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Refinement of the Global Ocean Tidal Charts
전구해양 조석도의 개선

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1. INTRODUCTION

This paper briefly outline the approach we are now setting for improving the existing global ocean tidal charts in next few years. There has been notable progress in predicting global ocean tide in mid 90s to improve correction procedures for tidal signals in altimetry with more accurate tidal models (http://podaac.jpl.nasa.gov/) than existing ones. However, in general, the global predictive tidal constants in the form of 0.5°~1° resolution data tables are not sufficiently accurate for coastal, shallow water regions. Furthermore, most models using advanced analysis and data assimilation using satellite altimeter data do not demonstrate the better accuracy than pure hydrodynamic model (e.g. Grenoble FES95.2). Choi et al (1999) have also shown that traditional pure hydrodynamic model with 5 minutes grid resolution could represent tides in the deeper ocean and shallow marginal seas reasonably well. It has also shown that analyses of satellite data from GEOSAT GDR JGM-3 could represent distribution of tides in the ocean reasonably well (Fang et al, 2000). We are attempting the next stages of cooperative effort between Laboratory for Coastal and Ocean Dynamics Studies, Sungkyunkwan University and NMDIS, SOA and IOCAS, China for eventual provision of detailed global tidal distribution with sufficient accuracy, which can be utilized to understand general tidal dynamics and also for practical utilization.

2. METHOD AND EXPERIMENTS

2.1 Analysis of T/P X-over and Along Track altimeter data

The TOPEX/POSEIDON satellite was launched in August 1992. Many papers were published on tide model of T/P data. Some of these tide models were based on harmonic analysis method, but much more others were based on response method.

The T/P ground track repeats every 9.9156 days. This sampling causes the diurnal and semidiurnal tides to alias into signals of very long period. Tidal aliasing for T/P was discussed in many papers. As discussed by Schrama and Ray (1994), a strict application of Rayleigh's criterion for separating nearby periods requires data spans of nearly 3 years to separate M2 and S2, 9 years to separate K2 and P1, and 9 years for K1 and the semiannual Ssa. The data set used in this paper was provided as Merged Geophysical Data Record (MGDR) by the French Space Agency, Center National d'Etudes Spatiales (CNES). In this study we processed over 6 years T/P

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data, from Cycle 11 (January 1993) to Cycle 249 (April 1999). According to Schrama and Ray (1994), the time span of the along track data may not long enough to separate K2 and P1, K1 and Ssa. In other hand, there is one time more data in the time series of cross over points than that of along track data points. The cross over data of each cycle was also offered in CNES MGDR data set in addition to the along track data. So by applying the tidal harmonic analysis method to the time series of cross over points, there is possibility to separate some tidal constituents which were aliased in along track time series.

The tidal harmonic analysis of sea level residuals ζ is based on the observation equation:

$$\zeta\left(\phi_j, \lambda_j, t_{j,k}\right) = \sum_{i=1}^{N} A_i f_i \cos\chi_{i,j,k} + B_i f_i \sin\chi_{i,j,k} + C_j \quad (1)$$

where

$$\chi_{i,j,k} = \varpi_i t_{j,k} + V_i + u_i$$

On each point, the number of measurements is required to be greater than that of tidal constants. This will lead to a set of over-determined equations which can be easily resolved through least-square technique.

$$Ax = b \quad (2)$$

where

$$A = \{a_{i,j}\}, \qquad i, j = 1, 2, \cdots, N.$$

Instead of Rayleigh's criterion, the coefficient matrix $\{a_{i,j}\}$ was employed to decide which two tidal constituents are aliased or can not be separated with the time series we used.

$$a_{i,j}/a_{i,i}\ (i \neq j) < C_0 \quad (3)$$

$$a_{i,j}/a_{i,i}\ (i \neq j) \geq C_0 \quad (4)$$

If (3) is satisfied, there is no aliasing between tidal constituent i and tidal constituent j. If (4) is satisfied, tidal constituent i was considered aliased with tidal constituent j. That means the matrix may be "ill" and equation (2) may not be resolved. So some relationship should be introduced to separate tidal constituent i and tidal constituent j.

