

Determination of Global Mean Sea Surface Using Multi-satellite Altimetric Data

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Abstract. In this paper, the overall editing criteria for altimetric data are considered and the coordinate datums of various altimetric data are unified to an unique one. A method of full-combined crossover adjustment for different altimetric tracks is used to improve the radial orbits of Geosat, ERS-1 and ERS-2 data. In addition, the method for determining Mean Sea Surface (MSS) by using multi-altimetric data is developed. The data used to compute WHU2000 MSS includes 7 years of Topex/Poseidon data (from cycle 11 to 249), 2 years of Geosat ERM data (from cycle 1 to 44), 5 years of ERS2 data (from cycle 1 to 52) and all ERS-1 168-day data. The WHU2000 MSS is determined with a grid resolution of $2' \times 2'$ within the $\pm 82^\circ$ latitude and its precision is better than 0.05m. For an external check, WHU2000 MSS is compared with CLS_SHOM98.2 MSS, GFZ MSS95A and OSU MSS95, and the corresponding STandard Deviation (STD) of the comparing differences are $\pm 0.090\text{m}$, $\pm 0.211\text{m}$ and $\pm 0.079\text{m}$ respectively. The results of the comparisons show that the precision of WHU2000 MSS is in the same level with CLS_SHOW98.2 and OSU MSS95 but its resolution is higher than the latter ones.

Keywords. Altimetry, Mean Sea Surface, Crossover adjustment

1 Introduction

The determination of MSS is an important scientific problem in the fields of geoscience and environment science nowadays. MSS referenced to an earth ellipsoid contains the information of geoid and Sea Surface Topography (SST), therefore it is widely used in geoid determination and in the study of sea surface temporal variability, crust movement, ocean circulation et al. Satellite altimetry is a technique of space geodesy developed in 1970's

with the techniques of space, electronics and microwave to measure the global Sea Surface Height (SSH). Since satellite altimetry can provide highly repeated observations of the sea surface height on all days and weather, it has been extended to the multi-applied fields of geoscience instead of the initial single purpose of determining sea geoid figure (Jiang (2001)). Since 1973, 10 satellites with 11 altimeters have been launched, which are Skylab, Geos-3, Seasat, Geosat, ERS-1, ERS-2, TOPEX/POSEIDON (T/P), GFO, Jason-1 and Envisat. Millions of altimetric measurements have been acquired and provide plenty of information for the investigation of global sea level changes, the Earth gravity field, submarine topography, ocean lithosphere and ocean circulation, see for example Wang et al. (2000), Li (2002), Rapp et al. (1994) and Rummel et al. (1993). Some universities and institutes have released many MSS models using these information resources, which include OSU MSS95 in $3.75'$ grids (Yi (1995)), CLS_SHOM98.2 in $3.75'$ grids (Hernandez et al. (2000)), GFZ MSS95A in $3'$ grids and KMS99 MSS in $3.75'$ grids (Knudsen et al. (1998)), etc, and the typical models among them are the first three ones. OSU MSS95 is a MSS with relatively high precision developed by Ohio State University (OSU) using Geosat, ERS-1 and T/P altimetric data, and the model is usually taken as reference sea surface for altimetric data processing. It is widely used in oceanography and geophysics. GFZ MSS95A was developed by GeoForschungsZentrum (GFZ), Germany. The last version of this model was taken as the reference sea surface for the data processing of ERS-1. CLS_SHOM98.2 MSS was presented by Collecte Localisation Satellites (CLS), France. The model used multi-altimetric data, and its ultimate aim is to provide a reference sea surface for the altimetric data of Jason-1 and Envisat (Hernandez et al. (2000)). In china, some researchers also presented the local MSS models of China Sea and its adjacent

area, see Deng et al. (1996), Li et al. (2001) and Wang (1999). The newly trends of developments in this field is to combine more altimetric data for the determination of mean sea surface with higher resolution and higher precision. There are three main factors which continuously affect the accuracy of MSS. The first is the reliability of geophysical corrections and environment models. The second is the effects of orbit errors. The third is the inconsistency of coordinate datums between different altimetry satellites launched on different times and for different missions. The efforts should continuously be made to overcome the above unfavorable factors for further improving the precision of the MSS.

