier, the study of ocean tides has progressed dramatically. This progression comes about with the development of models of unprecedented accuracy by a number of researchers such as Matsumoto, Anderson and Le Provost.

The reason for the proliferation of models stems first from the fact that the tidal signal in T/P altimetric data is the largest contributor to sea surface height variability, and accounts for more than 80% of the signal variance. Therefore, tides are immediately apparent in even the briefest examination of an altimetric dataset. Second, the quality and length of the T/P dataset, and the efficient distribution of T/P altimetry by data centres, has enabled ready and precise analysis.

Intercomparison of the global ocean tide models demonstrated the high accuracy and consistency of all recent ocean tide models (Shum *et al*. 1997). From a comparison with a common 104 tide gauge data set the general result is that, six of the new global ocean tide models have RMS agreement better than 3cm (Anderson *et al*. 1995).

The need for increasing accuracy in shelf regions calls for the inclusion of more than just semidiurnal and diurnal constituents in global ocean tide models. This is because shallow water constituents, of which there can be more than one hundred, cause a considerable part of the tidal variability on the shelves. The global models consist of eight constituents called the eight leading tidal constituents, namely M_2, S_2, N_2, K_2, K_1, O_1, P_1 and Q_1. Whereas the shallow water constituents for example MN_4, M_4, MS_4, MK_4 and S_4 that can be derived via satellite altimetry depend on their corresponding amplitudes and the accuracy of the altimeter's ability to sense amplitudes that have magnitudes no smaller than the accuracy of the altimeter (Anderson, 1999). The amplitudes vary according to geographical position, and also depends on depth as well as on the tidal dynamics of the region.

This research concentrates on the eight main dirunal and semi diurnal constituents M_2, S_2, N_2, K_2, K_1, O_1, P_1 and Q_1, for the area commonly known as the Straits of Malacca (of the eight constituents, only the 2 largest for the region are shown, M_2 and K_1). The geographical extent of the area is 90^0 west to 105^0 east in longitude and 0^0 north to 15^0 north in latitude, the reason for choosing such a broad geographical extent will be discussed further on. The eight main diurnal and semi diurnal constituents are chosen as before we can concentrate on the shallow water constituents as previously mentioned these constituents themselves need to be ascertained accurately enough for basic applications such as mentioned above.

DATA PROCESSING AND EDITING PROCEDURES

T/P is a 'designer altimeter', designed to do the best possible altimetry with available technology. One aspect of this is that it is in a higher orbit (~1340km) than GEOSAT and most observational satellites (e.g. the NOAA AVHHR), which are generally around 800 - 900km. The higher altitude makes orbit calculations better through the fact that the Earth's gravity field is smoother at this height and there is also less atmospheric drag. T/P's orbit has an inclination of 66 degrees (i.e. a prograde orbit) and a repeat cycle of approximately 10 days. The first repeat cycle began on the 23rd of September 1992.

After all corrections have taken place, the residual Sea Surface Height (rSSH) is then derived, which suits best the application of Satellite Altiemtry to empirical tide modelling.

The rSSH is given by the following:

$$\text{rSSH} = \text{SSH} - \text{H\_MSS} - \text{Inverse Barometer} \qquad (1.0)$$

where:

SSH is the Sea Surface Height above the reference ellipsoid
H_MSS is the mean sea surface height above the reference ellipsoid
Inverse Barometer (Used to correct for the hydrostatic response of the sea surface due to increase and decrease in atmospheric pressure)

Tidal effects were not removed from this data, as it is not pertanent to do so, in order to derive the tide model itself, however it may prove to be an advantage in reducing long wavelength errors in the modelling process. A remove restore approach could be adopted, but is not done so in this case.

TIDE MODELLING USING SATELLITE ALTIMETER DATA

The response method is a robust tidal analysis method, which assumes that the tidal elevation can be expressed as a weighted sum of the tide generating potential lagged by a certain amount of time $\boldsymbol{t}_s$

$$z_0 = \sum_s w(s) V(t - t_s) \qquad (2)$$

where the weights $w(s)$ represent the sea level response to a unit impulse $V(t) = d(t)$. The Fourier transform of the impulse response $w(s)$ is the "admittance" of the ocean system.

