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PREFACE

The Chinese National Committee of IAG is pleased to present the 2003-2006 quadrennial China National Report on Geodesy to the Chinese National Committee for IUGG.

During the last four years, significant advances have been made in the study of Geodesy in China. The presentation of the 2003-2006 China National Report on Geodesy is a reflection to these advances, and provides the record of Chinese contributions to geodesy. The report includes the following contents:

（1）Crustal movement and astro-geodynamics research.

（2）Gravity measurement and partial gravity field refining in China.

（4）Geocentric coordinate framework maintenance.

（5）Ocean geodesy in China.

（6）Advances made in data processing in China.

（7）The height determination of Qomolangma Feng (Mt. Everest).

The current report is published only in CD. 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 with colleagues all over the world.

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THE HEIGHT DETERMINATION OF QOMOLANGMA FENG (MT. EVEREST) IN 2005

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Qomolangma Feng – Mt. Everest (ME in shorter) is located in the east part of Chinese-Nepal boundary. ME is the highest mountain in the world. It lies in the collision zone along the boundary of Eurasian and Indian plates. As the impact of crustal movement and global warming the height and its variation of the ME is one of focuses in geosciences study[1-8].

A new campaign for the height determination of ME (HDME in short) was carried out in 2005 by China (2005 campaign in shorter). Various kinds of geodetic technique such as GPS, leveling, gravimetry, trigonometric leveling, laser ranging, height traverse, and radar detection, etc. were involved in the 2005 campaign.

On 22 May 2005 at 11:08 am (Beijing Time) Chinese surveyor-mountaineer team succeeded to reach the summit of ME. A survey target was set up on the summit at 11:30am, and the GPS was put into operation on the summit from 11:43 am to 00:19 pm, recorded total 36-minute GPS data. The Ground Penetrating Radar (GPR) started its detection work from 11:38 am, and ended at 00:18 pm, recorded 39-minute data. At 00:20 pm the team started to go down following the order to end the geodetic data acquisition work on the summit. As more or less one hour stay on the ME summit is the life limitation for the human being.

I. GEODETIC DATA ACQUISITION AND PROCESSING IN THE 2005 CAMPAIGN

1. Geodetic Data Acquisition and Processing for Vertical Control

The initial height in the 2005 campaign came from the height of Chinese 1st order benchmark 'I Sala 40 base point', about 160km far from the ME. Started from the benchmark the height of the most ground observation sites in the 2005 campaign could be obtained via 2nd and 3rd order connection leveling. The total length of the leveling lines with different orders in the 2005 campaign was about 400km. For refining the local geoid in the ME area the leveling points should coincide with GPS points as far as possible in the ME area.

2. Geodetic Data Acquisition and Processing for Horizontal Control

The horizontal control data acquisition in the 2005 campaign mainly relied on the GPS technique. According to different requirements 3 GPS networks were laid down in the 2005 campaign. *(1)* Qing-Tibet GPS monitoring network (GPSMN in shorter) consists of 30 points. It was the initial coordinate frame for all horizontal positioning in the 2005 campaign. *(2)* GPS control network in the ME area (GPSCN in shorter) consists of 32 points, 6 points of which consistent with those of GPSMN. *(3)* GPS connection network (GPSSN in shorter) includes one GPS point on the ME summit and 7 GPS points on the ground in the ME area. 2 GPS points of GPSSN are consistent with those of GPSCN.

The following technical rules are applied to the data processing of the above three GPS networks: using IGS precise ephemeris, WGS84 coordinate system, Gamit/Globk 10.2 edition software, ITRF2000 coordinate frame, and taking the average GPS observation time as the GPS adjustment epoch. 17 IGS tracking stations are taken as the reference coordinate frame for GPSMN data processing, and GPSMN as a fiducial network for GPSCN and GPSSN.

The accuracy of those GPS networks after data processing is as follows. The horizontal and elevation accuracy for GPSMN is ±1.2mm and ±3.5mm respectively, which for GPSCN，is ±4.9mm and ±12.8mm, and which for GPSSN，is ±4.6cm and ±3.0cm. The elevation accuracy is higher than the horizontal one in the GPSSN is mainly caused by the sway of the GPS antenna which is installed on the top of the survey target, due to the very strong wind on the summit.

II. TO RAISE THE GEODETIC MEASUREMENT ACCURACY ON THE ME SUMMIT

1. To Set up a Survey Target on the ME Summit

From the geodetic data acquisition point of view, the precondition for a precise HDME campaign is to set up a stable, unique surveying mark, for example, a survey target or GPS antenna on the ME summit during the period of HDME campaign. Geodetic height of the snow summit of ME was determined by GPS and classical geodetic technique (trigonometric leveling and laser ranging) in the 2005 campaign. So the survey target set up on the ME summit in the 2005 campaign is not only a target for measuring angle, but also an antenna for GPS positioning and a reflector for laser ranging.

In order to raise the accuracy and reliability of the HDME in a very short measurement period, the ground observation sites with GPS and classical geodetic techniques in the ME area should be located within 10-15 km apart from the ME summit. Under this condition the average elevation of those sites usually is more than 5000m. As Jack Frost and anoxic condition, it is really a very hard work to acquire the geodetic data for the HDME campaign in the ME area.

2. To Improve the Accuracy of GPS Positioning on the Summit

In the 1992 and 1999 HDME campaigns the GPS antenna was set directly on the snow surface of the ME summit, and the GPS sampling time was as usual 30 seconds. Because of the frequent motion of mountaineers on the ME summit, the GPS signals received by the GPS receiver on the summit were interrupted more than 15 times in a very short GPS observation period (usually less than 40 minutes) in the 1992 and 1999. It was very unfavorable for the GPS precise positioning on the ME summit.

After reviewing the lessons and experiences in the past GPS campaigns for the HDME, three measures were taken in the 2005 campaign to raise the GPS positioning accuracy. First one is to lift the position of GPS antenna on the ME summit in order to reduce the interference and interruption of GPS received signal. The GPS antenna was set on the top of the survey target, about 2.5m high above the snow surface of the ME summit. Second one is to shorten the sampling time of GPS signal. Considering the characteristics of a short GPS operation time on the ME summit, one second GPS sampling interval was applied in the GPSSN. Third one is to lay down 7 GPS ground sites with simultaneous measurement of the GPS on the ME summit in the

GPSSN. One of the 7 GPS ground sites, only 70km away from the GPS on the summit, is a temporally continuous operation GPS station. So the height determination accuracy of the ME snow summit with GPS in the 2005 campaign was raised approximately two time in comparison with those in the past HDME campaigns.

3. To Improve the Accuracy of the HDME with Classical Geodetic Techniques

Some measures were taken also to improve the accuracy of the HDME with classical geodetic techniques in the 2005 campaign. In addition to the 6 trigonometric leveling sites 5 laser ranging sites were also set up in the ME area to determine the height of ME. Because of the combination of angle measurement and ranging for the HDME, then the error ellipse for the height and position determination of the survey target on the ME summit becomes a near round figure with much smaller axes. Hence the accuracy of the geodetic height of the ME snow summit obtained in 2005 with classical techniques was also improved remarkably.

III. REFINE LOCAL GRAVITY FIELD IN THE ME AREA

The fundamental work to refine local gravity field in the ME area is to calculate the local gridded gravity anomaly, geoid and the deflection of the verticals with better resolution, accuracy and better fitting to the Chinese vertical datum[1-3,7,10,11].

1. New Surface Gravimetry

As the crustal movement in the ME area is active, it is meaningful to have more up-to-date surface gravity data for refining and densify the local gridded gravity data in the ME area. 96 gravity points were newly measured in the 2005 campaign. 5 points of those gravity points are located along the climbing route to the ME summit, and the highest altitude of the 5 points is 7790m.

2 To Select the Isostasy Gravity Model and Isostatic Depth[7,8,10-13]

Considering the topographic and geological structure, the densification of gravity data here usually takes the isostasy model in the ME area. After the comparison it was decide in the 2005 campaign that the isostatic gravity anomaly in the ME area will be obtained from Airy-Heiskanen isostasy model with isostatic depth of 34km.

3. To Compute the Gridded Gravity Anomaly in the ME Area

When the gridded gravity data in the ME area were computed with the remove-restore technique in the 2005 campaign, ground gravity data in the ME area are still not enough for the computation, especially the even distribution and high resolution of the local ground gravity data. Hence DEM data in the ME area have to be well utilized in order to compensate on some level the inadequate of gravity data in the ME area. The DEM data in the ME area are obtained mainly from Chinese (1″×1″) DTM，DSM of SRTM3(3″×3″), and DTM of GTOPO30 (30″×30″).