2 The Data and Pre-processing

The data used in the computation of WHU2000 MSS is described as follows:

- 7 years of T/P data (from 11cycle to 249cycle);
- all the ERS-1/168 data including Phase E from 94.04 to 94.09 and Phase F from 94.10 to 95.03;
- 52 cycles of ERS-2/35 data (from 1cycle to 52cycle);
- 44 cycles of Geosat/ERM data (from 1cycle to 44cycle).

The method of data pre-processing is based on data user handbooks and advanced experiences, see Chen et al. (1995), Deng et al. (1996), Denker et al. (1991), Karagano et al. (2000), Wang (2000), Yi (1995) and Hwang (1989). The geophysical correction models of higher precision are used and the data editing criteria are considered. By the modified criteria, the raw data of Geosat, ERS-1/2 and T/P is pre-processed. All the invalid data is deleted and the corresponding refined geophysical and environmental corrections are adopted.

3 Data Processing and Determination of the Model

3.1 Time-averaging of SSH

The repeated ground tracks of altimetric satellites do not exactly coincide with each other, and the separations of them would be about 1or 2km. In order to reduce the anomalous temporal changes of SSH caused by some significant oceanographic phenomena, such as EL Nino or La Nina occurred during particular seasons or years, the altimetric SSH data of satellites with repeated orbits is time-averaged for all available cycles and the mean tracks are obtained.

Mean track is derived from a selected reference tracks and the related collinear tracks. After the reference tracks are determined, the SSH at each point of the collinear tracks corresponding to the point of the reference track can be computed. Two methods can be used for the computing. One is to calculate the correction for geoid gradient (Brenner et al. (1990)), and another is to perform collinear analysis (Yi (1995)). In this paper, the collinear analysis is used to calculate the time-averaging of SSH, and the steps are:

- Calculate the Mean Sea Surface Height (MSSH) of the data points with the same latitude which include the data point on a selected reference track and the corresponding interpolated data points on the collinear tracks;
- If the difference between SSH and MSSH is larger than 1.0m, the data will be deleted;
- Re-compute the new MSSH and generate the mean tracks of all altimetric satellites.

After collinear average, the crossover differences before/after averaging are compared and listed in Table 1. From Table 1, it shows that the effect of the time variation on sea surface has been reduced by time-averaging and the precision of the sea surface height is improved (better than 10cm).

Table 1. The differences of Crossovers before/after Time-averaging over collinear tracks (Unit: m)

Data Type	Before			After		
	Mean	RMS	STD	Mean	RMS	STD
T/P	0.002	0.077	0.077	0.004	0.029	0.029
ERS-2	0.049	0.164	0.156	0.030	0.092	0.087
Geosat /ERM	0.058	0.121	0.106	0.015	0.074	0.073

3.2 Reducing Time Variation of SSH in Geodetic Missions of Altimetric Satellites

For the altimetric satellite with repeated missions (ERS-1/2 35、Geosat/ ERM、T/P), the effect of time variation of SSH on the MSS can be reduced by time-averaging, but the approach can not be valid for the tracks of the satellites with Geodetic missions (e.g., ERS-1 168、Geosat/GM) because no repeat tracks can be used for such missions.

In this study, the Sea Level Anomalies (SLA) model developed by Center of Space Research (CSR), USA is used to correct altimetric data with floating orbit missions and the effect of time variation on SSH will be significantly removed.

This model is derived from T/P data, including monthly averaged and annual averaged anomalies. The method for corrections is to use the monthly sea surface anomaly model corresponding to the time of ERS-1/168 mission and to interpolate the time variation of SSH at the points of tracks using the information on the location and time of altimetric data points.

