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FOREWORD

The Chinese National Committee for IUGG is pleased to present the 1999-2002 quadrennial China National Report on Geodesy and Geophysics to the membership of the International Union of Geodesy and Geophysics.

During the last four years, significant advances have been made in the study of Geodesy and Geophysics in China. The research of Geodesy and Geophysics played an important role in the sustainable development of economy and society by tackling the problems of resources, environment, natural disasters, and Geo-informatics. The observations, experiments, and theoretical modeling also have contributed to the understanding of the nature of the Earth, in which inter-disciplinary investigations are becoming more and more active.

The presentation of the 1999-2002 China National Report to the IUGG is a reflection to these advances, and provides the record of Chinese contributions to geodesy and geophysics. It is hoped that this National Report would be of help for Chinese scientists in exchanging the results and ideas in the research and application of geodesy and geophysics with colleagues all over the world.

The current National Report is the sixth China National Report to the IUGG. It contains seven parts compiled by the following sub-committees: 1. Geodesy; 2. Geomagnetism and Aeronomy; 3. Hydrological Sciences; 4. Meteorology and Atmosphere Sciences; 5. Physical Sciences of Oceans; 6. Seismology and Physics of Earth's Interior; 7. Volcanology and Geochemistry. The authors of each report are based on invitation. The Chinese National Committee for IUGG sincerely acknowledges the effort made by its sub-committees and the sponsorship and support of the Department of International Affairs, Chinese Association for Science and Technology (CAST).

CHEN Junyong, President
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PREFACE

This report gives an outline of the advances made in the field of geodesy in China during the four-year period of 1999-2002. It includes the following contents:

□1□Progress in space geodesy techniques such as satellite positioning, SLR,VLBI measurement and satellite altimetry and their applications in geodynamics research such as plate movement measurement, inner-plate deformation monitoring, earth rotation change and sea level change.

□2□Gravity measurement and partial gravity field refining in China.

□3□Partial Geoid refining in China.

□4□Superconductive gravity measurement and the research on terrestrial tide.

□5□Ocean geodesy in China.

□6□Advances made in data processing in China.

The current report is published only in CD.

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ON A CHINESE NEW GEOID
WITH HIGH RESOLUTION AND HIGH ACCURACY

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The effort for the geoid determination in China has lasted for nearly half a century. A large-scale measurement of astro-gravimetric leveling network was carried out from 1950s to the 1970s. The average resolutions of the network are 1.5°´1.5° in the eastern area of China and 2.5°´ 2.5° in the west. The China (Quasi) Geoid (CQG80) derived from this network shows that the difference between the remote measured points of this network and Xi'an Geodetic Origin is estimated at ±2.7 m in average.

It is obvious that CQG80 is far from meeting the needs of China's economic development and national defense as well as the research on geo-science in this country. Now a new (quasi) geoid (CQG2000) was computed in early 2001 to meet the needs of the first part of the new century, which is with high accuracy, high resolution and covers all the territories of China. The accuracy of CQG2000 has been upgraded one magnitude, from 3-5 m of the CQG80 to the grade of centimeter. And its average resolution has been raised from 2°´2° to 15′´ 15′. Additionally the coverage of CQG2000 has extended to all the mainland and maritime areas of China. CQG2000 has passed the field test and production check and accepted by National Bureau of Surveying and Mapping, so it has been officially issued for public use in the whole country.

Three technical problems were encountered during the computation of CQG2000. The first is the research and computation of China's mainland geoid. The second is the research and computation of China's maritime geoid. And the third one is the research and computation of the match of China's mainland and maritime geoids.

I. RESEARCH AND COMPUTATION OF CHINA'S MAINLAND GEOID

The usual way internationally to solve this problem is to make a combined adjustment of a local gravity geoid with a GPS leveling network, which is improved meantime through local gravity and topographic materials. This is a feasible way to deal with such problems in China at present. The major problem in China is that the resolution of the gravimetric data is rather low and the data are unevenly distributed. In view of the situation, the following project is taken to compute China's mainland gravity geoid after research and experiment:

1. Computation Project for China Mainland Gravity Geoid

（1）Remove/restore method is adopted for this project

As the best global gravity potential model for time being and the high-resolution digital terrain model (DTM) are available in China, then the so-called remove/restore method can be used for the computation of China mainland geoid, which belongs to a local gravity geoid.

Using the overlapping property of gravity potential fields the method deals with the contributions of different wavelengths separately and then overlaps them directly to restore the local gravity potential field, which is to be approximated. The key aim of this method is to use local gravity and DTM data to improve the local (quasi) geoid (essentially to improve its short wave lengths), which is derived by global gravity potential model.

After the comparison in the testing computations, the geoid height is divided into two parts in the computation. The first part is the model (quasi) geoid height and model gravity anomaly, obtained from the global gravity geopotential model. The second part is the residual (quasi) geoid height, which is obtained by the residual gravity anomaly. The latter is the surface gravity anomaly after removing the model gravity anomaly in the first part.

（2）The gravity geoid is computed with the classic Stokes’ formula and Molodensky’ series (taking account of the 1st order term).

As the FFT/FHT techniques applied to those formula and series are quite mature, the classic formulas are usually the first choice by most countries when computing their gravity geoid.

（3）The classic terrain isostasy model (Airy-Heiskanen system) is used for gravity reduction.

It is due to the following factors: there are vast mountainous areas, low gravity resolutions in China, and the topographic isostatic anomaly is smoother than the Bouguer anomaly, there is no systemic effect of Bouguer anomaly in the areas with good isostatic compensation, then the estimated interpolation error in the classic isostasy model is smaller.

（4）Strict 1D FFT technique is used for the computation.

Generally speaking, the resolutions of the ground gravity data in China are low and the distribution of them is uneven. Terrain isostatic anomaly is used for interpolation and gridded, and then restored to gridded value of terrain (or geoid) free air gravity anomaly. After the gravity model value is subtracted from the anomaly, Stokes formula and Molodensky formula with G_1 term correction are used to compute the residual geoid height and height anomaly. All the computation is based on 1D FFT technique.

2. Mathematical Model for China Mainland Gravity (Quasi) Geoid

(1) The computation of gravity geoid undulation

To determine the geoid height, theoretically, the gravity anomaly over the entire earth must be known. But in practice, only the terrain gravity data of a local area can be obtained. Therefore, the determination of a local geoid is usually done with lower pass filter principle, i.e. to compute it by combining the global gravity potential model with local gravity and topographic data. For this purpose the height of local geoid is divided into two parts. Its first part is computed from the global gravity potential field, and the second part is obtained from Stokes integral with 1D FFT/FHT techniques.

(2) The computation of height anomaly

The height anomaly is obtained by substituting Faye gravity anomaly into Stokes formula. In addition, in view of the fact that China's land stretches as far as about 50^o from north to south, so ellipsoid correction has to be taken into account in the computation of the (quasi) geoid.

3. Height Anomaly Control Network in China (HACN2000)

(1) Accuracy evaluation for the A-order network in HACN2000

One of the important bases for the computation of CQG2000 is the height anomaly control network (HACN2000) established with GPS leveling technique. According to the requirement of CQG2000, the network is established in two orders, A-order and B-order. The A-order in HACN2000 is established in accordance with the standards of the national A-order GPS positioning and national 1st or 2nd-order leveling control network. The major objective of the A-order HACN2000 is to transfer accurately the height anomaly in a large span across the country in order to reduce error accumulation. So far 30 points of the A-order HACN2000 have been accomplished which are evenly distributed over China with an average distance of 700 km. Its relative accuracy is at the grade of 10^{-9}.

Another part of HACH2000 is the B-order height anomaly control network. It is measured with the national B-order GPS positioning standards and national 2nd or 3rd-order leveling network. There are 750 points of the B-order HACN2000, which are distributed in the east, central, and west parts of China with the resolutions of 80, 130 and 250 km respectively. The accuracy evaluation formula for the A-order HACN2000 (against Xi'an geodetic origin) is

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where *L* is the accumulated length from the point along the A-order network to Xi'an geodetic origin. Taking the furthest point into account, let *L* =3000 km, then =±0.21 m.

（2）Accuracy evaluation for the B-order network of HACH2000

The formula of the accuracy evaluation of the B-order HACH2000 against Xi'an geodetic origin is

(central and East China),

(West China).

If the most remote point of B-order in West China is taken into consideration, i.e. let *L*=3000 km. Substitute it into the above formula, then the accuracy of the height anomaly against Xi'an geodetic origin is .

As far as the B-order points in central and east China are concerned, the corresponding accuracy is not worse than ±0.23 m if the above formula is used in the computation. It can be seen from this that the accuracy of height anomaly at the corresponding point of HACN2000, which contains China A-order and B-order GPS leveling networks, is no worse than ±0.3 m.

4. Fitting of Gravity (Quasi) Geoid to HACN2000

The systemic or random differences between the gravity (quasi) geoid and the (quasi) geoid obtained from the GPS leveling are caused by various factors. For example, the geoid computed by use of terrain gravity data, potential model and DTM is not connected with certain coordinate system. While the computation of GPS leveling is strictly consistent with the specified coordinate system, potential model and height datum. These factors will lead to the differences of the two kinds of geoids (Table 1).

Table 1. Differences of Height Anomalies between Gravity Geoid and HACN2000

Num. of points	Max. value	Min. value	Aver. value	Standard value
671	1.407 m	-1.518 m	-0.084 m	±0.432 m
28	0.850 m	-1.476 m	0.046 m	±0.481 m

The results of test computation show that the systemic part of the differences between height anomalies of China's gravity (quasi) geoid and those of HACN2000 can not be fitted with each other by coordinate transformation parameters. The differences can not be effectively improved by coordinate transformation of 3 parameters. Therefore quadric multinomial is used to make the fitting, which is important for reducing the systemic error and match the gravity geoid into a specified coordinate framework.

In order to test the accuracy of the above fitted geoid (the mainland part of CQG2000), we chose 80 GPS leveling points from China Crustal Movements Observation Network to conduct the field check, which are evenly distributed in China mainland and with 10^{-9} relative accuracy. The test results of the field check demonstrate that the height anomaly of the mainland part of CQG2000 has reached the precision of decimeter. The RMS in the area east to 102°E is no larger than ±0.3 m. And the in the area west to 102°E , the RMSs are ±0.4 m north to 36°N and ±0.6 m south to 36°N respectively. The nominal resolution of CQG2000 is 5'×5' in the mainland areas, practically no worse than 15'×15' and 30' ×30' in the east part and west part respectively.

II. RESEARCH AND COMPUTATION OF CHINA MARITIME GEOID

1. Scheme for the Computation of China Maritime Geoid

The following scheme is adopted for the computation of China maritime geoid after research and test computation.

(1) Three kinds of data obtained from Geosat, TOPEX/POSEIDON(T/P) and ERS-2 are used for joint data processing. Deflections of the vertical are considered as the basic (input) data to determine the marine gravity field.

(2) The crossing points are solved by total combination of the three kinds altimeter satellite orbits in pairs. The deflections of the vertical are taken at the crossing point.

(3) GRS 1980 and ITRF93 (reference frame for T/P orbit) are taken as the reference frame for China maritime geoid. The orbit of ERS-2 also belongs to ITRF

system. However the biases in the Geosat data caused by the reference frame have to be corrected

(4) Molodensky formula for geoid height inverse from the deflections of the vertical is used to compute the maritime geoid. The gravity anomalies derived from inverse Vening-Meinesz formula are used for internal check with those from Stokes formula, and the gravity dada measured by ship are compared with those obtained from altimeter as an external check.

2. Testing of the Computed Results of China Maritime Geoid

(1) Accuracy test of marine gravity anomalies inverse solved from satellite altimetry

The gridded deflections of the vertical in China maritime area are computed from satellite altimeter with 1500 Gb vast data, then they are inverted into the gravity anomalies. Compared and checked with about 600 000 ship measured gravity anomalies, the RMS and standard error are ±9.35 mGal and ±9.34 mGal respectively. The results computed with accurate 2D plane convolution formula are compared with that computed with 1D rigorous convolution formula, and their maximum differences are –1.7 mGal and 1.8 mGal respectively.