4. To Refine Local Quasi Geoid in the ME Area

Based on five model gravity quasi geoids (corresponding to the five earth gravity models, EGM96, WDM94, IGG05B, DQM2000D and CG03C respectively), five refined local gravity quasi geoids in the ME area were obtained with the remove-restore technique taking account of the gridded topography and gravity data mentioned above. In order to take the Chinese Yellow Sea vertical datum as the height initial surface for the 2005 campaign, the five refined local gravity quasi geoids have to be fit to the 44 GPS leveling points in the ME area. The five refined local quasi geoids were obtained after the fitting.

For testing and comparing the accuracy of the five refined local quasi geoids, a number of height anomalies (measured) of some GPS leveling points are taken to compare the corresponding height anomalies at the same points, from the five refined local quasi geoids. The differences between the two kinds of values were in the interval of ±0.08m--±0.09m. It is to say, the accuracy of the five refined local quasi geoids in the ME area, corresponding to the five earth gravity model respectively, seemed to be almost equal to each other. Considering the popular utilization of EGM96 in China, it is finally decided that the refined local quasi geoid corresponding to EGM96 is used for the 2005 campaign.

The height anomaly at the survey target on the ME summit is -25.20m referring to the refined local quasi geoid mentioned above.

IV. DEPTH DETECTION OF THE ICE-SNOW LAYER ON THE ME SUMMIT

The ME summit is covered by snow perennially. The depth of ice-snow layer and the height variation of the rock surface of the ME summit are always concerned by scientists in the world. So to detect the thickness of the ice-snow layer on the ME summit timely is necessary for exploring the height variation of the rock surface of the ME summit.

It is the first time for Chinese surveying-mountaineer team to probe the ice-snow layer depth on the ME summit with GPR in the 2005 campaign. According to the profile of ice-snow depth around the survey target, 3.50m depth of ice-snow layer depth at the survey target with the accuracy of ±0.10m was detected by the GPR. Snow topography of the concerned area on the ME summit was obtained at the same time.

According to the analysis for the figure and length of the reflected waves from GPR on the ME summit in the 2005 campaign, there are three parts in the ice-snow layer of 3.50m. The thickness of the first (upper) part of the layer is almost 1.0m with a low density, and it should be a snow layer. The thickness of the second part is 1.5m or so with a little larger density, and it should be an ice layer. The thickness of the third part is 1.0m with a larger density than that of the ice layer, lower than of the fourth part, the rock layer, and it is estimated as a mixture layer of ice, the earth and pieces of rock. Under the 3.5m layer, i.e. all the reflected waves appeared on GPR from the fourth layer, their figure and length are very uniform, so it will be the real rock body of ME.

There are some characteristics technically for the GPR integrated with GPS in the 2005 campaign: One is the integration of GPS and GPR hardware, and the other is the integration of the time, making synchronization of GPS and GPR time counting, by which the GPR position (measured by GPS) matches with its detected depth at the same instant. The third one is to have a “highest” differential GPS positioning (or RTK) on the earth between the GPS of the survey target and the GPS of the GPR on the ME summit.

V. HEIGHT of ME

1. Geodetic Height of the Snow Surface of the ME Summit

In the 2005 campaign the geodetic height of the snow summit of ME (corresponding to the centre point of the survey target on the snow surface, and the same here after) with classical geodetic techniques was 8821.69m, and with GPS was 8821.40m. The weight average of the two results for the geodetic height of the snow surface of ME summit is 8821.47m.

2. Normal Height of the Snow Surface of ME Summit

The normal height of the snow surface of ME summit can be obtained from its geodetic height 8821.47m and the corresponding height anomaly -25.20m. Hence the normal height of the snow surface of ME summit is 8846.67m.

3. Orthometric Height of the Snow Surface of ME Summit

The difference between the geoid and quasi geoid at the survey target on the ME summit is 1.26m. The method how to obtain the difference is similar to that in the 1975 HDME campaign[1-3,13]. Hence the orthometric height (height above sea level) of the snow surface of ME summit is 8847.93m.

4. Orthometric Height of the Rock Surface of ME Summit.

Taking account of the orthometric height of the snow surface of ME summit 8847.93m, and the corresponding ice-snow layer thickness 3.50m, the orthometric height (height above sea level) of the rock surface of ME summit can be obtained as 8844.43m. The computation accuracy of the orthometric height value is ±0.21m[18], and the practical accuracy of the value, considering the measurement accuracy of the related geometric and physical factors in the HDME, may reach ±0.5m.

The 2005 campaign was fulfilled successfully by Chinese National Fundamental Geo-informatics Center and Shanxi Bureau of Surveying and Mapping, with help of Climbing Association of Tibet, organized by Chinese State Bureau of Surveying and Mapping, The authors of the paper would like to take this opportunity to extend their sincere appreciation to those mountaineers, surveyors and geodesists who made great contributions to the 2005 height determination of Qomolangma Feng (Mt. Everest).

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COMBINED ADJUSTMENT OF NATIOAL ASTRO-GEODETIC NETWORK AND THE NATIONAL GPS2000 GEODETIC NETWORKS

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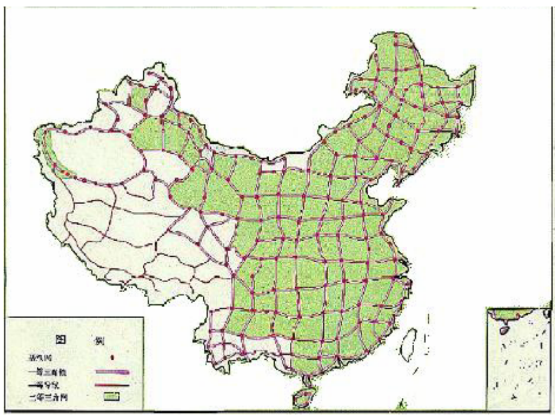
I. BACKGROUND

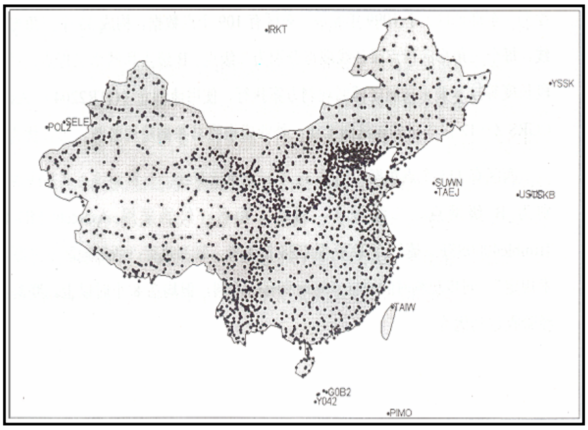
The Current geodetic coordinate systems of China are 1954 Beijing Coordinate System (BJ54) and 1980 Xian Coordinate System (Xian80) that have been used for more than 50 years and 20 years respectively. Both BJ54 and Xian80 are local reference coordinate systems. The origins of both coordinate systems are not consisting with the earth center. BJ54 is directly introduced from the former Soviet Union's coordinate system for which Krasovsky ellipsoid is adopted. Xian80 adopts IAG-75 ellipsoid and follows the principle of minimum of sum of square of hight anomaly. 1982 is the milestone of the establishment of Xian80 when the adjustment of the national astro-geodetic network (NAGN) was finally completed. The NAGN includes nearly 50,000 control points. Lack of external control, the accuracy of the NAGN is about 10-5~10-6. Obviously, such accuracy can not meet many demands for various applications. On the other hand, with the developments of surveying technologies, e.g. the integration of high-precision airborne GPS and inertial system into photogrammetric survey, control points with geocentric coordinates are needed.

In 90's of last century three national GPS networks were established by the State Bureau of Surveying and Mapping (SBSM), the Military Surveying and the Chinese Seismic Bureau (CSB) respectively. In 2003 the combination and readjustment of the three GPS networks yield the so-called National GPS 2000 network with accuracy of 10^{-7}~10^{-8} for the baseline.

The purpose of readjustment of astro-geodetic network is to tie astro-triangular points to WGS-84 coordinate system and to enhance the accuracy of whole network.