3.3 Unification of Reference Ellipsoid and Transformation of Reference Frames

The reference frames defined by the coordinates of tracking stations and earth ellipsoid parameters used in different altimetric satellite missions are not the same. For example, the major radius of reference ellipsoid for T/P data is 6378136.3m and its flattening is 1/298.257 while the major radius for ERS-2 and ERS-1/168 data is 6378137m and the flattening is 1/298.257223563. Because of the inconsistencies in the radius and flattening of the reference ellipsoids, the SSH values (from sea surface to that of reference ellipsoid) at the same point are not identical. Their datums should be unified in the combination of all kinds of data for determining MSS. In this paper, the reference ellipsoid parameters and reference frame of T/P altimetric satellite are taken as the unified datum, and the MSSs derived from the other altimetric satellites are all reduced to the datum. There are two steps: firstly, a transformation formula is used to unify the reference ellipsoid parameters (Chen et al. (1995)); secondly, a four-parameter model is then used to realize the unification of the reference frame. The four parameters are Δx , Δy , Δz and B , which express three shift parameters relative to the origin and one overall bias parameter of the transformation model respectively (Yi (1995)). More details on the model and computation can be found in Jiang (2001) and Yi (1995).

3.4 Crossover Adjustment of Multi-altimetric Data

After time-averaging and datum unification, the orbit errors, residual ocean variation and various physical corrections are still the main erroneous sources in the determination of SSH, therefore, it is necessary to perform crossover adjustment to reduce the effects of all three kinds of errors mentioned above. Crossover adjustment will involve solving a linear equation system with rank deficiency if no constraints can be applied to the system. We have to fix the time-averaged SSHs of T/P data as the constraints in solving the system, in

which the coordinate datum of the other altimeter data should be unified with the T/P frame.

At present, crossover adjustment commonly used is a dual satellite crossover adjustment between Geosat (or ERS-1, ERS-2) data and T/P data, in which precise T/P orbit is used to improve the orbit of the former one. A newly method developed by this study is a full combined crossover adjustment with almost all altimetric satellite tracks containing orbit error parameters, in which the error covariance is considered to obtain more stable solutions. In terms of the method, dual-crossover adjustment is improved and the crossover adjustment for multi-altimetric data is developed, that is, a combined crossover of the tracks of ERS-2, Geosat/ERM and ERS-1/168 are adjusted together with T/P tracks. In the adjustment, T/P arcs are fixed, and there are nine patterns of combination of ascending arcs and descending arcs which are: ERS-2~Geosat/ERM, ERS-2~ERS-2, ERS-2~ERS-1/168, ERS-2~T/P, ERS-1~Geosat/ERM, ERS-1~ERS-1, ERS-1~T/P, Geosat/ERM~Geosat/ERM, Geosat/ERM~T/P. In addition, a priori models of geoid and sea surface topography (EGM96) are introduced into the adjustment.

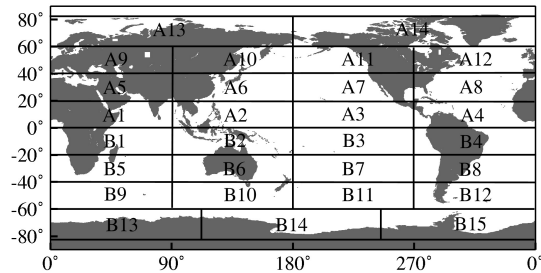
Smaller crossover differences or better fits can be obtained if the fitting of orbit errors in a higher degree and a smaller size of adjustment blocks are adopted for reducing the residual errors of fitting. To select appropriate blocks of crossover adjustment, three sizes of block, i.e., $20^\circ \times 20^\circ$ ($0^\circ < \varphi < 20^\circ$, $160^\circ < \lambda < 180^\circ$), $20^\circ \times 90^\circ$ ($0^\circ < \varphi < 20^\circ$, $0^\circ < \lambda < 100^\circ$) and $20^\circ \times 190^\circ$ ($0^\circ < \varphi < 20^\circ$, $0^\circ < \lambda < 190^\circ$) are tested and the size of the optimal block is determined by comparing the testing results. Table 2 shows the Root Mean Square (RMS) of crossover differences after performing the adjustment in these blocks.