(2) Accuracy estimation for the maritime geoid height inversed from satellite altimeter

To test the reliability of the geoid computation, one geoid is computed with Stokes formula by the gravity anomalies derived from inversion. Another geoid is inversed from the deflections of the vertical. Comparing the two geoids, the standard error is ±0.025 m, it means the confirmation of the precision of the computation results.

III. THE MATCH OF CHINA MAINLAND GEOID AND MARITIME GEOID

1. Principles for the Match of China Mainland and Maritime Geoids

It is rather complicated to identify the causes of the differences happening in the two geoids, one is determined by the ground gravity data, and the other determined by altimeter. Besides, it exists a gap of gravity data between the conjunction area of mainland and the shallow sea of China. Considering the practical situation in China, the following scheme is put forward for the match of the mainland and maritime geoids.

(1) The resolution and accuracy should keep consistent after the match of the maritime geoid with mainland geoid. The RMS of maritime geoids should be better

than ±0.3 m after the match, then it is necessary to ensure the new geoid CQG2000, which covers the total territory of China, reaches the accuracy at the magnitude of centimeter.

(2) Mainland geoid should remain unchanged after the match. The reason of using satellite altimetry data to extend the mainland geoid to the maritime areas is that the density and accuracy of the gravimetric data in east part of China are rather high, which can reduce the effect of the systemic error caused by altimetry data over the sea area.

(3) The match should meet the requirements of the potential theory. The geoid after match (CQG2000) should keep the original nature of equipotential surface. Therefore the match should be satisfied with Laplace equation.

(4) Earth gravity model EGM96 is used as the reference gravity field for the match, which will control the smooth match of the two geoids at middle and short wave lengths. Meanwhile GRS1980 is used in the match in order to keep consistent to the international reference ellipsoid.

2. Scheme for the Match of China Mainland and Maritime Geoids

Suppose the computations of China mainland geoid and the China maritime geoid obtained from altimeter have already been completed respectively before the match. Then the gridded mean gravity anomaly of China's coastal area and the gridded mean gravity anomaly of China's maritime area along the coastal area, which is inversed from the altimeter data, are selected and computed together with Stokes formula to determine a local gravity geoid. The selected coastal area should be as equal to or a bit larger than the adjacent maritime area. As a matter of fact the local gravity geoid only includes the above mentioned selected areas, i.e. a part of China mainland and China's maritime area, so hereinafter referred to it as China "mainland-sea local gravity geoid". Then the mainland area of the "mainland-sea local gravity geoid" is fitted to the overlapped part of the already completed mainland geoid. The derived fitting parameters are used to correct the total gravity geoid of China's total maritime areas, while the completed mainland geoid remains unchanged. Having strong control over the altimeteric gravity data in maritime areas at this stage, the mainland gravity data are used to calibrate the altimetric maritime geoid in order to reduce the systemic errors in the altimetric maritime geoid.

The purpose of the above mentioned scheme is to determine a unified "mainland-sea local gravity geoid" by calculating the gridded mean gravity anomaly of the mainland along China's coastal areas, and the gridded mean gravity anomaly was inversed from the altimeter data in China's maritime areas adjacent to the coastal area. Theoretically, the scheme is deliberate and reliable. The weakness of the scheme is that the gravity anomaly of EGM96 has to fill the gravity data gaps in the adjacent areas between mainland and sea of China, which may lead to the low precision of the maritime geoid at short wave length. In addition, in lacking of external (practical) check on the systemic errors possibly existed in the altimetric marine gravity anomaly, and it is difficult to estimate the real accuracy of geoid in the maritime area. In order to avoid the influence on the mainland geoid coming from maritime geoid in such match, the computed mainland geoid keeps unchanged and only the altimeter maritime geoid is corrected in the match.

3. Mathematical Model of the Match of China Mainland-Sea Geoids

After the determination of the "mainland-sea local gravity geoid" is computed with Stokes formula, it needs to be fitted to the overlapped part of the already computed mainland geoid. The fitting parameters in the computation are used to correct the marine gravity geoid. After comparison of the fitting models, a quartic multinomial is used to fit the two geoids by the least-square method to reduce and eliminate the differences between them.

The scheme presented in this paper takes the gravity data on the mainland and the marine data inversed from altimeter as a whole to derive a unified "mainland-sea local gravity (quasi) geoid". Then China mainland (quasi) geoid is used as a control factor to match the "mainland-sea local gravity (quasi) geoid". An adjusted China's unified mainland-sea (quasi) geoid (CQG2000) is then determined accordingly. The influence of systemic error caused by the altimeter marine gravity data can be controlled as the measured data (surface gravimetric data and GPS leveling data) are playing important roles during the procedure for the determination of CQG2000 in this scheme.

IV. CONCLUSIONS

1. Utilization of High Resolution DTM and Surface Gravity Data of China

High-resolution DTM and surface gravity data of China are used to compute China mainland gravity (quasi) geoid by remove/restore method on the basis of EGM96. The geoid is then fitted to China's height anomaly control network (HACN2000) to determine the mainland (quasi) geoid, i.e. the mainland part of the new geoid CQG2000.

2. Utilization of Vast Altimeter Data for China Maritime Geoid Determination

The vast satellite altimeter data of China's maritime areas are used to inverse China maritime geoid through the computation of the deflection of the vertical in order to reduce the systemic errors. The gravity values measured by ship are used to check the corresponding values derived from the altimeter data, which demonstrates all the computation is right.

3. The Least Square Method Is Used to Fit the Mainland and Maritime Geoids

The least square method is used to fit the mainland and maritime geoids and then to determine the new (quasi) geoid CQG2000.

4. Strict ID FFT or FHT is Used for Integral Computation

Strict ID FFT or FHT is used for integral calculation. Ellipsoid correction or G1 term is considered in the integral formula.

5. CQG2000 Has Been Tested by Production Practical

CQG2000 has been tested by production practical that the accuracy of height anomaly of CQG2000 has reached the designed value, at the level of centimeter. The RMS in the area east to 102°E is no worse than ±0.3 m. And that in the area west to 102°E, the mean square errors are ±0.4 m north to 36°N, and ±0.6 m south to 36°N respectively.

CQG2000 has covered China's total territory, i.e. all the mainland and maritime areas including the special economic zones. The resolutions in mainland are 15'×15' in the east area and 20'×20' in the west. Therefore the accuracy and resolution of CQG2000 has all been upgraded at one level Compared with China's existing geoid CQG1980.

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PROGRESS ON THE
EARTH'S GRAVITY FIELD IN CHINA

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I. ESTABLISHMENT OF NFGN 2000

As same as the establishment of other geodetic control network, the gravity network is also set up by the way of step control. The national fundamental gravity network (NFGN) can provide the gravity datum and the highest order control of gravimetry for different purposes. The first NFGN in P.R.China, named NFGN 57, was established in 1957, its mean accuracy is ± . Afterwards, NFGN 85 was constructed in 1985 for the requirements of the national economic construction and the development of science and technology. The systematic error of Potsdam absolute gravimetric system was corrected for NFGN 85, more gravity fiducial points are available, and the density of absolute gravimetric point improved. So the mean accuracy of NFGN 85 is better than that of NFGN 57 by one order of magnitude, and can arrive at ± . Now the accuracy and the reliability of NFGN 85 cannot meet with the requirements of resource exploration, national defense construction, surveying and mapping, spaceflight technology, geoscience, etc., due to the lower observation accuracy and inhomogeneous distribution of absolute gravimetric points, not completely reasonable figure structure of NFGN 85, some gravity basic points destroyed, etc. For these purposes, NFGN 2000 covering the whole territory of China except for Taiwan was designed and measured since 1999. This network consists of 133 gravity points, and there are 17 fiducial points (absolute gravimetric points) and 116 basic points (relative gravimetric points) among these gravity points. Furthermore, one derived point was laid out for every point of 106 basic points, which were used as the spare point of basic point. NFGN 2000 has the following characteristics and improvements by comparing to NFGN 85:

（1）17 high accuracy absolute gravimetric points were laid out reasonably and homogenously over the whole territory of China, which further improved the gravity datum of national fundamental gravity network.

（2）The figure structure of NFGN 2000 was designed optimally, and the observational figure structure and the figure strength of west China especially improved and enhanced, so the overall accuracy of NFGN 2000 was improved.

(3) The calibration line of gravimeter (long base line) and the national high accuracy calibration site of gravimeter constant (short base line), were reconstructed and improved for the unification of gravimetric scale and the precise calibration of various gravimeter constants.

(4) NFGN 2000 was connected to NFGN 85, and joined together with the gravity basic network of national important scientific engineering “Monitoring Network of Crustal Movement in China”.

The mobile absolute gravimeter FG-5 and LCR-G gravimeter were used in NFGN 2000. The effects of tide, pressure, polar movement, vertical gradient, etc., were corrected for the absolute gravimetric measurements of NFGN 2000. So the observation accuracy of gravity fiducial points is better than ± . For the relative gravimetric measurements, the effects of tide, pressure, height of instrument, zero drift, etc., were also corrected. The relative observation accuracy of gravity basic points is better than ± . Therefore, the standard error of NFGN 2000 is not larger than ± after adjustment. The heights of the gravity fiducial point, basic point and derived point are relative to China’s 1985 Yellow Sea Height Datum, and their planar coordinates with respect to Xi’an 80 coordinate system.

II. REFINEMENT OF LOCAL GEOID

The local or regional geoid with high resolution and high accuracy can provide the fundamental geo-spatial information not only for surveying and mapping, geophysics oceanography and geodynamics, but also for the construction of “digital China”, and now especially for applying GPS technique to determine orthometric or normal height in geodesy and surveying engineering. For these purposes, the new quasi-geoid model CQG2000 with the accuracy of decimeter level has been constructed, which covers the whole territory of China (Chen et al., 2001). The local quasi-geoid with the accuracy of centimeter level and the resolutions of 2¢.5 and 1km has also been determined respectively for Jiangsu Province and Shenzhen City, P.R.China. In future the local quasi-geoid with high accuracy for other provinces and developing regions in China will be determined continually. It is hopeful that the high accuracy quasi-geoid can be employed to the substitution of traditional third and fourth order spirit leveling, the large-scale digital mapping, etc. This will accelerate the construction of “digital city” and “digital China”.

With remove-restore technique Wuhan University calculated the quasi-geoid of Jiangsu Province using the following data: (1) 8756 discrete gravity data on land; (2) marine gravity anomalies on 422475 cross points derived from the multi-satellite altimetric data of version 3 T/P (cycle 1 to cycle 249), Geosat/GM/ERM, ERS-1, ERS-1/168 days, and ERS-2 (cycle 0 to cycle 52); (3) digital terrain model (DTM) with resolution of 18².75´28².125 covering the whole territory of Jiangsu Province, 2¢´2¢

global DTM2000 provided by NASA/NIMA; (4) high quality GPS/leveling data; and (5) WDM94 and EGM96 geo-potential models. Moreover, all integral computations such as terrain correction, first term correction of Molodensky solution, etc., were carried out by rigorous 1-D FFT technique. The resolution of the quasi-geoid is 2¢.5´2¢.5, and its accuracy is better than ±0.078 m.

With the fast development of science and technology, and the requirements of economic construction in Shenzhen City, the land planning department of Shenzhen decided to construct the Shenzhen quasi-geoid with the resolution of 1km and the accuracy of centimeter level in 2000. For

this purpose, the GPS/leveling network consisting of 73 control points was laid out in 2001, and 4870 discrete gravity points were also collected using Lacoste & Romberg model ‘G’ and “D” land gravimeter and model ‘S’ marine gravimeter. And then with almost the same method as that computing the quasi-geoid of Jiangsu Province, Wuhan University calculated the Shenzhen quasi-geoid with the resolution of 1km, using 65 high accuracy GPS/leveling data, 5213 discrete gravity data, digital topographic model with the resolution of 100 m which covers the whole territory of Shenzhen and its neighboring region, and WDM94 geo-potential model. The geoid covers the area of 8 km to 60 km along south-north direction and 79 km to 179 km along west-east direction in Shenzhen local grid coordinate system. Finally, the modeled geoid heights and geoid height differences were compared to those from 29 high precision GPS/leveling data that not used to the calculation of the geoid. And the check results show that the accuracies (standard deviations) of the geoid height and geoid height difference are ±0.014 m and ±0.019 m, respectively, and its overall relative accuracy is better than 1ppm.