According to the discussion above, the cross over data provided by CNES was processed first in this study. The satellite altitude contains a lot of information of the atmosphere and the ocean, such as geoid, tides, wave and currents et al. To determine the ocean tide effectively, a number of corrections are needed to correct the satellite altitude. The corrections used in this study for cross over points can be expressed as:

ζ =Sat_Alt — H_Alt — Dry_Corr — Wet_Corr — Iono_Corr — Inv_Bar — SSB_Corr — H_MSS — H_Set—H_Pol—H_Lt (5)

Where ζ is the corrected sea surface height, Sat_Alt is the satellite altitude above the reference ellipsoid, H_Alt is one per second altimeter range, Dry_Corr and Wet_Corr are dry and wet tropospheric corrections at measurement time, Iono_Corr is ionospheric correction, Inv_Bar is the inverse barometer correction, SSB_Corr is sea state bias correction, H_MSS is mean sea surface height above the reference ellipsoid (OSUMSS95), H_Set and H_Pol are the solid earth tide and the geocentric pole tide respectively, H_Lt is tidal loading effect computed from CSR3.0 model. All the corrections were applied to both ascending and descending part at the cross over points. Note that because there is no geoid data provided in the cross over files, ζ reference to the mean sea surface height (H_MSS) was used in this paper.

Time series of ζ at cross over points are produced after processing cross over files with (5). With the criterion of (3) and (4), we found that K1 and Ssa can be separated at cross over points, but K2 was still aliased with P1. So, in the cross over time series analysis, 9 constituents, Sa, Ssa, Q1, O1, K1, N2, M2, S2 and K2 were selected as main constituents. Also some other dinual and semidinual constituents such as P1, PI1, PSI1, NU2 et al were included as satellite constituents. But relations between satellite constituents and main constituents must be introduced. In this paper, the amplitude ratio from satellite constituent to its corresponding main constituent and the phase-lag difference between the satellite constituent and its corresponding main constituent (called difference-ratio relations) are introduced. Detailed descrption of difference-ratio relations and the harmonic analysis method used here can refer to Wang and Fang (1981) and Fang et al (1986). A brife descrption of the method is given in the following.

Similar to equation (1), the tidal level can be expressed as:

$$\zeta = x_0 + \left(\sum_{j=1}^{P} + \sum_{j=P+1}^{P+Q}\right) f_j H_j \cos\left(\sigma_j t + V_j - g_j\right) \quad (6)$$

Where P is the number of main constituents and Q is the number of satellite constituents. Since the difference-ratio relations were introduced, the satellite constituents can be considered as already known. So equation (6) can be written as:

$$x_0 + \sum_{j=1}^{P} f_j H_j \cos\left(\sigma_j t + V_j - g_j\right) = \zeta - \sum_{j=P+1}^{P+Q} f_j H_j \cos\left(\sigma_j t + V_j - g_j\right) \quad (7)$$

In each cross over points, the time series will form a set of equations like (7). The equations can be resolved by least-square technique. The procedure as follows:

1). Main and satellite constituents were set to be zero as initial conditions.

2). Main constituents were resolved according to the least-square equations.

3). New tidal harmonic constants of satellite constituents can be derived from the main constituents according to the difference-ratio relations.

4). Calculate the errors between the newly calculated tidal constants and previous value. If the maximum error is greater than a given value ε (10^{-8} in this paper), go to 2).

5). If the maximum error is smaller than the given value ε, predict the tidal level with the tidal harmonic constants analysed at every measurement time. Then calculate the errors between the predicted tidal level and the measured level ζ_i, and calculate standard deviations σ_i and the mean standard deviation σ. If $\sigma_i \ge \alpha\sigma$, ($\alpha = 3$ in this paper), discard the measured value ζ_i in time i and go to 1).

6). If $\sigma_i < \alpha\sigma$, output results and stop.

After the procedure mentioned above, the cross over analysis was finished. The harmonic tidal constants of the 9 main tidal constituents in cross over points can be obtained. And the harmonic constants of satellite constituents can be derived. Some figures (include figures here M2, S2, O1, K1 or and more) can be drawn and some comparisons with the observed tidal data and others' results can be made.

The along track data can be processed and analysed in a similar way. But there is still some difference between them. Following we will discuss the procedure to deal with the along track data.

Like the cross over data, a set of corrections are necessary to produce residual sea heights from which we can obtain more accurate tidal constants. The corrections applied to along track data are as follows:

ζ =Sat_Alt — H_Alt — Dry_Corr — Wet_Corr — Iono_Corr — Inv_Bar — SSB_Corr — H_Geo — H_Set—H_Pol—H_Lt (8)

All the corrections used here are as same as those used in cross over points (equation (5)) except the term H_Geo which is the geoid height. So at the along track points, ζ reference to the geoid height (H_Geo) instead of mean sea surface height (H_MSS).