From Table.2, it can be seen that the RMS of the crossover differences in $20^\circ \times 20^\circ$ block is 15% less than that in $20^\circ \times 90^\circ$ block and 8% less than that in $20^\circ \times 90^\circ$. To ensure a smaller discrepancy and higher computing efficiency, the $20^\circ \times 90^\circ$ block is adopted in the adjustment. Considering the distribution of altimetric data (between $\pm 82^\circ$ latitude) and the lands, the global sea is divided into 29 blocks including 14 blocks (A1~A14) on the Northern Hemisphere and 15 blocks (B1~B15) on the Southern Hemisphere. For the detailed division, see Fig. 1.

Table 2. The RMS of Crossovers of Missions before/after adjustment in different blocks (Unit: m)

Crossing Pair	20°×20°		20°×90°		20°×190°	
	before	after	before	after	before	after
ERS-2/ ERS-2	0.084	0.019	0.065	0.019	0.081	0.025
ERS-2/ Geosat	0.239	0.026	0.183	0.029	0.231	0.033
ERS-2/ ERS-1(168)	0.262	0.082	0.268	0.089	0.267	0.093
Geosat/ Geosat	0.038	0.022	0.077	0.025	0.075	0.034
Geosat/ ERS-1(168)	0.461	0.083	0.394	0.092	0.438	0.092
ERS-1/ ERS-1(168)	0.195	0.113	0.250	0.122	0.230	0.123
TP/ERS-2	0.070	0.020	0.056	0.020	0.066	0.027
TP/Geosat	0.191	0.024	0.170	0.026	0.204	0.028
TP/ERS- 1(168)	0.292	0.088	0.266	0.092	0.273	0.092

Combined crossover adjustment is performed in 29 blocks respectively. The statistic result is shown in Table 3, and the RMS values of the crossover differences are listed in Table 4. Table 4 shows that all the RMS values are better than 4.0cm except the ones that correlated with ERS-1/168, which is about 10.0cm. After the adjustment of crossovers, the radial orbit precisions of ERS1/168, ERS2 and Geosat data are obviously improved and the datum for all types of data is unified to an unique one.

**Fig. 1** Configuration of Crossover Adjustment Data Blocks**Table 3.** The Statistics of Crossover Points

Altimetric Data	T/P	ERS-2	Geosat/ERM	ERS-1/168
T/P	/	42862	20402	349477
ERS-2		44845	69240	740610
Geosat/ERM			16083	572796
ERS-1/168				3309622
Total	5165937			

Table 4. The RMS of crossovers discrepancies between Missions before/after adjustment (Unit: m)

Before Adjustment				
Altimetric Data	T/P	ERS-2	Geosat/ERM	ERS-1/168
T/P	0.0290	0.070	0.144	0.236
ERS-2		0.090	0.162	0.253
Geosat/ERM			0.071	0.319
ERS-1/168				0.246
After Adjustment				
T/P	0.0290	0.022	0.034	0.092
ERS-2		0.024	0.036	0.093
Geosat/ERM			0.029	0.096
ERS-1/168				0.114

3.5 Gridding Methods

After adjustment, the total data points of T/P, ERS-2, Geosat and ERS-1/168 tracks are 16378963. Shepard Method for fitting interpolation of gridding is used to generate grid data, and the resolution is 2'×2'. In computation, the local fitting radius is 2 times larger than grid interval. At least 2 points are needed in each quadrant of fitting area. If this condition is not satisfied, the searching radius is extended to 8', or even larger.

Because different altimetric data has different precisions, the precision of the data should be considered in the gridding procedure of discrete points. The precision of SSH can be derived by dividing the RMS of crossover differences after crossover adjustment by $\sqrt{2}$. From the Table 4, we can see that the precision of ERS-1/168 MSS is around 8 cm while those of T/P, ERS-2 and Geosat/ERM are about 2cm. Therefore, the weight of the data used for gridding can be determined by the corresponding RMS value.

The 2'×2' global mean sea surface WHU2000 generated using the above method is shown in Fig. 2. With a view of the precision of sea surface height after adjustment and the gridding errors, the precision of WHU2000 MSS model should be better than 5cm.