Chinese geodesists have always investigated the methods for transferring the height within long distance across sea. Up to now there are four methods used to the height transference, such as static leveling, dynamic leveling, GPS/leveling and conventional geodetic method. The conventional height transferring methods are not practical due to the time-consuming and labour-intensive. Wuhan University studied the method of the height transference within long distance across sea by combining the ellipsoidal height from GPS and the precise gravimetric geoidal height. Using this method the China’s 1985 Yellow Sea Height Datum is transferred to Yangshan Island, which is 30 km far away from Shanghai. The transferred heights are then compared with those determined from two independent sets of gauge records, and the differences are 1.0 cm and 5.0 cm respectively. Moreover, the transferred height differences on the island are also compared with those derived from third order precise spirit leveling, which indicates that the differences are 0.2 cm and 0.7 cm respectively. These test results show that the method is inexpensive, very effective and reliable for the height transference within long distance across sea.

III. SATELLITE ALTIMETRY

Since 1970s, the marine gravity field derived from multi-satellite altimetry missions has rapidly been developed. Combining processing the altimeter data of TOPEX/Poseidon (9-249 cycle), ERS2 (0-44 cycle), Geosat/GM(1-25 cycle) and Geosat/ERM (1-66 cycle), it was solved out for crossover points of respective satellite altimetric mission and the deflection of the vertical along altimetric track profiles, and then the marine gravity anomalies gridded in 2.5¢×2.5¢ size over the South China Sea were determined using inverse Vening-Meinesz formula. Comparing the gravity anomalies derived from the altimeter data with 600 000 gravity anomalies measured by marine gravimeter, it shows that RMS and STD of the difference between them are ± 9.4 mGal and ±9.3 mGal respectively. A new gravity recovery method with along-track vertical deflections is developed independently on the basis of the Laplace's equation in Cartesian system. The method can be easily approached with 1D Hilbert transform and the along-track gravity anomalies can be derived directly from the along-track slopes of sea surface height (SSH). In other words, only along-track slope of SSH needs to be calculated other than two slopes of along-track and cross track at crossover point（Li et al., 2001; Wang et al., 2001; Huang et al., 2001）.

Four-year altimeter data from T/P and one-year altimeter data from ERS-1 in the China sea and its vicinity are used to determine the mean sea surface (MSS) with stacking method along the satellite repeated collinear tracks. After the contributions of sea surface topography are reduced from the MSS, the 30'´30' geoid undulations are obtained, and the accuracy of geoid is 8.5 cm (RMS) (Xu et al., 1999). The marine deflection of the vertical is computed from the altimeter data of Topex/Poseidon, ERS-2 and Geosat/GM ERM, in which 2.5'´2.5' grids for calculation are used, and then 5.0¢´5.0¢ geoid determination of China Sea Area is carried out by Molodensky method. In order to check the computed results, the geoid which is directly solved out by Molodensky formula mentioned above is compared with that computed by Stokes formula using the deflection-inversed gravity anomaly data as an inner examination, and the standard deviation is ±0.025 m. Considering the reality that there is lack of gravity data in China coast area, an extending method is advanced for piecing the two types of geoid determined by different principle and data set. Finally, the continent-marine gravity geoid after piecing together is then fitted with quasi-geoid determined by National GPS leveling network, and the corrected gravity geoid called CQG2000 is obtained (Chen et al., 2001).

The method for determining mean sea surface (MSS) by using multi-altimetric data is developed. The data used to compute WHU2000 MSS include 7 years of Topex/Poseidon data (cycle 11 to 249), 2 years of Geosat ERM data (cycle 1 to 44), 5 years of ERS2 data (cycle 1 to 52) and all ERS-1 168-day data. The WHU2000 MSS is determined with resolution of 2¢´2¢ within the ±82° latitude and its precision is better than 0.05 m. Comparing WHU 2000MSS with 3.75¢×3.75¢ CLS-SHOM98.2

MSS, 3¢×3¢ GFZ MSS95A and 3.75¢×3.75¢ OSU MSS95, as an external check, the corresponding STDs of their differences are 0.090 m, 0.211 m and 0.079m respectively (Jiang et al., 2002； Li et al.， 2001).

The collinear method is used to determine MSS heights and their variations in the regions of China seas including Yellow Sea, East China Sea and South China Sea with T/P and ERS-1 altimeter data during the period from October of 1992 to June of 1998. After having done the corrections of T/P altimeter instruments bias, and geophysical environment corrections of tide, ionosphere, troposphere, sea-state bias and inverse barometry, we find that rising rates vary in different regions. Compared with global annual sea level ring rate (+2.1±1.3) mm/a, the annual rising rate in Yellow Sea, East China Sea and South China Sea is (+3.44±0.61) mm/a, (+3.12±0.47) mm/a and (-1.41±0.48) mm/a, respectively. From sea level anomalies, it can be seen clearly that the influences of El Nino in 1993, 1994, and 1997-1998 are greatest in South China Sea, less in East China Sea and least in Yellow Sea (Hu et al., 2001; Wang et al., 2000).

Based on the characteristic of the perfect spatial distribution of the *T*/*P* altimeter data, a spatial analysis method is performed, which transfers the constituents harmonic constant *H* and *g* into a pair of orthogonal parameters *U* and *V*, and then expresses each of them with a polynomial function. As parameters, the polynomial coefficients are derived with altimeter data on the least squares criteria. Thus the models of the main tidal wave in south sea are established. 72 weeks T/P data through weeks 11 to 82 are included in the calculation. The models are evaluated with different approaches and data set. The conclusion is that the tide models can provide partial tide amplitudes with 3cm accuracy, phase lags deviation of those amplitudes which are larger over 10 cm are within ±10°, and the tide models derived are better than those of Schwiderski and SR95.1 (Bao et al., 1999; Bao et al., 2000).

After the geoid is determined, the dynamic ocean topography with 15¢´15¢ grid over China oceans is separated from MSS heights. The RMS of difference between the computed dynamic topography and EGM96 SST model is 0.220 m (Jiang, 2001). The method that hydrodynamic models are reconciled with observation, e.g. altimeter and oceanographic data, is called as data assimilation. Observational equations are formed using finite difference method from the elevation-mode of steady current and its solid boundary condition with stationary sea surface topography as observation values and the square root of onflow friction coefficient as parameter, and the combination problem is solved with parameter adjustment. In the end, stationary sea surface topography of East China Sea, in 22°-41° and 116°-131°E, is calculated with T/P and ERS-2 altimeter and oceanographic data (Zhang et al., 2000).

Besides, the bathymetry model in South China Sea is calculated from gravity anomalies derived from altimteric data, and the interpretation on the characteristics of gravity anomalies is implied by the tectonic block boundaries and their inner structures using the 2.5¢´2.5¢ free air gravity anomalies derived with satellite altimetry data (Yao et al., 2001).

IV. HIGH DEGREE GEOPOTENTIAL MODELS

Since high resolution gravity anomaly data derived from satellite altimetry over global oceans are available now, it is possible for us to develop some ultra-high degree (n>360) geo-potential models. Recent three years, several research institutes in China have presented some such geo-potential models which include MOD99b/c/d, WDM2001, IGG-SCS00A/P and DQM2000A/B/C/D.

The maximum degree-orders of MOD99b/c/d series are 720 (b) and 1800 (c/d) respectively (Huang et al., 2001). In the development of the model series, the gravity data acquired in the continent of China and the global altimeter-derived 2’×2’ gridded marine gravity anomalies are used, and EGM96/GPM98CR are taken as the reference models. Based on the data tailor method, however, it only acts as a local improvement upon an existing global model. Unfortunately, it is possible for such local improved model to present some fluctuations in stairs-form around the boundary of tailoring area. In order to overcome this weakness of the method and to make the reference model used smoothly fitted with the local data, the idea on a local improving of reference model by tailoring is extended into a global improving procedure. Based on the global data file of gravity anomalies computed from the reference models, the model-derived anomaly data within the continent of China and the global oceans are updated by a new higher quality data set acquired from terrestrial gravity measurements and a global altimeter-derived marine gravity anomaly data set, and then the coefficients of the models to be developed are corrected by a global integral process. The geoidal undulations computed by MOD99b/c/d have been computed with those of 72 GPS leveling points and the altimeter-derived ones in 12 ocean areas respectively. The RMS of the differences between the MOD99 series-derived undulations and GPS leveling–measured ones is about 0.6 m, and the interval distribution of RMS of the differences between the models-derived undulations and the altimeter-derived ones is ±0.02 m - ±0.26 m in the oceans.

The maximum degree-order of WDM2001 is 720 (Li, 2000). 420 000 terrestrial gravity values acquired in the continent of China are adopted to form 15’×15’ gridded data set of gravity anomalies after data reduction processing. Using altimeter data set including the GRDs of T/P, ERS1/2, and Geosat/GM/ERM in the new edition, the deflection of the vertical is computed at crossover points of respective ground tracks, and then transferred into the gravity anomalies by the inverse Vening-Meinesz formula given by Molodensky. The resulting global marine gravity anomaly data along tracks are reduced in 15’×15’ gridded data set by interpolating and fitting procedure. The terrestrial gravity anomalies computed from EGM96 are used in the land outside the continent of China. Combining all the above three types of gravity anomaly data, a global 15’×15’ gridded data set is formed as the basic input data in the model computation. In addition, the satellite geo-potential model GRIM5-S1 with maximum degree 36 is also taken into account as a priori information of the low degree for developing the model. The geo-potential coefficients of WDM2001 are determined by use of rigorous spherical harmonic analyses and combined adjustment. The geoid undulations computed from this model are compared with those of 631 GPS leveling points, and the standard deviation of the differences in the comparison is ±0.56 m. The model is also compared with EGM96 and WDM94, and the corresponding results of the comparison in geoidal undulations are ±0.57 m and ±0.78 m respectively.

IGG-SCS00A (Lu et al., 2001a) is a regional ultra-high degree geo-potential model with a maximum degree-order of 3600, computed from 3’×3’ gridded altimeter-derived marine gravity anomalies in South China Sea and vicinity (105°-122°E, 0°-25°N) based on the integral formula for spherical harmonic expansion and using local integrals of spherical harmonics. For the start of the iteration procedure, geo-potential model GPM98C is used. The model gravity anomalies of IGG-SCS00A have been compared with the marine ones in South China Sea, and the RMS of discrepancies between them is ±3.2 mGal, and the geoidal undulations of the model have also been compared with 3’×3’ altimeter-derived marine ones, which shows that the RMS of the discrepancies between them is about ±0.2 m. Using 2’×2’ gridded altimeter-derived gravity anomalies in the same area as mentioned above, the computation of the model IGG-SCS-P is based on the Pseudo-Harmonic Regional Analysis (PHRA) method taking a scale factor as 5 and expanded to 1080 degree and order that really corresponds to 5400 degree and order in common spherical harmonic expansion (Lu et al., 2001b). A similar comparison to the above, but at 2’×2’ resolution level, shows that the corresponding RMS is ±2.4 mGal and ±0.19 m respectively.

The maximum degree-order of the model series DQM2000A/B/C/D is 540 (A), 720 (B), 1080 (C) and 2160 (D) respectively (Surveying and Mapping Institute of Xi’an, 2001). In the development of the models, EGM96 is taken as a basic reference model, and 200692 5’×5’ terrestrial gravity anomalies acquired in the continent of China are used as the basic input data. The method for computing the model series is based on a local spectrum-weighted integral improving procedure to the reference model used. The accuracies of DQM2000A/B/C/D used in computing the terrestrial gravity anomaly in the area of the continent of China are ±10.4 (A), ±10.6 (B), ±13.3 (C) and ±18.6 (D) (unit: mGal) respectively, and the accuracy of computing geoidal undulations from the models in the same area is ±0.5 m— ±0.7 m.