II. INTRODUCTION





The time span of the observations of astro-geodetic network is nearly 60 years. The position of astro-geodetic points may have moved with time, thus it is important to judge a co-occupied points. Also the factors which affect astronomic observation, direction and traverse or distance observation must be analysed before combined adjustment. Such as earth crust movement, the change of astronomic system, geoid improvement and so on. First, the observation types joining in combined adjustment and their accuracy simply introdused, and then factors analyses stated above would be discussed, which of them must be considered in data preprocessing in correcting the observations to WGS84 ellipsoid, how these correction added. The mathmatic model and stochastic model used in adjustment .The unknown parameters of whole network are about 150 thousands, such large scale data processing is very hard and complicated to fulfill in PC computer, Section four discuss effective solution scheme, final section main analyze results of combined adjustment and some conclusion.

III. DATA ANALYSIS

The kind of data: As to GPS2000, only adjustment coordinates and variance-covariance of co-location points with NAG join in adjustment. The observations of NAG include astronomical azimuth, directions and distances of triangulation network of order one and order two, zero-order traverse, baseline between GPS and geodetic point, The observations of 1688 points from 5 reform networks to instead of observations of 1375 points from original order two triangulation network. After necessary analyse of total 50970 points, 326902 observations, 48919 triangular points including 336 co-occupied points of these two networks, amount to 314976 direction observations, 2146 sides, 1064 astro-azimuths, 72 zero-order traverses, 1022 baselines are taken into account,.

Elements analyse

❖ how the plate movement affected on astro-geodetic network

After practical computation and analyse , the affections caused by the plate movements are not taken into account in adjustment.

❖if necessary to consider affection stem of changing from fourth fundermental Catalogue (FK4) to fiveth fundermental Catalogue (FK5)

The corrections to astronomic latitude, astronomic longitude, astro-azimuth because of datum changed are very small, so original astronomic observations don't need to be recalculated , only pole correction to CIO(IRP) take into account here

❖Recompute deflection of the vertical corresponding to WGS84 ellipsoid, the height anomaly of geodetic points is interpolated with CQG2000 quasi-geoid modelMany gravity data has been obtained Since 1980, nationwide height model has been widely used , technique of geoid and vertical deflection computation has also been improved ,so it is necessary to recomputer related items with new data and new technique

IV. THE SCHEME

1) Helmert block adjustment is used in combined adjustment .All observations are corrected to WGS84 ellipsoid.

2) Helmert covariance component estimation used to match the weight ratio of two networks

3) The territory network concerned observations of different kinds and different order. so it is necessary to determinate best weight ratio between two networks, among different observations or different order of same kind observation.

4) The unknown parameters of adjustment are two dimensions(B L) for the points in block and related points and three dimensions(B L H) for co-occupied points, so another error equation of leveling or triangle height is added.

5）Before combined adjustment, GPS network have been processing alone, adjustment coordinates of GPS network as approximate coordinate of co- occupied points.

6）Stochastic model

Stochastic model of territory observations determination is based on post variance obtain from "The nationwide adjustment of astro-geodetic network in 1980", unit weight is taken as 1.0,direction weight and side weight of electromagnetic wave distance measured are as follows

Prior weight of direction observation

	Chain 1	Order 1，traverse 1	Chain 2	Order 3、traverse 2	Patch 2、traverse 3
$m_{方}$	0.50″	0.65″	0.82″	1.19″	1.46″
wt	4.00	2.37	1.49	0.71	0.47

Weights of azimuth and side which was origional regards as orientation and length scale datum and now is regards as observations can be seen following

type	rms	weight
azimuth	0.8(sec)	1.6
baseline	$S_i/70\times10^4$（m）	$(70\times10^4)^2/S_i^2$

Baseline extending	$S_i/23\times10^4$（m）	$(23\times10^4)^2/S_i^2$

The observations of space network refer to adjustment coordinates and their variance-covariance of co-location points after nationwide adjustment of GPS 2000 network. Generally, the absolute position accuracy of GPS points in ITRF frame can be within cm level, relative accuracy can reach mm level. Baseline accuracy can be better than 10-7.prior weight in stochastic model of space network adopts “nationwide GPS 2000 adjustment ” determination .

The ratio of territory network to space network is 1

7) 16 blocks are divided for whole China territory (number these area from east to west), 1822 points on dividing line,47097 points in blocks

V. ACCURACY ANALYSES

Position accuracy of total 48919 points, baseline accuracy of 565 GPS points, the accuracy of 2146 side and 1046 azimuth are estimated in this adjustment.

1） Position accuracy of territory points

the statistic results show that the position accuracy of 30803 points are within 0.1m，is about 63.4%，46375 points within 0.3m ，about 95.5%，658 points are over 0.5m，about 1.3%，average position accuracy of network is 0.11m.The weakest position rms is 1.45m，located in Talimu basin in Xinjiang province (B=39°31′，L=80°55′) where only single traverse is cross basin and no GPS points there.

2）Position accuracy of space points

Position rms of 336 co-occupied points reach subcentimeters，of which 233 points within 0.01m，about 69.4%，314 points within 0.03m，about 93.6%，335 points within 0.05m，about 99.9%，only one point is over 0.05m，about 0.3%，the greatest one is about 0.06m，average is 0.01m。

3）RMS of azimuth

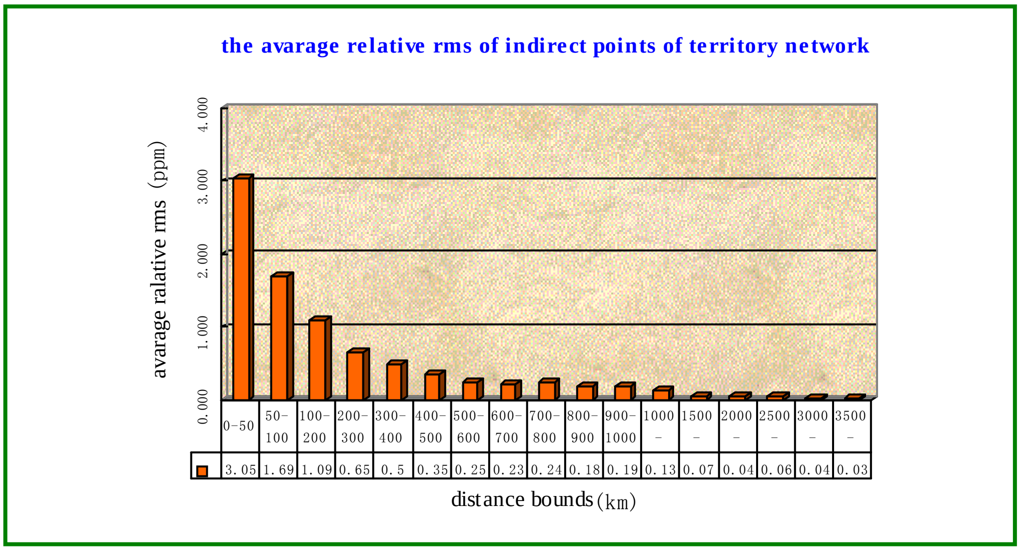
RMS of total 1064 azimuth is estimated. The greatest rms of azimuth is 0.56 second，average rms is 0.33 second。

4）Relative accuracy of direct side of territory network

The relative precise of total 2146 direct observed side are estimated. the average rms of side is about 4.275ppm

5）Relative accuracy of indirect side of territory network

Relative accuracy of 4552 indirect side are estimated，the figure below shows the average relative side rms of indirect points within different distances bounds .



6）Estimation of variance components

The variance of different order observations estimated with Helmert covariance component estimation can be seen in column 3 below, direction rms after adjustment is listed in column 4. From the form we can see that the post rms of directions is nearly the same as prior rms. Only weight flag 3 which stands for old basic triangle chain of order two has a little large difference. Flag 6 indicate items related with azimuth.

Prior and post rms of direction observation （unit：second）

Direction Flag	Prior rms	σ^2_{0i}	Post rms σ_i
1	0.50	0.84558	0.45978
2	0.65	0.92494	0.62513
3	0.82	0.83516	0.74937
4	1.19	0.98399	1.18043
5	1.46	0.93170	1.40926
6	0.80	1.12590	0.84887

VI. CONCLUDING REMARK

The adjustment processes concern 310 thousand directions, 3 thousand sides and azimuths. Unknown parameters are 157892，The ratio of prior unit weight to post of root mean square is 1.0025.