The notable feature of the response method is that it does not insist upon expressing the tides as sums of harmonic functions of specified tidal spectral line, but expressing the tides by admittance functions of each tidal species. This has an advantage when applied to satellite altimetry.

In comparison to the harmonic method, the response method has other advantageous. Such as, a serious problem in the harmonic method arises if the aliasing periods of some tidal constituents are too long, as in 4465.6 days for P_1 in GEOSAT's sampling interval. It is almost impossible to resolve such long period waves from a few years of altimetric measurements by the harmonic method. However, the response method is able to overcome this situation because admittance functions are determined through other constituents, which are resolved easily (Cartwright and Ray, 1990).

Equation (2) is modified through taking the potential as an input function and becomes

$$z_0(t) = \mathrm{Re}\sum_{n=2}^{3}\sum_{m=0}^{n}\sum_{k=-K}^{K}\left[w_{nm}(k)c^{*}_{nm}(t-k\Delta t)\right] \tag{2.1}$$

$$= \sum_{n=2}^{3}\sum_{m=0}^{n}\sum_{k=-K}^{K}\left[u_{nm}(k)a_{nm}(t-k\Delta t)+v_{nm}(k)b_{nm}(t-k\Delta t)\right] \tag{2.2}$$

where a_{nm} and b_{nm} are the real and imaginary part of the time dependent coefficient of the tide generating potential. Then $c_{nm} = a_{nm} + ib_{nm}$ and u_{nm}, v_{nm} are the corresponding weight functions and $w_{nm} = u_{nm} + iv_{nm}$, the integer k represents the "smoothness of admittance". K=1 was used for the development of the tide model.

The equation (2.1) is equivalent to fitting the oceanic admittance Z(w) which is given by Fourier transform of $w_{nm}(k)$:

$$Z_{nm}(w_{nmj}) = \sum w_{nm}(k)e^{-iw_{nmj}k\Delta t} \tag{2.3}$$

where w_{nmj} is in radians per day. $|Z|$ and arg(Z) represents respectively the magnification and phase lead of the ocean tide relative to the equilibrium tide for a harmonic component of frequency w_{nmj}.

The rSSH and the time in days relative to January 1st 1958 00:00:00 is used as the input into the modelling software, which measures the response to the tidal forcing and gives the amplitude and phase after being operated on by a FFT.

There are two ways of inputting the data, one is to grid the data into 0.5^0 bins so that for a period of no less than one year and not necessarily more than three years, as suggested by Vella *et al* 2001, there is a time series of rSSH in units of cm and time in units of days. Then for the corresponding cells the amplitude and phase are derived for the centroid of the cell. This is plausible due to the long wavelength aspects of the tide itself. The other method is to take for every repeat point of the cycle all the data at that point so there is a time series of data for each point. The amplitude and phase of the point are dervied and then used to grid the final tidal charts of the model. The first procedure described is used in the modelling of the tide model for this case.

The latitudes and longitudes are gridded so that data falling within a 0.5^0 by 0.5^0 grid cell, (the geographical extent of the area is 90^0 west in longitude to 105^0 east in longitude and 0^0 north to 15^0 north). The centre of each cell is used to define the grid.

The statistics describing the number of data in each cell and the mean and standard deviation of each cell is given in Tables 1 to 3. Three tables are described as follows, Table one shows the statistics for the data after the intial gridding procedures where the data is grouped into the cells. This data set contains cells which have a data quantity of less than 100 data. One of the criterium used for rejecting data is that each cell must have a minimum of 100 data or more. Table two describes the statistics of the data after the first rejection criterium is satisfied. The second rejection criterium is that any rSSH outside the three satandard deviation of the mean is also rejected, therefore Table three shows the final statistics of the data used in the modelling process.

RESULTS

Table 1 shows the original number of 0.5^0 cells was 297, this is before any statistical analysis is undertaken or any data editing occurs. The mean and standard deviation of the rSSH stays almost constant through out the data editing phase. This provides a check on gross errors which may occur due to the wrong processing methodology employed in processing the raw altimeter data.

	Statistics
Number of Data Cells	297
Mean Number of Data/Cell	927
Mean Value for all Cells	-5.4 cm
Mean of the Standard Deviation	15.3 cm

Table 1: Statistics before implementing rejection criterium

After the first editing stage Table 2 shows how the number of cells decreases to 251 which is an approximate decrease of 15%. This is an important criterium to observe, otherwise the solution from the least squares could become unstable and erroneous values are produced. This will further introduce errors when gridding if due attention is not given. The mean number of data per cell also increases, as now there are only cells with a minimum number of data, being 100.