V. SATELLITE GRAVITY GRADIOMETRY

At the beginning of 21st century, satellite gravity gradiometry or satellite-to-satellite tracking (SST) is known as one of the most promising techniques for the future progress in studying the earth’s gravity field. One of the primary scientific objective of ongoing satellite missions like GOCE is to provide with unprecedented accuracy, global and high-resolution estimates of the constant and time-variable part of the Earth's gravity field. In recent years, Chinese scholars always track the progress of these techniques, and focus on studying their fundamental theories and methods. Wuhan University studied the principle, technical mode, error sources and their characteristics about SGG and SST, and discussed the technical scheme and possibility for developing SGG and SST in China. In theory, the determination of the earth's gravity field using satellite gravity gradiometry data, is reduced to resolve satellite gravity gradiometry boundary value problem. The stochastic satellite gravity gradiometry boundary value problem was presented by Wuhan University, and corresponding practical computational models are derived. The generalized spherical harmonic series representation of the global and local gradient components for the full gravity tensor was given by Zhang et al. (2000), as well as the relationship between the generalized spherical harmonic function and the spherical harmonic function. A set of formulae for computing the geoid, gravity disturbance, gravity anomaly and deflection of the vertical from the second radial derivative of the disturbing potential are derived in detail using the basic differential equation with spherical approximation in physical geodesy and the modified Poisson integral formula. The derived integral in the space domain, expressed by a spherical geometric quantity, is then converted to a convolution form in the local planar rectangular coordinate system tangent to the geoid at the computing point, and the corresponding spectral formulae of 1-D FFT and 2-D FFT are presented for numerical computation (Li, 2002). It is hopeful that these achievements would be employed to recover the Earth's gravity field and to compute the gravity quantities in practice using satellite gravity gradiometry data.

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EARTH TIDES AND SUPERCONDUCTING GRAVIMETER MEASUREMENTS

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The main progresses in the fields of the measurement and theoretical research of the Earth tides as well as the superconducing gravimeter observations and its application to geodynamics achieved by Chinese scholars in recent years (1999-2002) are briefly reviewed in this paper.

I. EARTH TIDE MEASUREMENT

By fitting the orbits of satellite to the highly precise measurement of satellite laser ranging (SLR) to Lageos-1 and combining the altimetry-derived ocean parameters, Wu et al. recovered the amplitudes and phases of the Love number k_2 for different tidal waves. The obtained k_2 values for M_2, S_2, K_1 and Q_1 waves are 0.3027, 0.3014, 0.2573 and 0.2968 respectively. The phase lag of k_2 is 0.°12   0.°09 for M_2, and 0.°14   0.°12 for K_1. The amplitude and phase lag of k_2 for the 18.6-year tide are 0.3154   0.0070 and 3.°1   2.°0 respectively.

Institute of Geodesy and Geophysics of Chinese Academy of Sciences discussed how to use two different methods, i.e. the length of day (LOD) method and satellite orbit perturbation (SOP) method to study the Love number k_2 of the long period solid Earth tides M_f and M_m After taking the effect of non-equilibrium ocean tide in account, the real parts of k_2 given by these two methods agree well for M_f and M_m waves, but the imaginary part of k_2 obtained by the LOD method is negative. However the result determined by the SOP method is positive, which is consistent with the phase lag of k_2 predicted by the anelastic Earth model.

Using the SLR and ground gravity observation data, the solid Earth tidal displacement Love numbers h_2 and l_2 have been determined. The obtained h_2 values for M_2, S_2, K_1 and Q_2 waves are 0.6062, 0.6114, 0.5234 and 0.6024 respectively. The SLR solution indicates that the result of the vertical displacement Love number h_2 is better than one of the horizontal displacement Love number l_2.

Based on the comparison of the theoretical values predicted by two anelastic models with the recently observed ones of tides and the Earth rotation variations at M_2, M_f, M_m, Chandler wobble and 18.6-year frequencies, Zhu et al. (2000a) analyzed the response of mantle anelasticity at different tidal frequencies. The observed results of space geodesy were used to constrain the theoretical models of anelasticity. The results show that Zschau's model can interpret the observed amplitude of the anelastic Love number in the regime from the seismic frequency to the 18.6-year frequency, but at some frequencies, there are some discrepancies between the observed and theoretical phase lags. The anelastic Love numbers predicted by a single absorption band model do not accord well with the observed values at these frequencies.

Using the tidal solutions obtained from SLR and the ocean tidal solutions from satellite altimetry, Institute of Geodesy and Geophysics， CAS computed the secular changes in the Moon's orbit elements and the Earth rotation rate in the ecliptic reference system. The SLR-derived secular change in the Moon's mean motion caused by the total tidal dissipation is -24.78 arc sec/century^2. The secular change in the Earth rotation rate caused by the solar and lunar tides is -5.25×10^{-22} rad/s^2. Taking the non-tidal effect of the changes in the Earth rotation rate into account, the corresponding change in the length of day is 1.49 ms/century. Combining the tidal solutions determined by altimetry and SLR, the effects of the solid Earth and oceans on the secular variations of the Moon's mean motion and Earth rotation rate are distinguished. The result shows that the tidal energy dissipation in the solid Earth is about 3%-4% of the tidal energy dissipation in oceans.

A new method to calculate the secular change in the Earth rotation rate caused by the tidal dissipation was developed by Institute of Geodesy and Geophysics, CAS. In this method the tidal torques exerted by the tidal potential from the Earth on the Moon and the Sun are directly calculated. Based on the SLR-determined tidal parameters, the tidal secular change in the Earth rotation is obtained with high level of accuracy, the value is -6.01´10^{-22} rad/s^2. The tidal secular change in the Earth rotation derived from the astronomical records from 700 B.C. to. 1600 A.D. is -4.5´10^{-22} rad/s^2. After removing the tide effect, the non-tidal acceleration in the Earth rotation rate is 1.5´10^{-22} rad/s^2. So the secular change of geopotential coefficient is derived, that is =-3.2 ´10^{-11}/year. This value agrees very well with the results of estimated directly from satellite tracking data.

II. THEORETICAL STUDY OF EARTH TIDE

The computation of the Love numbers usually uses the numerical method to solve a system of ordinary differential equations (ODEs) that is singular at the Earth center. When using the traditional methods such as the Runge-Kutta method to solve such kinds of ODEs, the special treatment must be taken at the Earth center. Wuhan University applied a new method, the Chebyshev collocation method, to solve this problem. This method does not require the special treatment of the ODEs at the Earth center, and can give high precise results. The programs for computing the Love numbers and the loading Love numbers of the SNREI Earth model using the Chebyshev collocation method have been provided.

Wuhan University explained the fundamental concepts and theory of the Earth tides, including tidal generating force, tidal generating potential, tidal waves, Love numbers, various observable tidal phenomena, the theories of tidal and loading tidal deformation of the SNREI Earth model, etc.

Institute of Geodesy and Geophysics, CAS discussed the tidal motion equations of the anisotropic media in the upper mantle. Based on the parameters of the Earth's model given by Dziewonski, the Love numbers and loading Love numbers were calculated by using the classic Runge-Kutta numerical integral method. The results show that the effect of considering the anisotropic property in the upper mantle or not on the Love numbers is relatively small (about 0.06%). However, the effect to the loading Love numbers is relatively large (about 2.5%).

III. SUPERCONDUCTING GRAVIMETER OBSERVATION

Using the tidal observations obtained by the LCR-ET spring gravimeters during the cooperation of China-British and China-Germany, Institute of Geodesy and Geophysics, CAS determined the calibration factor of the superconducting gravimeter (SG) based on the method of the weighed sum of the main tidal wave amplitudes. Using the FG5 absolute gravimeter and the SG measurements at the same station during two periods in 1999 and 2000, Institute of Geodesy and Geophysics, CAS determined the calibration factor based on the method of the least square polynomial fit. It shows that the results obtained by these two methods are identical.

Using the international standard analysis methods, Institute of Geodesy and Geophysics, CAS filtered the data obtained in a period of 48 hours with a band-pass filter. According to the characteristics of different angular frequencies of tidal waves and the properties of the odd and even band filters, the tidal gravity waves, such as the diurnal, semidiurnal and ter-diurnal waves, are separated after the instrumental drift was eliminated from the observations. The tidal changing characteristics of the gravity field at different areas, such as China, Japan, Belgium, France and so on, are studied. The possible factors including choosing of the different tidal generating potentials and band filters, considering the air pressure correction or not, getting rid of error data, and so on, which may affect the accuracy of the analytic results, are discussed. The results show that the accuracy of the observed amplitude factors of the main waves is better than 0.04%. Based on the basic concept given by Venedikov, Institute of Geodesy and Geophysics, CAS developed "wavelet analysis method" in which a set of continuous wavelet filter functions to substitute three discrete odd and even filters were used. This method can be applied to analyze the data obtained by the different samplings.

Institute of Geodesy and Geophysics, CAS analyzed the observation data of 8 instruments, especially the long-term SG observations from 1988 to 1994, the improved values of the international gravity tidal reference (IGTR) at Wuhan Station were obtained with high precision. Comparing with the latest theoretical tidal model, the deviation of the amplitude factor decreased from the original one of 4.4‰ to the new one of 3.6‰. Institute of Geodesy and Geophysics, CAS calculated the synthesized gravity tide signals using Wuhan IGTR value, the latest gravity tidal theoretical model, the latest oceanic tidal model and the characteristic of nearly diurnal resonance in gravity tidal observations. The results show that the discrepancy between the synthesized tidal signals and the SG observations at Wuhan is 0.225 mGal.

Institute of Geodesy and Geophysics, CAS discussed the error estimation in the theoretical calculation of the atmospheric gravity signals with statistic technique. The effects of the uncertainty of Earth model, the air pressure data error and the lower density distribution of the station on the calculated results were also studied. Based on the observed gravity tidal residuals and the air pressure at Wuhan Station, and by using the techniques of the correlation and linear regression analysis, Institute of Geodesy and Geophysics, CAS studied the character of the atmospheric gravity in frequency and time domains respectively. After correcting air pressure, the observed gravity tidal residual amplitudes are reduced significantly at all frequency bands. It is shown that the correction using admittances in frequency domain is better than the one using admittances in time domain.

Based on the observation results of the SG at stations Wuhan and Tokyo, Institute of Geodesy and Geophysics, CAS investigated the suitability problem of the latest ocean tidal models (including Schwiderski, CSR3.0, FES95.2, ORI and ORI96). The residual vectors of the gravity tidal observations obtained by considering the loading correction with various ocean models or not were analyzed and compared. The results indicate that the oceanic loading effect is the main part of the residual vector of the gravity tidal observation. After the oceanic loading correction, the residual amplitude of the M2 wave at Wuhan Station is reduced about 70%, the residual amplitudes of the M2 and K_1 waves at Tokyo Station are reduced about 75% and 90% respectively. Based on the Farrell loading theory, the influence of the ocean loading on the surface gravity tide was calculated.

IV. APPLICATION OF SUPERCONDUCTING GRAVIMETER TO GEODYNAMICS

Institute of Geodesy and Geophysics, CAS determined precisely the period, quality factor and resonance intensity of the Earth’s free core nutation (FCN) using the SG observations. The result shows that the eigenperiod of the FCN is 429.0 sidereal days, which is accord with the former results and is about 30 sidereal days smaller than the theoretical value. It proves the conclusion that the real dynamics ellipticity of liquid core is larger 5% than that on the assumption of the hydrostatic equilibrium. The obtained quality factor is close to the one obtained with the VLBI observations. Meanwhile the influence of the ocean loading on the FCN resonant parameters was investigated. The result shows that the effects of different oceanic tidal models on the FCN eigenperiod and the real part of the resonant intensity are comparatively small, the main difference of the result is shown in the quality factor Q values, and the resonant intensity is strong dependent on the oceanic tide models. The influence of the uncertainty of different oceanic tidal models on the FCN parameters can be partly counteracted by staking of observations corrected with these models.