48919 point coordinates have been corrected to earth center coordinate system, The adjustment results compared with original nationwide adjustment are show follow form

item	Relative RMS side (ms/s)		Direction correction	Azimuth RMS
	Max	Min	Max	Max
before	1/54000	1/654000	－10.625”	2.1765
after	1/31124	1/1500000	−8.87”	0.56

From which we can see combined adjustment effectively decrease accumulation error of astro-geodetic and enhance the position, side, orientation, scale accuracy of whole network .Nearly 50 thousands earth center geodetic coordinates have gotten through combined adjustment, avoid to do transformation between WGS84 and XCS80. so it can also deduce transformation error, the products have served most applications which needed WGS84 coordinate system in many fields.

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NATIONAL GPS CORS DATA PROCESS AND GEOCENTERIC COORDINATE FRAMEWORK MAINTENANCE

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Abstract: The Crustal Movement Observation Network of China (CMONC) was founded in 1998, 25 GPS Fiducial Stations (including 5 GPS Fiducial Station of SBSM) are founded or rebuild by now. This analysis of domestic GPS Fiducial Stations includes the 25 GPS Fiducial stations of CMONC and 3 GPS Fiducial Stations of SBSM which are excluded in CMONC, so there are total 28 stations. The time spanned from March 1st, 1999 to December 31st, 2004, spanning six years (305 weeks). The author of this article deals with the daily data processing and analysis of GPS Fiducial Stations. After the adjustment on the result of the daily GPS data processing, we could obtain the precise GPS time series of stations coordinates. This article carried on the analysis to the time series, discovered the error character in time series of each GPS Fiducial Stations, in this foundation, we can exactly identify the actual precision of GPS station, to discover the rule of plate movement and estimate correlation of geophysics factor. Based on the observation data provided by domestic GPS Fiducial station, this article focuses on analysis of coordinate variety rules of GPS Fiducial station, and lead to a statistic analysis result of station coordinates and velocity precision. According to the common law of selection of framework points, we put forward a scheme fit to China as one of the basic principles of geocentric coordinates framework maintenance. On the basis of this, we can quantitative educed the precision of CPS fiducial station, and opened out the law of plate motion, and estimated many geophysics factors relatively. We use these methods include point coordinates, velocity precision, reliability of fiducial station and the result of the time series analysis and selection of framework point as the main methods for geocentric coordinates framework maintenance.

Ⅰ. INTRODUCTION OF BASIC CIRCUMSTANCE OF CORS STATION OF CHINA

The first GPS Fiducial Stations of State Bureau Of Surveying and Mapping (SBSM) was founded in 1993, at present 8 stations have been founded, there are BJFS, HAIK, HRBN, XANY, WUHN, XNIN, LHAS, URUM, respectively. The Crustal Movement Observation Network of China (CMONC) was founded by China Seismological Burea*u*, the Bureau of Surveying and Mapping of the General Staff, the Chinese Academy of Sciences and the State Bureau of Surveying and

Mapping in 1998 and started work from 1999. The fiducial stations included BJSH, JIXN, SUIY, HLAR, CHAN, TAIN, SHAO, WUHN, XIAM, GUAA, QION, YANG, XIAN, LUZH, KMIN, XIAG, XNIN, DXIN, DLHA, LHAS, URUM, WUSH, TASH, YONG, HAIK, HRBN, XANY.

Ⅱ. THE STRATEGY OF DATA PROCESSING

1. The Method of Data Processing

The software named GAMIT (10.05) /GLOBK (10.0) which used to data processing and adjustment for GPS Fiducial Stations, GAMIT is a comprehensive GPS analysis package developed at MIT and Scripps for the estimation of three-dimensional relative positions of ground stations and satellite orbits base on the GPS double-difference. Globk is a Kalman filter whose primary purpose is to combine solutions from the processing of primary data from space-geodetic or terrestrial observations. In order to strengthen the geometry relation between Domestic GPS Fiducial Stations and global IGS stations, in the daily GPS processing, we added peripheral 9 IGS stations, so we can obtained the non-bias solution of position and covariance. The goal was to improve the intensity of entire GPS network.

2. Adjustment and Velocity of GPS Fiducial Stations

We use GLOBK software to carries on adjustment after daily GPS solution. After joint processing and adjustment for GPS Fiducial Stations and IGS GPS stations, we can obtain the velocities and coordinates in model of global crust movements, In order to obtain the velocity field information of GPS Fiducial Stations, we adopt two steps: The first step, performing a least squares analysis, this step completes by GAMIT software. The Second step, according to GPS time series, estimating speed uses Kalman filter method, this step completes by GLOBK software. Our results are all transferred to ITRF2000 frames.

The result showed the precision of coordinates basically changes between 1.0-2.5mm in N direction, between 2.5-5.5mm in E direction and between 6.0-10.0mm in U direction. In the precision of velocity field, N direction is between 0.1-0.4mm/ year (mm/a), E direction is between 0.4-0.8mm/a, U direction is between 0.8-1.6mm/a. The precision of velocity fields are superior to coordinates precision, so it can reflect the change rule of the position.

Ⅲ. TIME SERIES ANALYSIS

The time series of precise coordinate are obtained after data processing and adjustment, we analyze time series of each GPS fiducial station to discover the periodic character in the north, east, elevation, total three directions. After periodicity and velocity are moved over, we can obtain the errors characters of time series of each GPS Fiducial Stations. In this foundation, we can exactly identify the actual precision of GPS station, to discover the rule of plate movement and estimate correlation of geophysics factor.

The movement of GPS Fiducial Stations mainly represent in the horizontal direction and the elevation direction. The movement in the horizontal direction mainly focuses on the movement of plate. The influence magnitude due to geophysics factor (for example some kind of tide movement, resilience after ice period and ground water and so on) generally below 5mm in horizontal direction, but in elevation direction it's bigger. Therefore linear movement is the main characteristic of horizontal direction, annual variation rate in horizontal direction is about several centimeters, and so linear movement in horizontal direction is easily obtained with repeated measurement. The movement in elevation direction comprise of linear movement and many periodic movement that have big amplitudes. The regulation of stations movement in elevation direction only could be discovered by the analysis of time series of long-term and continuously observation. After the data analysis, we can know that all stations have long-term item about one year in time series of elevation direction.

1. The Power Spectrum Analysis

The power spectrum function of geophysics phenomenon is the $1/f^{a}$ form, Power Spectrum are composed of two parts:

$$P(f) = P_0(f^{-a} + f_0^{-a}) \quad (1)$$

In the formula f_0 is the intersectant frequency composed of colored noise and the Gauss white noise; P_0, f_0, a is unknown parameter. If the time series noise is mainly composed of the colored noise, then the simplify formula (1) is

$$P(f) = P_0 f^{-a} \quad (2)$$

Logarithm form is:

$$\ln P(f) = \ln P_0 - a \ln f \quad (3)$$

in the formula, $P(f)$ is the power spectrum density, f is the frequency; P_0 and a is unknown parameter.

The time series noise of GPS coordinates includes the Gauss white noise and the colored noise, In this article we use FFT (the fast Fourier transformation) to obtain time series $P(f)$ of Lhasa, Shanghai, Harbin, Haik, and fits P_0 and a using least-squares principle. see Table 2

In the formula (3), the value a is the more bigger, the more smoother of stochastic process are represented , the energy of stochastic process makes the more approach to the low frequency region, The value a of primary geophysics phenomenon is between $1 < a < 3$, value a

between in this scope represents the shape Brownian movement [2]. In the power of GPS time series, $a=0$ corresponds to the white noise; $a=1$ corresponds to FLICKER noise; $alpha=2$ corresponds to stochastic noise; $a>1$ represents all colored noise. Obviously, the time series of 6 GPS stations listed in table 2 had been influenced from colored noise, all signals of 6 stations are not smooth, the influence mainly come from FLICKER noise and stochastically noise.

Generally, IGS stations also display the certain periodicity in the north and East, but the periodicity in elevation component is most obvious, the energy of periodic movement in elevation direction holds the very great proportion in total energy that distribute in three directions.

Through the FFT analysis, we know that anniversary and semiyearly periodic movement are existent in time series of elevation component, but the map of power spectrum only discuss question in frequency range, we have to carry out the analysis in domain of time and frequency base on the wavelet analysis theory and polynomial analysis.

2. Polynomial Fitting and Wavelet Analysis in Time Series

The method of spectral analysis can analyze the frequency characteristic of GPS fiducial station and discover the tendency of sequence periodic. But the time series of station coordinates receive many kinds influence due to geophysics phenomenon. The influence factor includes stochastic change and some fantastic sector; spectral analysis method cannot distinguish this. Intend to discover the movement rule and tendency we carry on the linear fitting and polynomial fitting in the elevation component. Simultaneous we carry on the wavelet analysis to study the time series characteristic in domain of time and frequency. The significance of wavelet analysis lies in decomposes the signal in the sub-spatial after the space analysis. And it is equal to one signal filter of time and frequency, so the method of wavelet analysis could be convenient used in the analysis of signal. The author of this article decomposes the anniversary item of time series in elevation component using the wavelet analysis method. Because the periodicity in the elevation direction is more obvious, in this article we analyzed the tendency of elevation direction using the wavelet filter named Symlets. The results of 4 stations named Lhasa, Urumqi, Beijing and Haikou list below.