	Statistics
Number of Data Cells	251
Mean Number of Data/Cell	1092
Mean Value for all Cells	-5.7 cm
Mean of the Standard Deviation	15.15 cm

Table 2: Statistics after implementing the 1st rejection criterium

The third criterium used for data editing is to neglect data that are more than 3 standard deviations outside the mean. This is a well known and used method of editing data. Table 3 does not show major changes in the number of data per cell, which indicates that most data are within a suitable range. Causes for data being outside an acceptable range may be due to the fact of water build up near coastal areas and the altimeter in ability to lock on to the sea surface sufficiently enough in order to measure these areas adequately.

	Statistics
Number of Data Cells	251
Mean Number of Data/Cell	1089
Mean Value for all Cells	-5.7 cm
Mean of the Standard Deviation	14.96 cm

Table 3: Statistics after implementing the 2nd rejection criterium

Figures 3 and 4 show the amplitude and phase of the M_2 and K_1 constituents modelled in the modelling process. Table 4 shows the statistics of the models when compared to local tide gauge data.

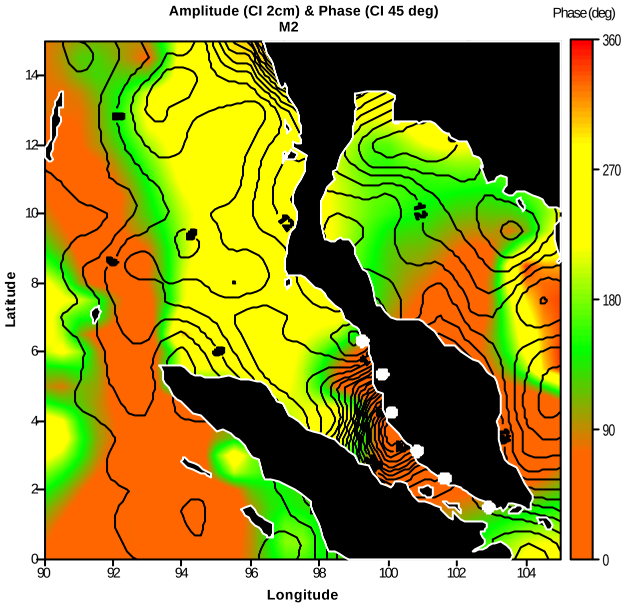

Figure 2: The amplitude and phase of the Altimeter derived M_2 constituent

From Figure 2, it is apparent how the phase of the M_2 constituent propogates down into the Straits of Malacca from the Indian Ocean. Toyoshima (1994) reports the most recent study of tidal characteristics around the Peninsular. The amplitude and phase lag of four fundamental constituents (M_2, S_2, K_1 and O_1) were derived using 5 years of observed tidal data obtained from 11 tidal stations. The semi-diurnal tide generated in the Indian Ocean takes about ten hours to transmit into the Malacca Strait from the north. The semi diurnal tide originating from the Pacific Ocean enters the South China Sea and goes westward to the east coast. This tide further proceeds southward to the Singapore Strait. It takes about 10 hours to meet the Indian Ocean at the southern tip of the Peninsular (Ses, 1997).

It can also be seen from Figure 2 how there is a certain amount of mixing occurring in the southern Straits of Malacca, this effect however is also accentuated due to the gridding techniques employed in deriving the maps shown.

The minimum raw amplitude (for M_2) used in gridding from the raw data is 0.39 cm and the maximum value used is 52.8 cm. These data are all converted to real and imaginary parts before gridding and then converted back for the comparisons. Likewise for the K_1 constituent, the minimum and maximum respectively for the amplitude is 0.1 cm and 33.5 cm. By relatice comparison these alues are under estimated, which is most probably explained in the method used for deriving the tide cells. Instead of solving the tide based on 0.5^0 cells, it would probably be better to derive the tide at each individual repeat point and then do the gridding, this however was not done for this research and no comparisons can be made.