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SATELLITE ALTIMETRY AND ITS APPLICATION

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During the period of this report, Chinese scientists in this field devised the editing criteria of multi-satellite altimeter data, improved each geophysical correction, and analyzed the error sources of satellite altimetry and the corresponding methods to eliminate those errors. They also developed the method of dual satellite crossover adjustment and a new technique of local crossover adjustment between multi-tracks, and used sea surface anomaly model to reduce the influence of sea surface time change on altimeter data of geodesy mission. In this method, the adjusted crossing pairs are composed of ERS-235 (ERS-135), Geosat/ERM (GM), ERS-1/168 and T/P. In the adjustment, the radial orbits of ERS-1, ERS-2, and Geosat SSH data are improved by a crossover adjustment with fixed T/P SSH data. After the data are processed, the root mean square (RMS) values of the difference at the crossover points for ERS1/168, Geosat/ERM and ERS2 are 0.114 m, 0.029 m, and 0.024 m respectively.

The co-line processing method is also studied, which is designed to eliminate the satellite orbit errors and determine mean sea level and its changes according to the satellite altimetry mission. Co-line processing can be used to compress the original observation data significantly, to reduce the influence of all kinds of time change factors and middle-short wave sea surface topography effectively, to reduce random noise and improve the precision of the altimeter data.

The question of establishing a unified datum is also solved. All sea surface height (SSH) data are constructed in a frame. There are systematic differences between SSH data of ERS-2 or SSH data of Geosat/ERM and SSH data of T/P because the reference frames and ellipsoids of them are different. When they are used together, all SSH data should be in a frame. In data processing, ERS-1, ERS-2 and Geosat SSH data are consisted with T/P SSH data in a frame after frame transformation and the crossover adjustment.

At School of Geodesy and Geomatics, Wuhan University, the methods for determining mean sea surface (MSS) are developed and the WHU2000 mean sea surface (MSS) model grided in 2¢´2¢ size is determined for latitudes below ±82°. The precision of this model is better than 0.05 m.

The methods for the recovery of gravity field from satellite altimetry are summarized, and the geoid and gravity anomaly grided in 2.5¢´2.5¢ size over China are recovered from multi-satellite altimeter data. Two methods are used in gravity recovery. The one is the deflection of the vertical along-track profiles with inverse Vening-Meinesz formula and the other is the least square collection (LSC) with shipboard gravity. Compared to the shipboard gravity and SIO gravity, the RMS of difference is 9.0 mGal and 15.03 mGal. After the geoid is determined, the dynamic ocean topography with the same grid over China oceans is separated from MSS height. The RMS of difference between the computed dynamic topography and EGM96 SST model is 0.220 m.

Based on the relationship between the gravity anomaly and mass deficiency of the ocean, the 2.5¢´2.5¢ bathymetry model in the South China Sea is inversed using multi-satellite altimeter data and geophysical data. In the study, the FFT technique has been put in practice, and the effect of proportion has been considered. On the other hand, the calculated result is compared with TBASE model and 49096 values of ship depth by GEODAS.

Scientists at Institute of Geodesy and Geophysics, CAS established two types of MSL models over China's offing and vicinity, using Geosat/ERM and T/P data and grided dual-conicoid model, respectively. The resolution of the models is 30¢´30¢, and RMS comes up to 8.5 cm. The geoid extracted by subtracting long wave long sea surface topography model (Nerem Model) from this model shows there is an obvious anomaly area in Okinawa Trough and Philippine Gouge. Comparing with OSU91A, the RMS of this geoid is 36 cm in East China Sea, 41 cm in South China Sea, 18 cm in the Pacific area. Based on the long wave sea surface topography model Nerem, 20 order sea surface topography model of over China's offing and vicinity is established according to mean sea level model of altimeter data and geoid model JGM3/OSU91A.

2¢´2¢ marine gravity anomaly model over the South China Sea (0^o-25^oN， 105^o-122^oE) IGG99 S is established by along-track inversion of vertical line deviation. RMS of IGG99 S is 14 mGal at the whole South China Sea, 10 mGal at South China Sea basin (10º18ºN， 110º118ºE). The iterative-cut solution of altimetry-gravity is improved and the gravity model over Chinese continent and its offing is established, whose interior precision comes up to 8.7 mGal (gravity anomaly) in continental area, 0.13 m (geoid) in marine area. Benthal topography and its structure are also recovered and a 600 km zone of fracture between 15ºN, 120ºE and 10ºN, 111ºE is detected, which is considered as a sea mount bounding resulting from the collision between India Plate and Eurasia Plate. In addition, the obvious vibrational periodical signal from China's offing sea surface and its space distribution are studied with altimeter data.

Scientists at research group of "THE STUDY ON CONTINENTAL AND SEA LEVEL VERTICAL MOVEMENT IN CHINESE COASTAL AREA", which consists of Chinese Academy of Surveying and Mapping, China National Marine Information Center, School of Geodesy and Geomatics of Wuhan University, and Shanghai

Astronomical Observatory, extracted tidal harmonic constants of 11 main partial tide (O_1, K_1, P_1, Q_1, M_2, S_2, K_2, N_2, M_4, M_6, MS_4) and annual partial tide S_a of Huanghai Sea and East China Sea by T/P altimeter data. The interior precision of partial M_1, M_2 are calculated according to crossover residue; their amplitudes are 2.4 cm and 0.8 cm respectively; the precision of epoch is 2.3°and 2.5°respectively. Compared with the harmonic constants of 13 island tide gauges, the amplitude precision of M_1 and M_2 is 3.8 cm and 2.0 cm respectively, epoch precision is 1.09°and 7.4°respectively. Harmonic constants of 8 main daily and half-day partial tides of South China Sea (S_a, S_{aa}, M_m, M_f, Q_1, O_1, P_1, K_1, N_2, M_2, S_2, k_2) are also acquired. Compared with the tide gauge data, amplitude errors of the partial tide are better than 2 cm; the bigger epoch error is 7°. Amplitudes and epochs of 28 partial tides of northwest Pacific are also calculated with method of difference comparison. Compared with the data of 12 tide gauges in that sea area amplitude precision of O_1, K_1, M_2, S_2 is 1.0 cm, 1.2 cm, 2.97 cm, 1.87 cm respectively. With T/P altimeter data and tide gauge data, an assimilation test has been made to optimize nonlinear open-boundary tidal data by adjoint method; it aims to establish a tidal model over China's offing.

This research group's study of the seasonal change of the global and China sea level with 7 years' T/P altimeter data shows there is a falling trend in the sea level of China Sea in the first season and fourth season, a rising trend in the second season and third season. But for the global sea level, it rose in the first season and fourth season, fell in the second and season third season. The monitoring by T/P altimeter data shows that the change rate of global sea level during January 1993 and May 1999 is 2.0±02 mm/year. In addition, 1997-1998 El Nino over tropic Pacific is monitored by T/P altimeter data; the precision of the monitoring is better than 7 cm.

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PROGRESS IN SLR AND VLBI ACTIVITIES IN CHINA

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I . SLR ACTIVITIES

The Chinese SLR Network consists of 5 fixed stations located in Shanghai, Changchun, Beijing, Wuhan and Kunming and 2 Mobile systems, namely CTLRS and CROS (Yang, 2001). The characteristics of the Chinese SLR stations are listed in Table 1. The active-passive mode-locked Nd:YAG lasers (100 mj, 200 ps) are used in Changchun, Beijing and Kunming, and the SFUR mode-locked Nd:YAG lasers (30 mj, 50 ps) are adopted in Shanghai, Wuhan, CTLRS and TROS. Except CTLRS, all stations are equipped with C-SPAD receivers, which have some advantages: single photon sensitivity, large dynamic range for return signals, low time jitter, compact and rugged design. All stations have the HP58503A GPS time and frequency receivers. Most of above-mentioned instrumentation were supported by the national project “the Crustal Movement Observation Network of China” and installed at the stations since 1997.

The single-shot ranging precision for Lageos for Shanghai, Changchun, Beijing and Wuhan is about 12-20 mm, and 20-30 mm for Kunming and the mobile systems. Shanghai Station developed a multi-satellite alternate tracking and control system and can easily switch tracking of space objects within 20 seconds. The Shanghai Station has daylight tracking capability (Yang, 1999).

Table 1. Characteristics of the Chinese SLR Stations (2002)

City	Shanghai	Changchun	Beijing	Wuhan	Kunming	CTLRS	TROS
Station ID	7837	7237	7249	7231	7820	*	**
Aperture of receiving telescope	60 cm	60 cm	60 cm	60 cm	120 cm	35 cm	38 cm
Aperture of transmitter	15 cm	15 cm	16 cm	10 cm	120 cm	10 cm	10 cm
Pulse energy (532 nm)	30 mJ	50 —100 mJ	50—100mJ	30 mJ	100—150mJ	30 mJ	30 mJ
Pulse width	50 ps	200 ps	200 ps	50 ps	200 ps	50 ps	50 ps
Repetition rate	4 —8 Hz	4 —10 Hz	4 —10 Hz	4 —8 Hz	4 —5 Hz	4 —8 Hz	4 —10 Hz
Type of receiver	SPAD	SPAD	SPAD	SPAD MCP-PMT	MCP-PMT SPAD	MCP-PMT	SPAD

(to be continued)

City	Shanghai	Changchun	Beijing	Wuhan	Kunming	CTLRS	TROS
Time interval unit	HP5370B	HP5370B	SR620	SR620	SR620	SR620	SR620
Frequency standard	HP58503A	HP58503A	HP58503A	HP58503A	HP58503A	HP58503A	HP58503A
Ranging precision	1—2 cm	1—2 cm	1—2 cm	1—2 cm	2—3 cm	2—3 cm	2—3 cm
Operation	Since 1983	Since 1992	Since 1994	Since 1988	Since 1998	Since 2000	Since 2000

Note: 7837 Shanghai Observatory, Chinese Academy of Sciences

7237 Changchun Satellite Observatory, Chinese Academy of Sciences

7249 Chinese Academy of Surveying and Mapping (Beijing)

7231 Institute of Geodesy and Geophysics, Chinese Academy of Sciences (Wuhan) and Institute of Seismology, the State Bureau of Seismology (Wuhan)

7820 Yunnan Observatory, Chinese Academy of Sciences(Kunming)

CTLRS Xi'an Institute of Surveying and Mapping

TROS Institute of Seismology, the State Bureau of Seismology (Wuhan)

The satellite laser ranging experiment with sub-centimeter single-shot precision was carried out at Shanghai Observatory in collaboration with the Czech Technical University. A portable Pico Event Timer and independent data acquisition and processing software package was brought to Shanghai and was operated in parallel to the existed SLR system and has tracked 10 passes satellites which have better distribution of retroreflectors with 7-8 mm single shot precision during August 16-22, 2001. No obvious biases were detected in the experiment.

Changchun Station has good weather and has achieved the requirements of a standard station both in data quality and quantity as issued by ILRS. The system biases for most of the stations are of serious concern, thus the calibration techniques and local surveys are carefully investigated.

The mobile system TROS was moved to Urumqi, the biggest city in the northwest border and had tracked 44 passes of Lageos from April 23 to June 5, 2001. Afterwards, the TROS was moved to Lhasa, Tibet in June 2001, and left in January 2002. It had obtained 102 passes from Lageos and 129 passes from other satellites.

The operation center and data center for the Chinese SLR Network have been set up at Shanghai Observatory. For almost twenty years, the Shanghai Observatory has pursued the high precision processing of SLR data for many geodetic and geophysical investigations. Shanghai Observatory developed the software package

SHORDE (Shanghai ORbit DEtermination), which has been used for the analysis of SLR data since 1982. Since September 1999, Shanghai Observatory has published the Lageos data analysis report for the global stations every week at web site: http://center.shao.ac.cn/APSG/Newsletter/index.htm Shanghai Observatory is acting as an associate analysis center within the ILRS (Feng, 2000).