The movement characteristic in elevation direction are different from horizontal direction, the linear movement in elevation direction is much more difficult to monitor, the first reason is measuring accuracy of GPS in elevation direction is lower 2-3 times than horizontal direction, the second reason is the station movement in elevation direction are caused by many geophysics factors, because the season change conduct the mainly effect, so the movement characteristic in elevation direction represent certain year periodicity, otherwise the change rate of linear movement is smaller per year (millimeter / year).After analysis in 28 GPS fiducial station, 75% station in elevation direction take the linear movement about 1-2 millimeters per year, it is smaller than the effect caused by anniversary and semiyearly periodic movement. Particularly some linear velocity of stations movement in elevation direction may be considered zero.

Through the result of polynomial fitting and the wavelet analysis, we can know that the time series of majority GPS fiducial stations in elevation component is approximate to sinusoid, the periodicity is about one year, the amplitude is 1 ~ 7cm. It shows that the seasonal change still conduct main affects in GPS elevation precision. From the result of wave analysis, there are regular curve in the anniversary movement of Beijing and Urumchi. The peak value of periodic appears about in May to July, the lowest value appears in October to December in Beijing station, while the peak value of periodic appears about in May to July, the lowest value appears in October to December in Urumchi station. The periodic tendency of HaiKou station is worth further studying because the amplitude of elevation increases year by year and the amplitude in 2005 has reduced in large scale. Lhasa station is also expressed the anniversary movement in elevation direction, peak value of Lhasa station appears about in January to March, lowest value appeared in September and October. We can conclude that time series characteristic in domain of time and frequency displays the obvious regional characteristic.

Ⅳ. SELECTION OF THE FRAMEWORK CONTROL POINT

At present, selection of GPS core stations mainly exhibited the study of ITRF. For example, in the ITRF2000, there are 54 fiducial stations have been picked as core stations. The four standards of choose is respectively: the station was continuous observing during nearly 3(or more) years; the station located in the rigid plate; the precision of velocity fields is better than 3mm/a; there are at least 3 velocity errors of dissimilar analysis results.

So far as the four standards of choose of GPS core stations of ITRF2000 concerned, there are still have some incertitude. The problems are mainly as follows: the first, the distance between GPS fiducial station and distorted region is not ascertainable. So we possible picked the station that its distance more than 100km or 500km from distortion region. The second, the velocity biases and threshold of errors are uncertainty. On the one hand, between the result of velocity fields of GPS fiducial stations and the continuous observing time have great relativity. On the other hand, there are various choose of velocity biases and threshold of errors, such as 1mm/a,3 mm/a,5mm/a and so on. The third, checkout result of stations to select through rigid plate expressed that it is may obtain a false result if we choose improper stations. Even rigid GPS fiducial stations also may not matching with motion of the entirely plate. The fourth, we should paid more attention that above four standards is not considered deviant changes of GPS fiducial stations, such as earthquake, circuitry broken, instruments malfunction. Therefore the selection of GPS core stations of ITRF2000 is still far enough from strict, and is still uncertainty and not facility for operation.

According to our research and integrated the result of study of the global, the basic standards is the same, namely:

★ Principle of continuity: the station was continuous observing during nearly 3(or more) years;

★ Principle of stability: located in the rigid plate and distant distorted regions;

★ Principle of High precision: the precision of velocity fields is better than 3mm/a;

★ Principle of various results: at least 3 velocity errors of dissimilar analysis results is better than 3mm/a;

With above four principles, we particularly emphasized the principles of stability and precision analysis of the time series of GPS fiducial stations. There are two principles as follows:

Since our country contribute to the building and geocentric coordinate framework maintenance, we add a principle to fit the fact of our country.

★ Principle of equilibrium: the fiducial station is well-proportioned distributing throughout our country.

In common condition, in order to convenience for use and economize time, we usually choose the IGS fiducial stations located in China and around the China as the stations for China geocentric coordinate framework maintenance, as well as the different between international network and location network. For expressed clarity the process of framework stations selection, we expanded the IGS fiducial stations around China in global in order to make more IGS stations to enlist and persuasion more power.

In connection with the reliability of China geocentric coordinate framework, we add another principle of selection, that is:

★ Principle of precision consistency. The mathematical basis of this principle is:

We analysis the location precision $\sigma_P = \lfloor \sigma_{Px} \quad \sigma_{Py} \quad \sigma_{Pz} \rfloor$ which it approximately accord with above 5 principles and precision of velocity fields $\sigma_V = \lfloor \sigma_{Vx} \quad \sigma_{Vy} \quad \sigma_{Vz} \rfloor$ as the time series, and discuss the error and variance of the time series of this precision value. According to the simplest principle of gross error detect, we regard the point did not fit to the framework point when its error is larger than twice of variance. We must point out that we eliminated the station only when it did not satisfy all principles because location precision included 3 subordinates and precision of velocity fields also included 3 subordinates.

Ⅴ. CONCLUSIONS

We can obtain the conclusions basing on above analysis:

The linear movement is the main characteristic in horizontal component, the magnitude and direction of variety is relative to plate movement and inner movement of plate. The residual of

GPS fiducial station is stochastic curve going with time variation. The value and precise of velocity is reliable and the precision of velocity is superior to coordinates precision, so variety rule of the station position could be reflected.

Through the result of Power Spectrum Analysis, we could know some stations display the certain periodicity in the north and East, but it is unobvious, the periodicity in elevation component is most obvious, the energy of periodic movement in elevation direction holds the very great proportion in total energy that distribute in three directions.

The result of polynomial fitting and wavelet analysis indicates the time series of GPS fiducial stations in elevation component is approximate to sinusoid, the cycle is about one year, the amplitude is 2 ~ 4cm. The crest and trough of time series appearing at different season indicates that the vertical accuracy of GPS measurements are mainly affected by seasonal variety, the season variety of time series include residual of oceanic tide model, atmospheric tide, the ground water and other geophysics factors, on the other hand, under the effect caused by the model of ionosphere and troposphere, the vertical precision of GPS measurement appear variety at different season and in different region.

The repeated survey should be occupied at the same season when we carry out the GPS observation in high precision. Simultaneity a long time series of GPS observations should be adopted intends to detect and remove the periodic error in station coordinate. Therefore the actual precision of three-dimensional positions could be detected.

Use the experience result from selection of framework point that combine processing IGS stations with civil stations, we put forward six principles for selecting framework points. There is principle of continuity, principle of stability, principle of high precision, principle of various results, principle of equilibrium, principle of precision consistency, respectively. Particularly, principle of equilibrium and Principle of precision consistency are more important to processing of combine IGS fiducial stations with civil stations.

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PROGRESS IN DEVELOPING LOCAL GEOID WITH HIGH RESOLUTION AND HIGH ACCURACY IN CHINA

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Determining the geoid with centimeter level will become a new milestone of geodesy. Geoid is a basic reference surface in geodesy, namely, the height datum for measuring the orthometric heights. To precisely determine the geoid, global gravity data with high accuracy and high resolution are needed. At present, the accuracy of the geoid still varies from decimeters to meters in the medium wave and long wave band which are the overwhelming majority, larger than 95 percent in the structure of the spectrum of the Earth's geopotential field. Improving the accuracy of the components of the medium wave and long wave is the key factor for refining the geopotential field and geoid, and the new satellite gravity exploration missions, which could provide global gravity data at a resolution of 50~100 km with high accuracy effectively and cheaply, will be an effective way to solve this problem. If the geoid with an accuracy of centimeter level is realized, then the GPS ellipsoidal heights (geodetic heights) could be transformed into orthometric heights directly and reach centimeter level, by using a geopotential model with relevant accuracy, and the burdensome levelling work could be practically replaced by GPS altimetry. This would be a great progress in measuring the orthometric height and normal height. The orthometric height data of terrain points are fundamental information, which is needed in social and economic development and research in geoscience.