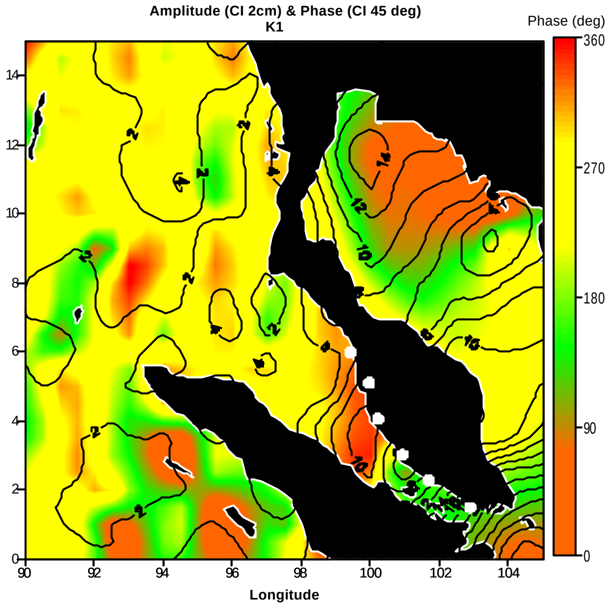

Figure 3: The amplitude and phase of the K_1 constituent.

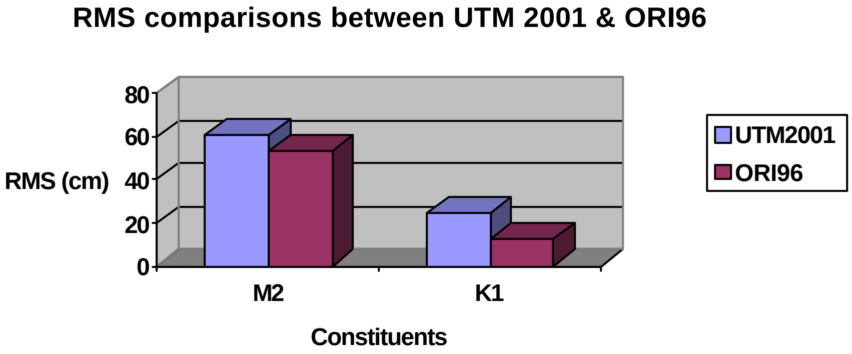

Figure 4: RMS comparisons

These comparisons show that there is much room for improvement when considering tide models produced by empirical methods only. Other studies have shown that for deep ocean tide models the rms comparisons between a series of tide gauges is in the range of 2-3cm's and for the area of the South China Sea bordering Malaysia in the East the comparisons are 15-20 cm's, (*ibid*).

It is also evident that in order to produce tide models that can be of use for navigation or environmental modelling, the modelling of shallow water tides in enclosed regions such as the Straits of Malacca need to employ other modelling techniques, such as hydro dynamical modelling or GPS bouy tide gauge systems. This would then make the tide models produced semi empirical models which do not solely rely on Satellite Altimetry.

CONCLUSIONS

Satellite altimetry has proven to be a major driving force behind the search for better, more imporved knowledge of the earth's tides in the deep open oceans. Recently, within the past few years attention has been focussing on areas of the globe which are densly populated costal zones, with respect to ocean modelling. These areas mostly are associated with having shallow bathymetry which create problems for satellite altimeters when measuring the altitude due to the increase in the roughness of the surface of the ocean. Also when the altimeter tracks over land and then needs to reacquire lock onto the ocean surface creates problems due to the time delay in doing so.

Because the majority of the worlds populations are coastal dwelling societies it is just as important to have accurate knowledge of the oceans in the coastal areas as it is in the open ocean areas. The Straits of Malacca is one fine example, being one of the busiest shipping lanes with a heavy volume of traffic, this area is one in which time and money need to be spent in order to develop apprpriate models which can adequateely deal with and hopefully help avoid potential dissaster scenarios from developing.

The tides have been modelled for this particular region, in the hope of developing a model adequate enough to help in the aid of navigation, marine engineering and environmental monitoring for a wide range of uses. It has been shown however, that the tides themselves are still elusive to altimeter methods alone in these semi enclosed seas, and do require extra techniques in order to improve the accuracy and reliability of such models in this region.

This is the topic of continuing and ongoing research at the University of Technology Malaysia, to develop awareness of these types of modelling techniques and also the availability of satellite derived data for such applications.

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