There is a new cooperation agreement between the National Astronomical Observatories, Chinese Academy of Sciences and San Juan Observatory, Argentina. A new fixed SLR station will be installed at San Juan Observatory by 2003. The plan is supported by the Ministry of Science and Technology, China. The characteristics of the SLR system will be the same as the Beijing Station.

II. VLBI ACTIVITIES

There are two 25-m fixed radio telescopes working for VLBI observations in China. One is at Sheshan near Shanghai and the other at Nanshan near Urumqi. During last four years, the receivers and recording terminals have been improved. The VLBA and MKIIIA terminals of the above stations have been upgraded to MKIV in 2000.

The parameters of the receivers at both stations are listed in Table 2. The two VLBI stations are the members of European VLBI Network (EVN) and International VLBI Service (IVS) for Geodesy and Astrometry (Hong, 2002).

Table 2. VLBI Receivers of Sheshan and Nanshan Stations

Band (cm)	Bandwidth (MHz)	Eff. (%)	Type	Polarization	T system (K)
		Sheshan Station, Shanghai			
18(L)	1620-1680	40	Room Temp	LCP&RCP	~100
13(S)	2150-2350	45	Room Temp	RCP	~100
6(C)	4700-5100	58	Cryogenic	LCP	45-50
3.6(X)	8200-9000	48	Cryogenic	RCP	~50
1.3(K)	22100-22600	~20	Cryogenic	RCP&LCP	~110
		Nanshan Station, Urumqi			
92(P)	314-340	30	Room Temp	LCP	150
18(L)	1400-1720	52	Cryogenic	L/RCP	25
13(S)	2150-2450	48	Room Temp	RCP	100
6(C)	4750-5150	55	Cryogenic	LCP	38
3.6(X)	8200-8600	50	Cryogenic	RCP	45
1.3(K)	22200-24500	35	Cryogenic	LCP	180

A mobile VLBI system with a 3.5-m antenna has been developed by Xi’an Institute of Surveying and Mapping in collaboration with the Shanghai Astronomical Observatory in 2000. The mobile system dedicates for the geodetic research and settled down in Kunming since 2000. It has S/X-band receivers and a S2 recording terminal.

The above-mentioned two 25-m and one 3.5-m antennas combine into a VLBI network in China, which is used for monitoring the crustal deformation.

The Shanghai VLBI correlator has been developed since 1995 and the first fringes of astronomical observation data were obtained in 2000. The correlator is a two-station FX mode one. A plan for developing a 4-station correlator with a disk array and real time VLBI experiments is under consideration.

The research of VLBI applications in geodesy and geodynamics has been done by Li Jiling, Wang Guangli, et al. of Shanghai Astronomical Observatory. They worked on the new polar motion series (Li, 2000), global solution of VLBI observations (Li, 2000), the statistical selection of on-plate sites (Li, 2001), the VLBI experiments and data analysis during the campaigns of the Asia-Pacific Space Geodynamics (APSG) project from 1997 to 2000 (Wang, 2002).

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RESEARCH WORK RELATED TO PRESENT TIME CRUSTAL DEFORMATION MEASUREMENT IN CHINA

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I. INTRODUCTION

China continent crustal motion is still one of the hot spots of studying the intraplate crustal motion and continent dynamics. It undergoes the strong collision of Indian plate and the subduction of Philippine Sea plate and the Pacific plate. The intraplate deformation is very complicated and diversiform. So, it is important to study the crustal deformation around China for lithosphere dynamics and earthquake focal. To monitor and study the crustal motion in China, some nationwide GPS networks and several regional GPS monitoring networks have been set up in the 1990s. Using recent 10-year GPS measurement data of about 1000 sites from these networks and three-campaign GPS measurements provided by the Asia-Pacific Regional Geodetic Project (APRGP), a lot of monitoring results of crustal motion of China and its surrounding regions are obtained during this report time. The monitoring and investigating work of Chinese crustal motion have made great progress. In this report, the research work related to crustal motion measurement of China from 1999 to 2002 is highlighted.

II. DATA COLLECTION AND REDUCTION

In order to monitor and study the crustal motion in China, some nationwide GPS networks and several regional GPS monitoring networks have been set up since 1991. The National (Climbing) key project on basic research " Investigation on Present-day Crustal Motion and Geodynamics" establishes the first nationwide GPS network named the Crustal Motion Monitoring Network of China (CMMNC). The CMMNC included 24 GPS sites that were situated in each geologic tectonic block in China with an average baseline length 1000 km. Four GPS campaigns in CMMNC were carried in 1992, 1994, 1996 and 1999 respectively. The project "Crustal Motion Observation Network of China (CMONC)" was started in 1997. It mainly relies on GPS technique and consists of a continuously operated state fiducial network of 25 sites, a repeated surveyed (once per year) state basic network of 56 sites The first campaign of CMONC was carried out in August 1998. The fiducial network has been operated continuously since January 1, 1999. Beginning from the early 1990s, several regional GPS monitoring networks about 1000 stations for active tectonic studies were established in China, including Tibet-Himalaya, Tianshan-Tarim, Altun Mountain, Qilian Mountain, Sichua-Yunnan, North China and Fujian coast network, and carried out repeated measurement for several periods between 1991 and 2001 (Zhu et al., 2000a; Wang Q. et al.,2001a; Ma et al., 2001; Cheng et al., 2001). All these GPS measurement data have been processed by GAMIT/GLOBK or GIPSY software and used to monitor present-day crustal motion in China. The estimated accuracy of the horizontal velocity of the sites is shown in (unit: mm/a):

Table 1. Estimated Accuracies of Horizontal Velocity of Sites

APRGP	CMMNC	CMONC	Region	net.
NS	0.5-1.3	0.4-0.6	0.6-0.8	0.8-1.5
EW	0.8-2.0	0.7-0.9	0.8-1.5	1.0-2.5

Applying recent 10-year GPS measurement data from these nationwide and regional networks in China and GPS data of three campaigns from the Asia-Pacific Regional Geodetic Project (APRGP), a lot of monitoring results of Chinese crustal motion have been obtained in the period of 1999-2002. (Zhou et al., 2000; Wang Q. et al., 2000; Wang Q. et al., 2001a; Wang Q. et al., 2001b; Huang et al.,1999; Huang et al.,2002; Liu et al., 2001; Lai et al.,2001; Fu et al.,2002a; Fu et al.,2002b; Wang X. et al., 2002; Zhu et al.,1999; Zhu et al., 2000a; Zhu et al., 2000b; Zhu et al., 2002) The velocity fields of these monitoring results are defined in the different terrestrial reference frames such as ITRF94, 96, 97, ITRF2000 and some regional reference frames. In order to form a united velocity field of Chinese crustal motion, through the comparisons and the rotation transformations between different velocity solutions, a combined, consistent and unified velocity fields of China and its surrounding regions in ITRF 97 and ITRF 2000 are produced (Wang Q. et al., 2001; Zhu et al., 2002; Wang X. et al., 2002;).

III. ESTABLISHMENT OF PRESENT TIME GLOBAL PLATE MOTION MODEL

In order to study the characteristics of contemporary crustal deformation, some present-time plate motion models named ITRF96VEL, ITRF97VEL, ITRF2000VEL are established by incorporating ITRF96, ITRF97 and ITRF2000 velocity fields respectively. These velocity fields are derived from the combined solutions of the space geodetic data of VLBI, SLR, GPS and DORIS , and totally independent of any tectonic plate motion models (Zhang et al., 1999; Zhu et al., 2000c; Zhu et al., 2002; Xiong et al., 2000; Fu et al., 2002; Wang X. et al., 2002;). For the methods and criteria of establishing present-time global plate motion models can see Zhu et al., 2000c. Because the velocity fields of ITRF 2000 etc. represent the crustal motion of current 20 years span, these present-time plate motion models can better describe present-time features of global plate motion than the geological model NNR-NUVEL1A. In general these models are consistent with the geological model NNR-NUVEL1A, but there are differences of about 10 percent in rotation magnitude and 15 degrees between the Euler poles for some important plates. These differences are very significant for the measurement of present-time crustal deformation in 1mm/a accuracy. So, the plate models ITRF2000VEL etc. are more suitable as the background of deformation investigation for current short time scale than the NNR-NUVEL1A.

According to the following formula, the total angular momentum of all tectonic plates with regards to the ITRF96VEL, ITRF97VEL and ITRF2000VEL are calculated.

where ***L*** is the total angular momentum of all tectonic plates, and are the rotation tensor and Euler vector of the pth plate. Table 2 shows the magnitude of the total angular momentum for the different plate motion models.

Table 2. The Magnitude of the Total Angular Momentum

Model	NNR-NUVEL1A	ITRF96VEL	ITRF97VEL	ITRF2000VEL
L(sterad/m.a)	.865E-04	0.193E-02	0.175E-02	0.204E-02

In Table 2, the magnitude L of the total angular momentum for the NNR-NUVEL1A should be zero in accordance with the definition of the NNR reference frame. The nonzero value is due to round-off error. But the nonzero values of the total angular momentum with regards to ITRF96VEL etc. models show that the ITRF96, ITRF97 and ITRF2000 are not an NNR reference frame and are not sufficiently concordant with the definition of CTRF. Therefore, the consistency of the ITRF series can not be maintained. And the net rotation of ITRF etc. relative to the NNR reference frame will influence some studies about long-term variation of the Earth rotation parameters. Though the inconsistency and influence are smaller, they are still worthy of consideration with precision improvement of space geodetic techniques (Zhang et al., 1999; Zhu et al., 2000c; Zhu et al., 2002).

IV. FEATURE OF PRESENT-TIME CRUSTAL DEFORMATION IN CHINA

Taking the ITRF97VEL or ITRF2000VEL motion of the Eurasia plate as the background motion, the deformation velocities about 500 sites in China and its surrounding regions are determined (Wang Q. et al., 2001; Zhu et al., 2002; Fu et al., 2002a; Wang X. et al., 2002; Huang et al., 2002; Wei et al., 2002; Li et al., 2001). Their results are shown in Table 3 and Fig.1.

Fig.1. Contemporary crustal deformation in China and surrounding regions relative to Eurasian plate from ITRF2000VEL

Table 3. Horizon Deformation Velocities of Tectonic Blocks and Fault Belts in China

Tectonic blocks or fault belt	Deformation rate(mm/a)	Orientation
Himalayas block	36-21(reduce from south to north)	NNE
East part of Tibet block	25-18(reduce from south to north)	NNE to NE (from S to N)
West part of Tibet block	15	N
Qilian Mountain fault	5-10	ENE to E (from W to E)
Altun Mountain fault	9-4	NNW to NNE (from W to E)
West part of Tarim block	12-16	NNW
East part of Tarim block	4-8	N
Tianshan block	3-6	NNE to NE
Chuandian block	10-20	ESE to SSE (from N to SE); W(from SE to SW) SSE to SSW (from SE to EW)
Heilongjiang block	2-3	S
North China block	7-3 (reduce from W to E)	SE
South China block	15-8 (reduce from W to E)	SE

From Table 3 and Fig.1, we can see that the Chinese crustal deformation is very inhomogeneous. The North-South seismic belt is an important boundary of the deformation. The crustal deformations in the west of China are stronger and more completed than those in the east of China, the motion direction also changes from north direction to south direction across this zone. The deformation velocities gradually reduce from south to north in the west of China by energy release in several W-E direction arc suture zones.