Global Navigation Satellite System (GNSS) has brought about a profound revolution in the field of navigation and positioning, and made an important effect on the development of geospatial information. With the development of Global Positioning System (GPS) technology, the accuracy of positioning is more improved. The relative accuracy of the order of 0.001ppm could be obtained, and the accuracy in the vertical component is about 5mm or higher. Using the precise 3-dimensional ellipsoidal coordinates derived from global positioning technique and the geoid with centimeter-level accuracy, the orthometric height will be accurately determined, and the modernization of the elevation survey will be realized.

Based on the already completed 5′×5′ China quasi-geoid grid digital model (CQG2000), we have mainly focused on the refinement of geoid for some regions, medium and big cities in the recent 4 years, in order to serve for the demands of the high-speed development of economy in these regions and cities.

I. THEORIES AND METHODS

1. *The Establishment of GPS/Leveling Networks and Data Processing*

(1) *The establishment of GPS/leveling networks*

The GPS/Leveling network includes fiducial network and basic network. The purpose of fiducial network is not only to provide the high accuracy geocentric coordinates combining with IGS stations, but also improve the accuracy of basic network. Now Continuously Operating Reference Stations (CORS) are established in a few provinces and cities in China, and so these stations should be selected as fiducial stations if the quasi-geoid is determined in these areas. The distance between two fiducial stations is about 30-60km, and each site was occupied for 2-4 days.

The GPS/leveling heights could be obtained by the establishment of basic network. Moreover, the local coordinates might be modified and connected with WGS84 coordinates by the network. At least 60% of basic stations should be levelled by high precise levelling method in order to determine precise geoid. The distance between two basic stations is about 7-15km, and each site was occupied for 8 hours.

(2) *The method of Data Processing*

This approach determines the station position in a single, self-consistent reference frame (Arnadottir, 2006). Some International Geodetic Service (IGS) stations in China and its adjacent areas are selected as the fiducial station (See Fig. 1). The strategy of daily（or session） solution is described as the following:

- Daily (session) solution is calculated using an ionospheric-free combination (LC), double-difference, phase solution.
- Precise satellite orbits and Earth rotation parameters from IGS are used and tightly constrained according the related accuracy.
- GPS satellite orbit parameters were estimated together with all station coordinates.
- The sample interview is 30 seconds, and the cut-off angle is set to 15 degree.
- Tropospheric delay corrections are applied using Saastamoinen model, Dry Niell mapping function with 13 zenith delay estimates for each station.
- Antenna phase center corrections for satellites and receivers, and the models use IGS phase center calibrations.

- Ocean tide loading correction is applied using the model provided by GAMIT.
- Model corrections for satellite clock offsets (the clock parameters are taken from Broadcast Ephemeris; Model corrections for receivers clock offsets (the clock offset are computed from pseudoranges.

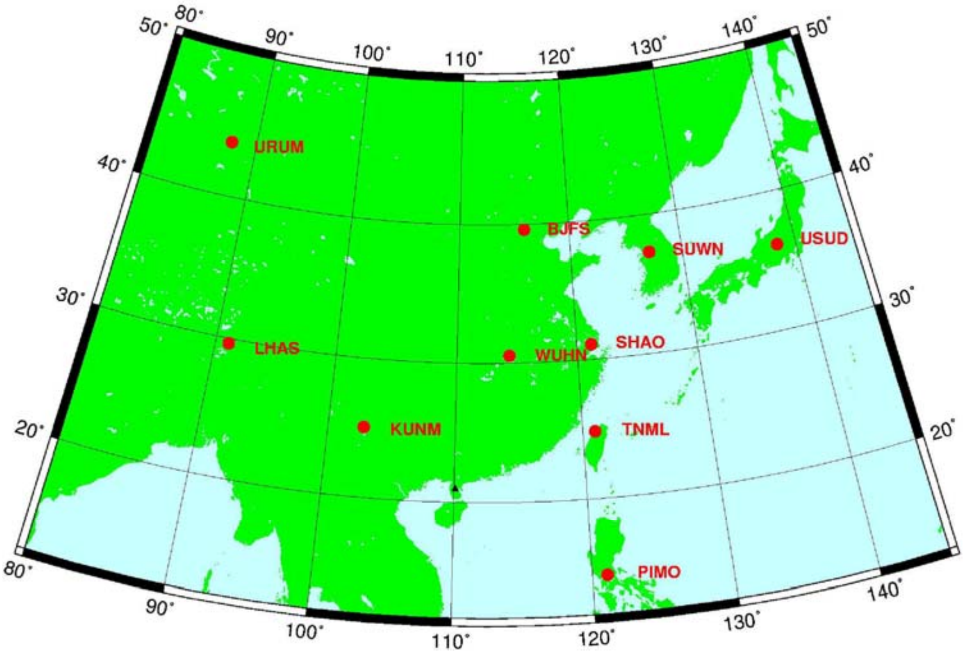

Figure 1 The distribution of selected IGS sites in China and its adjacent areas

2. *The Acquisition of High-Resolution Grid Gravity Anomaly*

The topographic-isostatic correction is adopted to get high-resolution grid (e.g. $1.5'\times1.5'$) gravity anomaly. The interpolation and extrapolation of gravity anomaly is realized by remove-recovery approach.

3. *Method of Gravity Quasi-Geoid Determination*

(1) *Molodensky method*

The classical Molodensky series are used, with the 1st order considered.

(2) *Second Helmert condensation method*

The Second Helmert condensation method, which determines the quasi-geoid, contains the following procedures: precise solution of the effects caused by different types of topographic potential and gravitation, which are also called the indirect effects of the residual topographic potential between Newton topographic mass gravitation potential and condensation potential; effects to Helmert gravity anomaly caused by gravitation of topographic mass gravitation potential and condensation potential. Following aspects should also be concerned in Helmert gravity anomaly: the correction between quasi-geoid and geoid, normal gravity correction from the ellipsoid to Helmert quasi-surface, ellipsoidal correction and atmospheric impact, etc. Based on the Second Helmert condensation method, a complete practical formula in quasi-deoid determination is achieved.

4. *Numerical Integration Calculation*

In the integration related to the all methods mentioned above, the closed 1-dimensional FFT approach is adopted, which includes the contents as follows: the 1-order, 2-order correction and 1-order Molosensky correction (or G_1), in the Taylor expansion of different types of topographic corrections.

5. *Calculation of Topographic-Isostatic Correction in Sea-Land Edge Area*

In the sea-land edge area, the spherical cap harmonic region of the calculating point contains two parts: one on land while the other in ocean, where the topographic-isostatic correction formula has different forms. According to the principle of topographic-isostatic correction, a unified closed formula of topographic-isostatic correction in the sea-land area is achieved. Hence, the correction accuracy is improved in this special kind of areas (Li et al., 2003).

6. *Sea-Land Unified Closed Determination of Quasi-Geoid*

Since there is no GPS-leveling grid point in ocean area, the mean sea level height (ellipsoid height) of the grid point in high-accuracy (centimeter-level) mean sea level altimetry is set as GPS ellipsoid height, just similar to the points on land. The normal height of this grid point is determined by the sea topographic difference between the local height datum point of tidal station and the grid point. Then this grid point could be considered as “GPS-leveling point in ocean area”, like GPS-leveling points on land. The height anomaly in local height reference is determined; and accordingly, the marine altimetry-derived quasi-geoid is determined. The unified fit of gravity quasi-geoid and GPS-leveling quasi-geoid in both land and ocean areas can be realized. Then the sea-land uniform quasi-geoid in national height system is determined (Wang et al., 2005).

7. *The Fit between Gravity Quasi-Geoid and GPS-Leveling Quasi-Geoid*

Usually, we can select the proper fitting function based on the analysis of the differential system errors of these two kinds of quasi-geoids. Since it is difficult to analyze the contribution of different kinds of system errors exactly, we use two kinds of fitting functions as follows:

(1) Polynomial fitting. Basing on the fitted area, we adopt quartic at most.

(2) Determine the fitting function with spherical cap harmonic analysis method.

Consider the fitted area as a spherical cap, and the center of the spherical cap is the center of the fitted area. Establish the grid data of the difference between the two kinds of quasi-geoids in the spherical cap area, and use the integer degree non-integer order general spherical harmonic analysis method, which is spherical cap harmonic analysis method, to calculate the spherical cap harmonic expansion coefficients, which are corresponding to the order of data resolution. This spherical cap harmonic expansion series is the fitting function. And this method has the characteristics of rigorousness and high degree of accuracy.