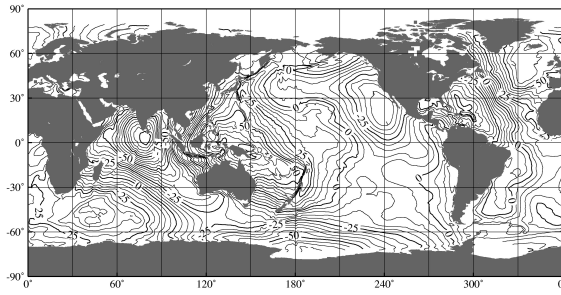


Fig. 2 The map of WHU2000 MSS at a 2'×2' grid (Oceanwide ±82° Latitude)

4 Results and Analysis

As an external check, WHU2000 MSS is compared with CLS_SHOM98.2, GFZ MSS95A and OSU MSS95 respectively. The gridded values of WHU2000 MSS are compared with of those the first two models. Because the gridded values of OSU MSS95 model are not available, the interpolated values given in the raw data of Geosat, ERS-2 and T/P are used for comparison. The results are listed in Table 5 and Table 6.

Table 5. Statistics of the differences between four MSS grid models in the area of 82N~82 S

(All Height differences are included.)				
	Mean (m)	RMS (m)	STD (m)	POINTS
WHU2000 MSS – CLS_SHOM98.2	0.041	0.175	0.169	9190755
WHU2000 MSS – GFZ MSS95A	-0.367	0.437	0.237	14153429
WHU2000 MSS – OSU MSS95	-0.071	0.112	0.087	2754722
CLS_SHOM98.2 – OSU MSS95	0.000	0.102	0.102	9603934
GFZ MSS95A – OSU MSS95	0.277	0.240	0.138	No Statistics

Table 5 shows the compared results of all points. In Table 6, the points with the difference 3 times larger than the RMS (0.5m for CLS_SHOM98.2 MSS and OSU MSS95 while 1.2m for GFZ MSS95A) are removed (Hernandez et al. (2000)). In Table 5 and Table 6, the results of comparison of CLS_SHOM98.2 MSS, GFZ MSS95A with OSU MSS95 respectively are provided by Dr. F. Hernandez and Dr. R. Matthias.

Table 6 shows that the corresponding STDs of the compared differences of WHU2000 MSS with the CLS_SHOM98.2 MSS and OSU MSS95 MSS are 0.090m and 0.079m respectively, and that

compared with GFZ MSS95A is 0.211m. GFZ MSS 95A has a large difference compared with the other three models, and the reason would be that its reference datum uses different gravity model. GFZ MSS95A uses the reference datum of ERS-1, and the gravity model used for its orbit determination is PGM035. However, the reference datum of other three models is T/P and the gravity model used for their orbit determination is JGM-2. The results indicate that the precision of WHU2000 MSS is in the same level with CLS_SHOM98.2 and OSU MSS95 but its resolution is higher.

Table 6. Statistics of the differences between four MSS grid models in the areas of 82N~82S

(The Height differences larger than 0.5m are excluded.)

	Mean (m)	RMS (m)	STD (m)	POINTS
WHU2000 MSS – CLS_SHOM98.2	0.042	0.099	0.090	9005065
WHU2000 MSS – GFZ MSS95A	-0.361	0.418	0.211	14056477
WHU2000 MSS – OSU MSS95	-0.071	0.106	0.079	2752025
CLS_SHOM98.2 – OSU MSS95	0.005	0.078	0.078	8750055

5 Conclusions

In this paper, a global MSS model WHU2000 MSS is derived by use of multi-satellite altimetric data. The model has a 2'×2' grid resolution, and its precision is better than 0.05m. In data processing, the coordinate datums of various altimetric data are unified to a unique one. A method of full-combined crossover adjustment for different altimetric tracks is used to improve the radial orbits of Geosat, ERS-1 and ERS-2 data. For an external Check, WHU2000 MSS is compared with CLS_SHOM98.2 MSS, GFZ MSS95A and OSU MSS95, and the corresponding STD of the comparing differences are ±0.079m respectively. The overall precision of WHU2000 MSS is in the same level with CLS-SHOM98.2 and OSU MSS95 but its resolution is higher than those of the compared models. In order to further improve the MSS model, the new data sources, such as Jason-1 and Envisat data, and new geoid model, e.g. obtained from GOCE mission should be used for the determination of MSS.

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