The Himalaya-Tibet is the most active region in China or even in global continent deformation. The Qinghai-Tibetan Plateau is shortening in north-south direction and extending in west-east direction due to the strong shove of Indian plate. The convergence rate of about 15 mm/a and 9-13 mm/a are accommodated across Himalayan block and the west Tianshan respectively. Within southern Tibet, between the longitudes of 80°E to 91°E, there is E-W extension of 20.2±1.2 mm/a. The slip rates of KJFZ in south Tibet and Altun Mountain fault are 2-3 mm/a and 4-6 mm/a respectively. Our GPS results indicate more than 50 percent of convergence between India and Eurasia is absorbed by the crustal thickening in Himalayan and Tianshan and there is a lesser than 7 mm/a shortening across the Longmen Mountain fault and its adjacent foreland. These results support the supposition of crustal thickening (Wang Q. et al., 2001; Wang X. et al., 2002; Shen et al., 2001; Zhu et al., 2002; Ren et al., 2002).

The Heilongjiang block is the most stable blocks in China. The South-China block also is a stable block. The North-China block consists of three sub-blocks. The Ordos sub-block is its main body, although its boundary is very active, its inner is ‘cool’ and steady. The deformation velocities of North-China block are slower than that of South-China block, the difference of motion between the South China block and the North China block can not identify whether crust thickening dominates the lateral transfer; but other results (such as the slip rate on the Altun Mountain fault and KJFZ, and contraction rate across Longmen Mountain fault) support the supposition of crust thickening. The action of Australian plate on Eurasian plate is absorbed rapidly by Java island arc and almost do not affect the crustal deformations of China. The west subduction of Pacific plate is absorbed rapidly by Japan island and Japan straits and do not affect the crustal deformations of China; but, the Philippine plate has great effect on crustal motion of Taiwan. Therefore, combining the results from geology and seismology, we can say, the present-time crustal motion in China is affected not only by Indian plate but also by Philippine sea plate. But, it is not related to the Pacific plate and Australian plate. In addition, the results of GPS measurements show the new division rule of blocks is more reasonable than that of the old. Especially, the introduction of Lhasa sub-block and Qiangtang sub-block in Tibet block can interpret the GPS results, which are not interpreted by the old one Tibet block.

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CRUSTAL MOVEMENT OBSERVATION NETWORK OF CHINA (CMONOC)

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The scientific objective of the Crustal Movement Observation Network of China (abbreviated as CMONOC) is taking the earthquake prediction as the dominant, giving consideration to the need of geodesy and providing services to the fields of wide-area differential GPS, meteorology and satellite-borne synthetic aperture radar interferometry, etc.

The key techniques for the engineering construction of CMONOC are the high-precision and high-stability observation, the large-amount collection of data, and the rapid and accurate real-time data processing.

The total engineering of CMONOC consists of four parts: the fiducial network, the basic network, the local network and the system for data transmission, data processing and data analysis.

As the principal frame of CMONOC, the fiducial network consists of 25 GPS stations for continuous observation. VLBI and SLR observations are also made at some of the stations. With an average distance of about 700 km between the adjacent stations, the main function of the fiducial network is to monitor the tectonic movement of the first-order blocks in Chinese mainland. The new fiducial stations are all built on the bedrocks. The observation accuracies are ±1.3 mm for the annual length variation of GPS baseline between the adjacent fiducial stations, ±1.5 mm for the annual variation of baseline between the adjacent VLBI stations, ±2.1 cm for the determination of absolute coordinates of the fixed SLR stations, and ±0.8-4.9μGal for the absolute gravity survey. The fiducial network was put into operation on April 1, 2000.

The basic network is composed of 56 GPS stations for regular repeated measurement. As a complement to the fiducial network, the basic network is mainly used to monitor the crustal deformation in and between the first-order blocks. The basic stations are uniformly arranged together with the fiducial stations with an average distance of about 350 km. Two measurements of basic network were carried out both in 1998 and 2000 with the accuracy of less than ±3 mm for the horizontal component and less than ±10 mm for the vertical component.

The local network is constituted by 1000 GPS stations (1056 stations including the basic network) for irregular repeated measurement. They are arranged in ten monitored areas. About 700 of them are concentrated along the principal tectonic and seismic zones to monitor the activity status of the zones for earthquake prediction; about 300 of them are uniformly arranged over the whole country as a complement to the fiducial and basic networks to monitor the movements in the major blocks. The local network was established in the August of 1998, the first measurement was carried out in 1999 and more than 800 stations were remeasured in 2001. The calculated results indicate that the observation accuracy is less than ±3 mm for the horizontal component and less than ±10 mm for the vertical component.

The data system consists of a data center and three data-sharing subsystems. The data center is responsible for network operation and management, routine data processing and analysis, which are directly applied to earthquake prediction and disaster mitigation. The data center also provides the basic data to each data-sharing subsystem and the related ministries and commissions. The data-sharing subsystems mainly provide service to the research in astrogeodynamics and the Asia-Pacific Space Geodynamics Program, as well as the national geodetic control net and the fundamental surveying and mapping. The construction of the data system was totally accomplished in 2000. Its principal technical indexes are 310 Mb daily for data collection, 50 Gb for on-line data storage and 220 stations daily for data processing.

By the end of 2000, tested and checked by the State Acceptance Committee, the complete network engineering reached and surpassed the designed requirements in various technique indexes and was put into operation.

Covering an area of 95% in Chinese mainland, CMONOC has raised the accuracy for traditional measurement of crustal movement in China by three orders of magnitude and the observation efficiency by tens times. It has preliminarily realized the quasi-instantaneous monitoring over the whole country and fundamentally improved the manner and function of dynamic monitoring on the surface of the Earth. It has heightened the ability to predict great earthquake in China. China Seismological Bureau has already used the GPS-observed data in the annual seismologic consideration and better results have been obtained in the long and medium-term earthquake predictions. It has increased the accuracy of the geodetic control network and helps to refine the datum for surveying and mapping. It has also significantly promoted the state key basic researches. The “Current Crustal Movement and Geodynamic Research” in the China Climbing Project and the “Mechanism and Prediction of Continental Earthquake” in the State Key Basic Research Project have both regarded the CMONOC as the principal supporting condition for project establishments and further studies. The observation of the network has provided significant basic data for these projects.

In the past three years, the CMONOC operates normally and large amounts of observed data have been obtained. Seven fiducial stations have been used as IGS stations and their data have been used for the international exchange. The data obtained from the network have been used in the scientific studies and more than one hundred papers have been published. The following map of horizontal crustal movement rate in Chinese mainland is based on the data from the CMONOC. Up to now, this is the map drawn with the most detailed, accurate and homogeneous data and by the most strict processing method.

With the progresses achieved in the science and technology and the national economy, especially the development in the West China, the existed CMONOC can not meet the need in various fields. The Chinese geodesists are preparing to make a continuation for it. The fiducial stations will be increased to 260 and the local stations to 2000 in the next several years. Cooperated with IGS, CMONOC will establish the mirror image of IGS data in China in order to provide WEB and FTP services of GPS data through Internet.

Fig.1. Map of horizontal crustal movement rate in Chinese mainland
(from Wang Min in the Data Center of CMONOC and to be published)

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THE DEVELOPMENT OF MARINE GEODESY IN CHINA

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I. THE ESTABLISHMENT OF THE MARINE GEODETIC NETWORK

Based on the national Order A and B GPS networks, the Chinese Ministry of Communications, National Ocean Administration, Chinese Navy and so on have undertaken GPS geodetic connection to the present long-term tidal gauges and set up a monitoring network of tidal gauges. In order to get local vertical control with GPS leveling, some departments have set up small local GPS networks.

In Xiaolangdi Reservoir profile survey, GPS network was laid out by using active densification method. With maneuverable and high efficient operation, the accuracy obtained was well above the requirement of Order D.

The layout proposal and operating method of geodetic network under the tough conditions of South China Sea were studied. After data processing, the accurate coordinate of the control point of South China Sea in ITRF was obtained and thus the geodetic networks of South China Sea and the mainland were linked together as a whole.

Chinese scholars have also studied the basic principles of GPS altimetry and its application. Since Jan. 1 of 2002, founded by the Maritime Safety Administration of Chinese Ministry of Communications, RBN-DGPS has been fully accomplished and come into operation. Within 300 km offshore along Chinese coast, the positioning accuracy reached up to 5-10 m.

II. BATHYMETRY, GRAVITY SURVEY AND THE DATA PROCESSING

During the past four years, 2 500 000 km^2 of sea areas, including East China Sea, South China Sea and the Northwest Pacific Ocean, have been surveyed and the survey line was 1 800 000 km. More than 1 000 charts on different scales were published. More than 2 000 marine research stations were set up. Chinese scholars have made a further and more extensive study on multi-beam echo sounding technology and the data processing. A series of position reduction formulas and their error equations for swath sounding were derived. The dynamic effect of the marine sounding, i.e., the influence of vessel attitude, was taken into full account in derivation of the equations.

Chinese scholars also researched into the mechanism as a result of sound velocity influencing on multi-beam sounding, and the technical method of sound velocity correction by taking SeaBeam 2100 Multi-beam Sounding System for example. The detection of abnormal data in marine survey was studied and the robust interpolation comparison test based on robust M-estimation by an iterative calculation procedure was proposed. Based on discrete fast wavelet transform technique, an optimum wavelet threshold filter algorithm for seabed topographic signal reconstructing from echo sounding signal affected by ambient noise was put forward. This method is of particular advantage to reduce experience error and raise labor efficiency. By using geodetic height from GPS, the reduction of soundings was proposed. It is a real-time depth sounding method without taking into account of dynamic draught and tidal data. In view of the different kinds of error sources from multi-beam sounding, the influence on fair chart and correction method were studied. The strict analysis and correction formulas were proposed in accordance with the time lag and offset effect.

Chinese scholars have recovered the seabed topography from altimeter data and set up the improved model with consideration of the compensation effect of isostasy. The accuracy of the recovery was in the same level of the world.

Chinese scholars have developed a Hydrographic Data Processing System. The system function includes control survey calculation, coast topographic data processing and charting, soundings processing and charting, marine gravity data processing and charting, tidal observation and analysis and hydrographic data management, etc.

In respect of the adjustment of gravity network, mathematical model was adopted to characterize the change of the dynamic systematic errors, the crossover adjustment was carried out simultaneously to determine the model parameters and the compensation of systematic errors was realized. This is the self-calibrating adjustment suggested by Chinese scholars and it has achieved a good result in practical application. By making use of altimeter data, analytical and numerical inversion of the Stokes formula and inverse Vening-Meinesz formula for the recovery of marine gravity anomalies were studied and the estimated gravity anomalies were compared to the real marine gravity data from shipboard measurements at sea. The result shows that by using the recovery of gravity anomalies from altimeter data, the derived magnitude of accuracy in the gravity anomalies gridded in $15' \times 15'$ is better than 5 mGal, $30' \times 30'$ better than 4 mGal and $1^\circ \times 1^\circ$ better than 3 mGal.

Chinese scholars also derived a strict formula for the convolution formula and determined the marine gravity anomalies gridded in $2.5' \times 2.5'$ over the South China Sea using inverse Vening-Meinesz formula.

III. COAST TOPOGRAPHIC SURVEY

In resent years, electronic plane-table or GPS RTK has been used for the coast topographic survey in China. By using this technique, either control point for surveying can be set up quickly or even the topographic survey can be conducted directly without control point. More than six kinds of topography survey softwares have been in the use. During the past two years, aerial photogrammetry has been spread out in coast topographic survey.

IV. HYDROGRAPHIC INSTRUMENTS

The technology of GPS carrier phase measurement was put forward to determine vessel attitude, the test of the technology was taken and the measurement accuracy reached up to 0.28° . The two main error sources influencing the depth accuracy of airborne laser sounding, i.e., the accessories error and the depth error, were analyzed and studied. The concept of Shipborne Shallow Water Laser Bathymetry was put forward and a measurement plan of laser double-frequency phase method used for shallow water bathymetry was studied. The simulated test of the system was accomplished in laboratory and it approved the feasibility of the measurement plan. Now the Shipborne Shallow Water Laser Bathymetric System is under study and development. The pressure gauges suitable for different kinds of ocean environments were produced and they were used in marine survey and tidal study. Airborne Laser Sounding System was developed and produced and the test was taken in the South China Sea. The repetition frequency of laser was 200 Hz, the sounding depth was 50 m and the depth accuracy was ±0.3 m.