A problem here is how to form the time series at along track points. The orbit of the satellite repeats to within ±1Km every 127 orbit revolutions and has an exact repeat period of 9.9156 days (Fu et al., 1994). So the along track data have been interpolated onto a reference ground track, thereby aligning all repeat cycles to the same positions. This procedure is named collinear interpolation. The reference cycle should have an orbit in the middle of the within ±1Km orbit range and should have little absent observations of the one-second-data. Here the cycle 91 was selected as the reference cycle. Detail of the collinear technique used in this paper can refer to Dong et al (2000). After the collinear interpolation, the time series at along track points were formed.

Application the criterion of (3) and (4), we found that K1 and Ssa are inseparatable as we knew in addition to K2 and P1. So the selection of tidal constituents should be different from cross over data. In an other consideration, the less the main constituents selected, the more accurate the analysis results. Then, in the along track data analysis, only 4 constituents, Sa, Ssa, O1 and M2, are selected as main constituents. The others selected in cross over analysis are considered as satellite constituents. Because the harmonic constants of Q1, K1, N2, S2 and K2 have been obtained in the cross over points, the difference-ratio relations of these 5 constituents with their corresponding main constituents O1 and M2 can be interpolated to the along track points. As the first step, the difference-ratio relations of the 5 constituents from the cross over results were interpolated to 10' by 10' grid through a simple interpolation method together with some observation data from the fastmode and delay mode of BODC tidal constants. Then the grided difference-ratio relations were interpolated to the along track points also with the same interpolation method. The difference-ratio relations for other satellite constituents were obtained from theory relations as used in cross over analysis. The analysis procedure for along track time series is same as that for cross over analysis mentioned above.

Finally, the harmonic tidal constants of the main constituents and satellite constituents were obtained. Some figures (include figures here M2, S2, O1, K1 or and more) can be drawn and some comparisons with the observed tidal data and others' results can be made.

2.2 Coastal observation from IHO data and Pelagic measurement

The T/P data analysis results may not good in coastal regions. The cross over results can not reflect the tidal distribution in the coastal regions because there are only a few cross over points in the coastal region where the tides vary rapidly from place to place. So this may cause problems in the co-tide charts and difference-ratio relations in the coastal regions. If the coastal observation data is added to the T/P results, better co-tidal charts can be expected, especially in the coastal region (refer to Morimoto and Yanagi et al (2000).

There are more than 200 coastal observations from IHO data and also many pelagic measurements in the coastal. Some of these data were selected to draw the co-tide charts together with the analysis results from T/P altimetric data. The selected IHO data and Pelagic were interpolated to the grid points firstly together with cross over results through a simple interpolation method. There were no obvious improvements in the co-tidal charts in some coastal regions yet because of the less data there. But more reasonable difference-ratio relations can be obtained in the coastal region.

The selected data can also be applied to draw the co-tide charts together with the analysis results from along track data like what was performed by Morimoto and Yanagi et al (2000). Better co-tide charts can be expected now.

There is also another way to improve the along track results. The more reasonable difference-ratio relations from selected data and cross over results mentioned above can be used to the analysis procedure of the along track data. Then the selected data were added to the newly analysis results to produce a new grid data set. The comparison between the new grid data and the other observation data may show better results. The co-tide charts from the new grid data can be drawn now. It was better than the previous results, especially in the coastal region. These co-tide charts can also be shown here (figure).

2.3 Simplified data assimilation (Nudging method)

Generally, a hydrodynamic interpolation may cause more reasonable results than a simple interpolation, especially in the rapidly variation region such as the coastal. Matsumoto et al (1995) analysed the cross over data with response method and then interpolated the results to grid points through a hydrodynamic interpolation model. The tidal solutions with 0.5°grid system were obtained for eight major constituents (i.e., M2, S2, N2, K2, K1, O1, P1 and Q1).

Nudging method is a kind of simplified data assimilation method and has been proved to be quite effectively. Nudging method is based on hydrodynamic model and the observed data. We have the global hydrodynamic tidal model (some description of the model here). The model can be employed to form a nudging model together with the analysis results from T/P cross over data. Better results at least not worse than that of Matsumoto et al (1995) can be expected.

More accurate results can be obtained if the 5 difference-ratio relations are more reasonable. The more reasonable difference-ratio relations can be obtained from the nudging model mentioned above. When these relations are employed to the analysis of the along track data, much better results can be expected.

2.4 Adjoint data assimilation

Nudging method mentioned above is only a simple data assimilation method. Adjoint data assimilation method, which was considered as a much more reasonable data assimilation method, has been developed rapidly in physical oceanography in recent years. The method is thus named because the adjoint of the model equations is used to compute the directions in which unknown model parameters should be adjusted to achieve a better fit of the model to the data. Used iteratively with a gradient-descent algorithm, the method allows unknown model parameters to be inferred from the data (Griffin and Thompson, 1996). These parameters include bottom friction coefficient, initial conditions, boundary conditions, depth, wind stress, temperature and heat flux et al. Ghil and Malanotte-Rizzoli (1991) gave a comprehensive review of data assimilation in meteorology and oceanography.