II. THE ADOPTED MAIN DATA TYPE

1. The Measured Gravity Anomaly Values at Ground Points

2. The measured height anomaly values at the points in GPS network

3. Shuttle Radar Topography Mission (SRTM) 3″×3″ digital terrain model

4. NASA 2′×2′ ocean bottom topography data DTM 2000

5. Reference Geopotential Model: EGM96 (360 degree/order) or WDM94 (360 degree/order), and the latter was established by Wuhan University

III. BRIEF INTRODUCTION TO THE LOCAL QUASI-GEOIDS OF SOME PROVINCES AND CITIES IN CHINA

1. Using shuttle radar topography mission data, gravity data and GPS leveling, high accuracy quasi-geoid of the city of Wuxi was established in 2003, the accuracy was 2.2cm, checked with 30 independent GPS leveling points.

2. In the calculations of the quasi-geoid of Caidam Basin in Qinghai province, 83 GPS leveling data and 166078 gravity data were adopted, and EGM96 Earth geopotential model was taken as the reference geopotential field. The gravimetric quasi-geoid, determined based on Molodensky method, is finally fitted to the GPS leveling points of Chinese 1985 and 1956 Yellow Sea Height System, completing comparisons and analysis with GPS leveling. The accuracy of the obtained 1’.5×1’.5 grid quasi-geoid was better than ±0.100m.

3. The quasi-geoid for the city of Qingdao was established in 2004. In this case, WDM94 was taken as reference model, and rigorous reduction method for terrain gravity data and calculation model for quasi-geoid were adopted. A gravimetric quasi-geoid with an accuracy of 2.5cm was achieved and the vertical variances of the GPS leveling quasi-geoid were removed. Finally, results show that the inner-coincidance accuracy of the obtained quasi-geoid is ±1.5cm. The external check with 270 GPS leveling points in this region was carried out and the external accuracy was ±1.8cm. A rigorous land-sea combined algorithm, which guaranteed a high accuracy of the quasi-geoid when there are both land and sea in the

calculation region, was introduced in the calculation of the quasi-geoid of the city of Qingdao. The results show that the Qingdao quasi-geoid becomes the most accurate city quasi-geoid at that time in China.

4. In the research and calculations of the quasi-geoid of Hebei province in 2004, 37498 point gravity data and 114 GPS leveling data were adopted. A quasi-geoid, with a resolution of 2′ 30″ and an accuracy better than ±0.065m was established based on the rigorous theory and algorithm of the determination of quasi-geoid.

5. In the calculations of the quasi-geoid of Tarim Basin and the circumjacent area in Xinjiang province in 2004, 269633 point gravity data and 66 GPS leveling data were adopted and EGM96 was taken as reference model. Based on SRTM 3″ ×3″ digital terrain model, the interpolations and predictions of the grid gravity anomalies were calculated through topography-isostatic reduction and "remove-restore" approach. The gravimetric quasi-geoid was finally fitted to the GPS leveling points. The accuracy of the obtained 2′ 30″ ×2′ 30″ grid quasi-geoid was better than ±0.20m.

6. In the calculations of the quasi-geoid of the city of Changzhou in 2005, 3610 point gravity data and 60 high accurate GPS leveling data were adopted，EGM96 was also taken as the reference model, a grid gravimetric quasi-geoid with an accuracy of ±0.022m and a resolution of 2′ 30″ ×2′ 30″ was obtained, and after the fitting to GPS leveling points, the accuracy of the GPS quasi-geoid was better than ±0.014m. The interpolations and predictions of the grid gravity anomalies, the terrain model and the calculation method are as same as the previous one.

7. In the determination of the quasi-geoid of Qinghai province in 2005, 213862 point gravity data and 101 high accurate GPS leveling data were used, SRTM 3″×3″ digital terrain model and EGM96 model were adopted, and a gravimetric quasi-geoid was obtained. Based on the above, the spherical cap harmonic analysis method was first used in the united solutions of the gravimetric quasi-geoid and GPS leveling. A uniform whole quasi-geoid of the province with an accuracy of ±0.186m and a resolution of 2′30″×2′30″was obtained.

8. In the case of the calculations of the quasi-geoid for Songbei district in the city of Harbin, 1250 point gravity data and 34 high accurate GPS leveling data were used, WDM94 geopotential model and SRTM 3″×3″digital terrain model were adopted. First, a gravimetric quasi-geoid was obtained based on the rigorous theory and computing method of geopotential field determination. Compared with GPS leveling data of 1985 and 1956 Yellow Sea height system, the standard deviations were ±0.027m、±0.021m respectively. Secondly, the spherical cap harmonic analysis method was used in the united solutions of the gravimetric quasi-geoid and GPS leveling, two grid quasi-geoids with a resolution of 2′ 30″ ×2′ 30″ of 1985 and

1956 Yellow Sea height system was obtained. The accuracies of these quasi-geoids were ±0.013m and ±0.012m respectively.

9. In the calculations of the quasi-geoid for Guangdong province, 417,336 point gravity data and 88 high accurate GPS leveling data were used, the geopotential field model, digital terrain model and methods for gravity reduction were the same as the previous cases. Rigorous land-sea combined terrain correction algorithm was adopted in terrain correction and the accuracy of terrain correction at the land-sea interface was improved. The Molodensky method and the second Helmert condensation method were adopted respectively in the calculations of the quasi-geoid, and it guaranteed the accuracy of the land-sea combined quasi-geoid. The spherical cap harmonic analysis method was used in the united solutions of the gravimetric quasi-geoid and GPS leveling. In addition, 74 independent GPS leveling points with uniform distribution were surveyed on-the-spot, and the external check was carried out and the accuracy achieved ±0.045m. Checked with 36 independent GPS leveling points in the city of Shunde and 65 ones in the city of Dongguan, the accuracies were ±0.019m and ±0.018m respectively, and the deviations were 0.058m and -0.016m respectively. Therefore, the quasi-geoid of Guangdong province (with accuracy better than ±0.050m) is the most accurate provincial-level quasi-geoid in China so far.

10. In the calculations of the quasi-geoid for the city of Dongguan, EGM96 was taken as the reference geopotential field, and 7273 point gravity data and 62 high accurate GPS leveling data were used in the calculations. Topographic-isosatic reduction was adopted for gravity reduction, and SRTM 3″ ×3″ digital terrain model was adopted also. In addition, a 2′ ×2′ DTM2000 model provided by NASA was applied in this case. The terrain correction algorithm and the gravimetric quasi-geoid determination approach are as same as those adopted in Guangdong province. The gravimetric quasi-geoid was compared with discrete GPS quasi-geoid, which was obtained by independent data source, and the accuracy was ±0.012m. Based on the spherical cap harmonic analysis method, a 2′30″×2′30″ grid quasi-geoid with accuracy better than ±0.01m was obtained through the united solutions of the gravimetric quasi-geoid and GPS leveling. This result is no longer centimeter level, but one-centimeter geoid in real sense, and it could replace the long-distance second-grade leveling, and it is the most accurate city quasi-geoid in China so far.

11. In the case of the quasi-geoid for the city of Guangzhou (Bureau of Urban Planning of Guangzhou Municipality), 5621 point gravity data and 143 high accurate GPS leveling data were used, the reference geopotential field, the digital terrain model and the method for gravity reduction were the same as those in the case of the city of Dongguan. The spherical cap harmonic analysis method was also used for fitting gravimetric quasi-geoid to GPS leveling, and this local harmonic analysis method can reflect the characters of the local geoid with a high resolution objectively. To evaluate the accuracy of the quasi-geoid of Guangzhou

objectively, 38 independent GPS leveling points with uniform distribution in the five districts of Guangzhou (urban, Zengcheng, Huadu, Conghua and Fanyunansha) were measured on-the-spot, and the outer check was carried out, the accuracy achieved ±8mm.

12. In the determination of the quasi-geoid for the city of Shenyang, 852 point gravity data and 40 high accurate GPS leveling data were used, and SRTM 3″ ×3″ digital terrain model and EGM96 were also adopted，the method of gravity reduction and fast algorithms were as the same as the previous ones. The gravimetric quasi-geoid was compared with discrete GPS quasi-geoid, and the accuracy was ±0.024m. Using the spherical cap harmonic analysis method for united solutions of the gravimetric quasi-geoid and GPS leveling, a 2′ 30″ ×2′ 30″ grid quasi-geoid with an accuracy of ±0.01m was obtained.