V. VERTICAL DATUM

Present situation of marine surveying vertical datum and its existing problems were researched into and the proposal for improvement of marine vertical datum was recommended. Based on the frequency spectrum of mean sea level (MSL) and relation model between two tidal stations, the mathematical model for hydrographic datum transfer were studied and more precise models were developed.

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ACHIEVEMENTS OF GEODETIC DATA PROCESSING IN CHINA

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I. ROBUST ESTIMATION

Within the last four years, much attention has been paid to parameter estimation for correlated observations and Lp estimation, in the robust estimation field. A set of self-contained theory system on robust estimation is researched based on equivalent variance-covariance[11]. A new robust estimator for correlated observations (RECO) by bi-factor equivalent weight elements was developed, which keeps the symmetry and the correlation of the observations unchanged[35,37].

The robust estimators of parameters and variance factor with minimum mean square error are derived, all parameters of which are determined according to statistics[26].

The parameter estimation problem when outliers and ill-conditioning exist simultaneously is researched. A class of new estimators, shrunken type robust estimators, are proposed by grafting the biased estimation techniques philosophy into the robust estimator, and their properties are discussed[3]. The un-biasness for the robust estimation of the location parameters is discussed, based on the hypothesis that the weight function is an anti-symmetrical function[40]. The unbiased estimation of posterior variance and the optimal robust estimate have been studied. It is demonstrated that for stochastic error model and mean shift error model, they have the same estimate formula[17].

Robust Kalman filtering model and its application in GPS monitoring networks are studied. The Robust Kalman filtering model based on the rules of the influences of the outliers on the state vectors is derived[39]. The theory and the method as well as the robustness of the parameter estimation based on the principle of information spread are researched[24]. Givens-Gentleman orthogonal transformation is applied to robust estimation. The formulas of posterior root mean square error and the covariance matrix of the parameter estimates have been derived. The calculation of equivalent weights is discussed. The numerical stability is analyzed for extended Givens-Gentleman orthogonal transformation[29].

L_p estimator is an influential class of robust estimation which has been widely studied in China. The *p*-norm distribution is a distributive class which includes the most frequently used distributions such as Laplace, normal and rectangular ones. The *p*-norm distribution can be represented by the linear combination of Laplace distribution and normal distribution or by the linear combination of normal distribution and rectangular distribution approximately. The approximate distribution has the same first four-order moments as the original *p*-norm distribution. Because every density function used in the approximate formulas has a simple form, using the approximate density function to replace the *p*-norm ones will simplify the problems of *p*-norm distributed data processing obviously[19]. Based on the theory of the *M*-estimation for the location parameters, the influence functions of the L_p estimates of the parameters (one dimension and multi-dimension) are derived, the robustness of L_p estimation when the observational errors obey the contaminated distribution is analyzed, and the asymptotic variance and efficiency of the L_p estimation have been determined too[46].

The optimal L_P estimation based on the global minimum of the asymptotic variance, and the optimal value of parameter *p* has been determined under the contaminated distribution. The results show that the L_p estimation with the value of parameter *p* between 1.2 and 1.5 is the optimal estimation if the data contain different outliers[46].

The mathematical model of L_∞ estimation is given. The general method of solving L_∞ estimation with linear programme is advanced, and according to the dual principle of linear programme, the dual model of L_∞ estimation is given[48]. Based on the formula of probability density and distribution function of monistic Laplace distribution, the probability density of the median estimator is derived, when the sum of observations is even. The authors proved that the L_1-estimates of parameters are unbiased[27].

Chinese geodesist suggested instant, or through a few steps, approaches to the optimal solutions, based on the existing experiences, and using simplex method [42].

In the applications of robust estimation, the special displacement of strain models is determined by means of robust estimation technique[21]. The robust estimation was applied in the parameter estimation for a dynamic model of the sea surface[31] and geodetic datum transformation[32] as well as the determination of systematic errors of satellite laser range[33].

II. OUTLIER DETECTING AND THEORY OF RELIABILITY

A new idea and a distinctive method for outlier detecting and estimating are proposed by Ou[12]. The determinate and analytic representation relationship between real errors and observation values is applied to fitting the real errors. The unique solution on real errors in this equation is obtained by using the idea of "Quasi-Stable Adjustment", the new concept on "Quasi-Accurate Observation" is presented. Then the rank-deficiency equations on real errors are resolved by adding the conditions in which the minimum of the norm of the real errors related to quasi-accurate observations is restrained. The new method called as "Quasi-Accurate Detection of gross errors (QUAD)" is derived[13]. The key of QUAD is how to select the Quasi-accurate Observations (QAO) reasonably. An effective scheme, which is divided into two steps, is summarized by Institute of Geodesy and Geophysics of Chinese Academy of Sciences [15]. In the first step called "Preliminary Selection", the observations are classified into 4 sorts among which only the "sort 2" and the parts of "sort 3" are able to be chosen as QAOs. In the second step, called "Fine Selection"， the observations corresponding to small absolute values of the estimates of errors, which are calculated at the previous step, are chosen as QAOs.

On the basis of expectation drift model, the relationship between outlier correcting and deleting is researched[18]. It is demonstrated that on the basis of the same expectation drift model, outlier correcting and deleting are equivalent in the estimates of parameter and the square sum of residuals.

In the area of the quality control of the surveying data processing, a new and united index of reliability is introduced[16]. This index is determined completely by the construction of a system (such as a surveying network), and it is not necessary to include the probability element (non-central parameter) which is effected on by some factors chosen subjectively. It is shown that the hypothesis test may not detect all gross errors but the quasi-accurate detection may do it easily. The reliability for the situation of correlated observations is also discussed[14]. In the correlated observations, the redundancy measures are over ［0,1］, at times even some of them are negative, so that the redundancy measures may not reflect the characteristics of the reliability. A new measurable indication of reliability is suggested: i.e. $\gamma_i=(PR)_{ii}/p_{ii}$, here P is the weight matrix of observations, R the adjustment factor matrix, the subscript i represents the place of the observation i. γ_i is in ［0，1］. The smaller γ_i is, the poorer the reliability corresponding to the observation i is. The new indication γ_i is united one. It is suitable not only for independent observations, but also for correlated observations.

III. ADAPTIVE KALMAN FILTERING

The reliability of the linear Kalman filtering results usually degrades when the kinematic model noise is not accurately modeled in filtering or the measurement noises at any measurement epoch are not normally distributed. A new adaptively robust filtering is proposed based on the robust M (Maximum likelihood type) estimation[34]. It consists in weighting the influence of the updated parameters in accordance with the magnitude of discrepancy between the updated parameters and the robust estimates obtained from the kinematic measurements and in weighting individual measurement at each discrete epoch. A general estimator for adaptively robust filter is developed, which includes the estimators of classical Kalman filter, adaptive Kalman filter, robust Kalman filter, sequential least squares (LS) adjustment and robust sequential adjustment. In addition to the robustizing properties, feasibility in implementation of the new filter is achieved through the equivalent weights of the measurements and the predicted state parameters. The relations of analytical expressions and covariance matrices between the basic random vectors, such as residual vectors, innovation vectors and correction vectors of predicted state, are derived and discussed. The shortcomings of covariance matrices by the averages of the residual vectors, innovation vectors and correction vectors of the kinematic states timing their transposes within a fixed window, are analyzed. The robust filtering, the Sage adaptive filtering and the adaptively robust filtering are compared. It is shown, by derivations, that the new adaptively robust filtering is not only simple in calculation but also robust in controlling the measurement outliers and kinematic state disturbing[36]. An improved adaptive Kalman filter combining the Sage adaptive filtering and a new adaptively robust Kalman filter with an adaptive factor is proposed[30]. If the state is smooth, then the Sage filter is applied, otherwise the new adaptive Kalman filter works.

An improved method of adaptive Kalman Filtering for GPS high kinematic positioning is also proposed based on Sage filtering[6].

IV. PARAMETER ESTIMATION FOR NONLINEAR MODELS

In the parameter estimation of nonlinear model， a direct calculation method is proposed. The influences of quadric terms and cubic terms have been taken into consideration. The precision of estimators can be evaluated by classical method[23]. The estimators obtained by the new method have fine statistic characters. The estimation of the unit weight variance is studied[25]. Two objective functions of nonlinear model are given under two kinds of parameter estimation guides[7]. The iterative methods of nonlinear functions are discussed. Based on that, two sorts of best solutions─circulating search method which does not depend on functional derivatives and iterative method that is based on differential theory—are presented.

Nonlinear curvature measures of strength for the model of adjustment of free-networks with general rank deficiency are studied[9]. On the basis of concerning the nonlinear curvature measures of strength for the model of adjustment, nonlinear curvature measures of strength for the model of adjustment of free-networks with general rank deficiency is put forward[9]. Two new computational methods to nonlinear adjustment of free-networks in consideration of the second-order derivatives, are put forward from the precise orthogonality condition equation to nonlinear least squares[10].

In addition to the three existing nonlinear squares algorithms—Gauss-Newton method, damped least squares method and quasi-Newton method on least squares, a better algorithm—SQPM (Sequential Quadratic Programming Method) as one of the most powerful algorithms of nonlinear programming is applied. And the step-length policy of SQPM is improved in order to advance the iterative convergence[2]. An improved Marquardt method applied into nonlinear adjustment is proposed[8].

Tao described the quality requirement of the inversion problem of parameter estimation. The resolution of the inversion theory and the precision of the parameter estimation are compared and analyzed. In order to get favorable results, he puts forward several schemes for the nonlinear adjustment. The principles of the parameter choice and corresponding statistical test methods are presented[22].

The generalized normal distribution is defined by the generating function of stochastic vectors, and the variance matrix of normal stochastic vectors is spread from the full rank matrix to the singular matrix. According to the property of generating function, the digital feature of the quadratic function of normal stochastic vectors is inferred, and the result is applied to error propagation. The expression of the error propagation formula with regard to the quadratic for non-linear function is obtained[47].

V. OTHER DEVELOPMENTS IN DATA PROCESSING

A new biased estimator called partial root root estimator is proposed through analyzing the corresponding properties of root root estimator, Stein shrunken estimator, and Sclove partial shrunken estimator. Its properties are discussed[4,5]. A direct solution to generalized ridge estimate is studied[38].

The rule of fitting is researched. In many problems of data processing, by appropriate use of the method of fitting, indefinite rank-deficiency problems can be converted into relatively definite ones, giving valuable results[43]. A few remarks on collocation is made[44]. The current solution of collocation is least squares one under the bi-fitting constraint. The stochastic parameters and the observational errors are treated equally, as errors. It results in that the estimate of the systematic parameters is the best one, but the estimate of the random parameters is not the best estimate, which regard to the realization to be sought, it is biased. The covariance of the estimate is not suitable to be a measure of accuracy of the estimates of the random parameters. The bi-fitting rule is grounded on maximal probability density, but at the same time it leads the estimate of the random parameters toward its expectation, which results in a self-deviation[45]. As one of applications of collocation, a new approximation model with random variables is proposed[44].

A combined adjustment of the nationwide astro-geodetic and GPS geodetic networks was accomplished early in 1998. The principles adopted and the models used in the adjustment and present results are reported[28]. As a result of adjustment, the systematic scale deviation of the astro-geodetic network has been removed, its local distortion mitigated and its integral precision improved. And more importantly a geocentric geodetic reference system as materialized by the coordinates of nearly 50000 geodetic points has been set up with better than one half meter accuracy for horizontal components[28]. Some strategy on solving high order normal equation for combined adjustment of astro-geodetic and space networks by using conjugate gradient method was researched. A scheme of adjusting the coefficients and a strategy of separation as well as mergence between the adjustment and inversion are proposed[1].

The Helmert method for Variance Component Estimation (VCE) can be successfully applied to Precise Orbit Determination (POD). An improved Helmert method for variance component estimation is developed by using the priori information of the estimated parameters to avoid the occurrence of negative variance[41].

A semiparametric regression and model refining is researched[20]. It is hopefully to be a new research direction in the coming years.

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