Quite large memories and much faster CPU are required for an adjoint data assimilation model. So what will be performed here is a local region model instead of a global model. The open boundary conditions will be optimized in this study by assimilating the observed data into the adjoint model. The adjoint model is obtained by using Lagrange multipliers. Detail description of the adjoint model can be referred to Han et al (2000).

In this study, the Northwest Pacific will be selected as model region. Several assimilation experiments will be carried out, that is:

1) Assimilate harmonic constants from cross over results only into the adjoint model.
2) Assimilate harmonic constants from along track results only into the adjoint model.
3) Assimilate harmonic constants from both along track results and tidal gauges.

Comparisons will be made according to these experiments. Also the adjoint results can be compared with the tidal gauges data which are not used in the adjoint assimilation procedure.

3. RESULTS AND DISCUSSION

Some primary results have been obtained and is given in the following.

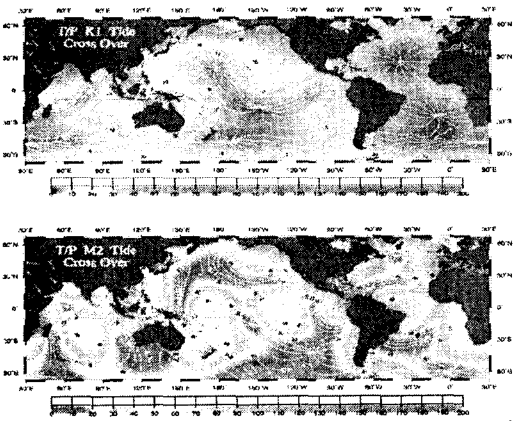

Fig. 1. Cotidal charts for K1 constituent (upper) and M2 constituent (lower) derived from T/P cross over data

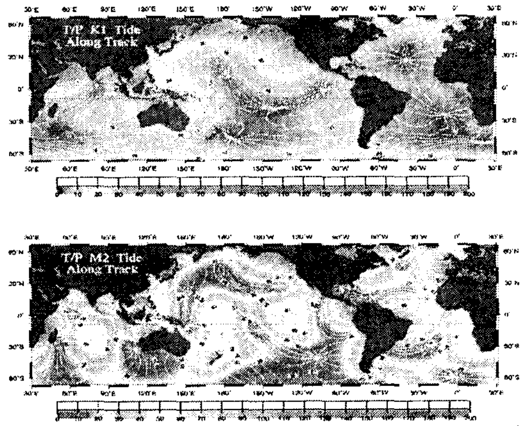

Fig. 2. Cotidal charts for K1 constituent (upper) and M2 constituent (lower) derived from T/P along track data

Limited by the length of the paper, only tidal charts of K1 and M2 were shown here in that they are the most important diurnal and semidiurnal tides. Note that K1 constituent from along track data was derived from O1 according to the different-ratio relations from cross over results.

Figure 1 shows the cotidal charts for K1 and M2 obtained from T/P cross over data, while figure 2 shows the same cotidal charts but from T/P along track data. Figure 1 and figure 2 have shown quite similar tidal distribution of K1 and M2 in the deep-ocean region. They are also consistent with previous results both in amplitude and amphidromic systems. It was shown that the results are satisfied and the method adopted here is valuable.

At the same time, there are still some difference between the cross over results and the along track results. Both results are not very good in coastal region. The T/P data and its corrections may not have enough accuracy in the coastal region. An other reason for this problem in the coastal region may be that there are fewer points in the rapidly varying coastal region, especially for the cross over data. If the coastal observation data is added to the T/P results (Morimoto and Yanagi et al, 2000), better co-tidal charts can be expected in the coastal region (refer to section 2.2).

The cotidal charts (especially K1 from along track data) also show that the contours are not smooth in some region. So maybe some smoothness is necessary for the results. The results shown here are from a simple interpolation. It seems that a hydrodynamic interpolation is much reasonable. We hope that better results can be obtained after the nudging method is performed as mentioned in section 2.3. As a much more reasonable data assimilation method, adjoint data assimilation has been developed rapidly in recent years. Much better results can be expected if the adjoint data assimilation method is employed to assimilate the T/P data. According to this consideration, we are trying to do something on the adjoint assimilation of T/P data as metioned in section 2.4.

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