IV. Main Results

What follows are the main results of the refinements of the quasi-geoid for provinces and cities:

Guangdong province:

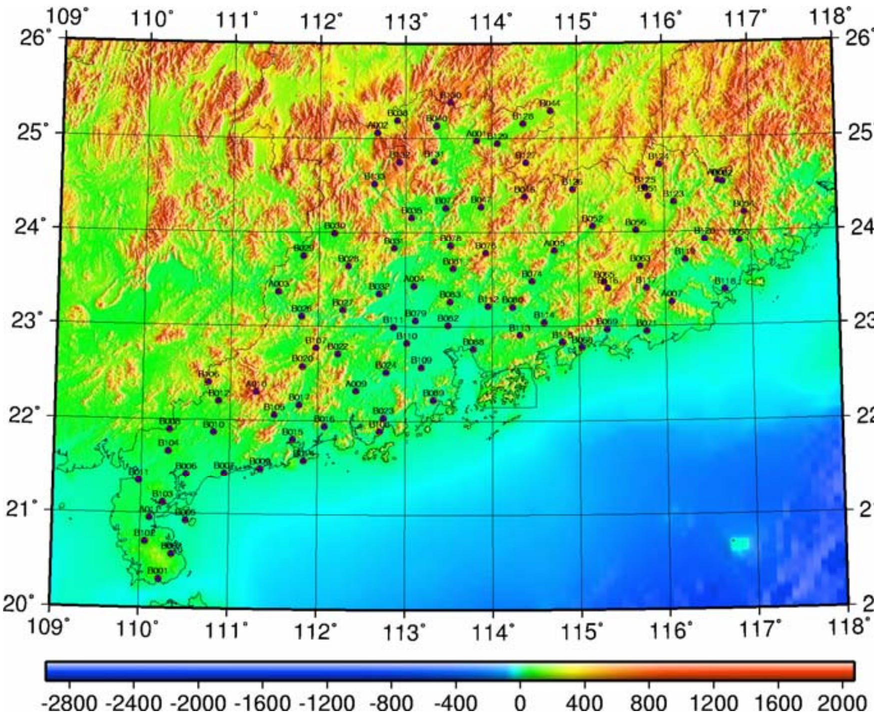

Figure 2 GPS leveling points in Guangdong province

Table 1 Comparisons between GPS leveling and Molodenky gravimetric quasi-geoid (unit: m)

Number of points	Max	Min	Mean	Rms	Std
88	0.280	-0.396	-0.161	±0.191	±0.102

Table 2 Comparisons between GPS leveling and heights of GPS quasi-geoid (unit: m)

Number of points	Max	Min	Mean	Rms	Std
88	0.109	-0.120	-0.001	±0.041	±0.041

Table 3 Comparisons between GPS leveling and heights of Helmert gravimetric quasi-geoid (unit: m)

Number of points	Max	Min	Mean	Rms	Std
88	0.190	-0.324	-0.157	±0.172	±0.070

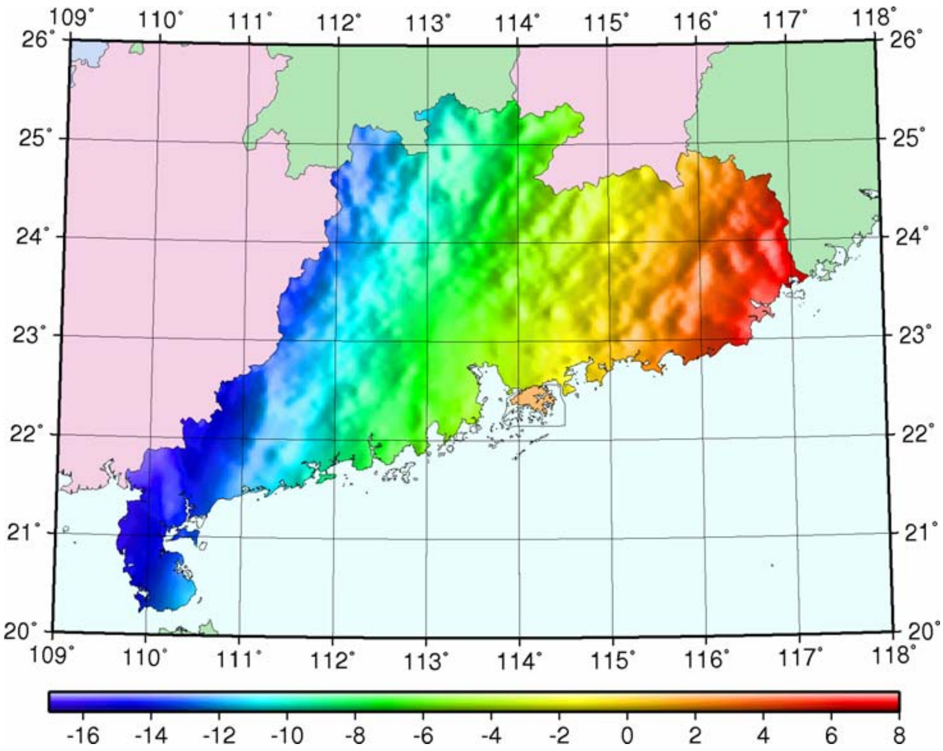

Figure 3 The 2′30″×2′30″ quasi-geoid of Guangdong province

Guangxi province:

Table 4 Comparisons between GPS leveling and heights of gravimetric quasi-geoid (unit: m)

Number of points	Max	Min	Mean	Rms	Std
94	0.000	-0.349	-0.154	±0.169	±0.070

Table 5 Statistics of remnants between GPS leveling and heights of quasi-geoid (unit: m)

Leveling results	Number of points	Max	Min	Mean	Rms	Std
1986	94	0.088	-0.084	-0.001	±0.033	±0.033

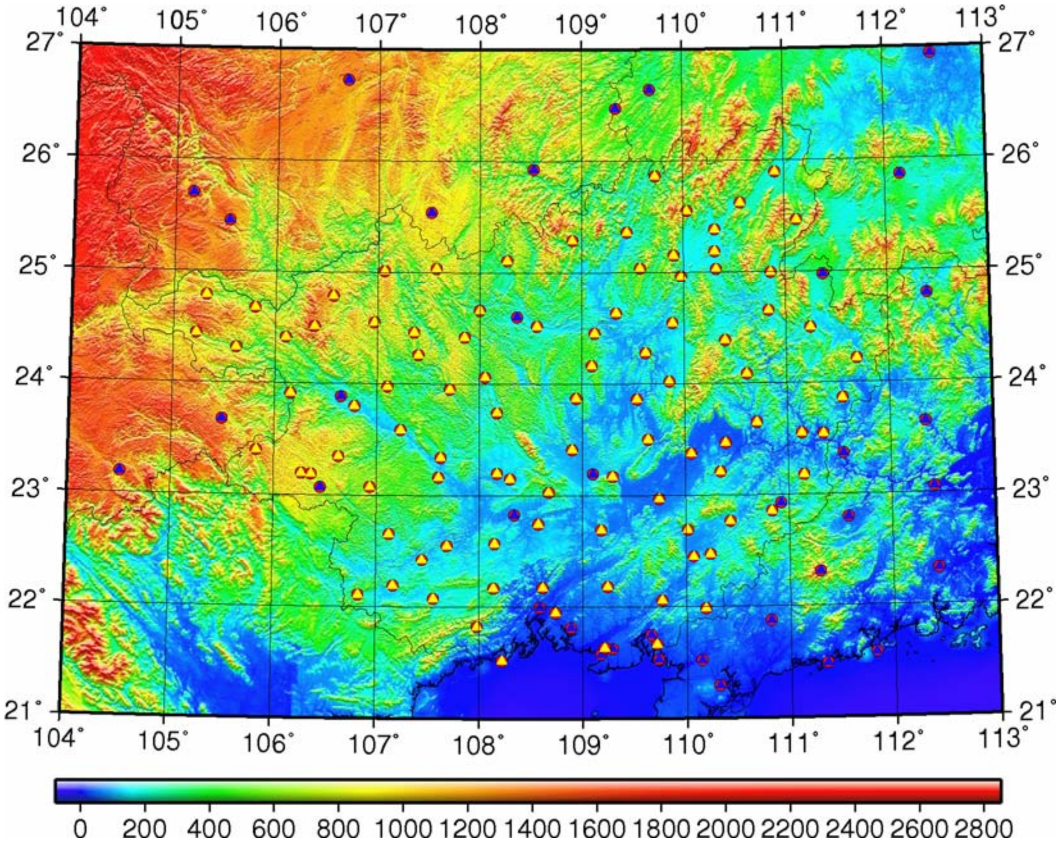

Figure 4 GPS leveling points in Guangxi province

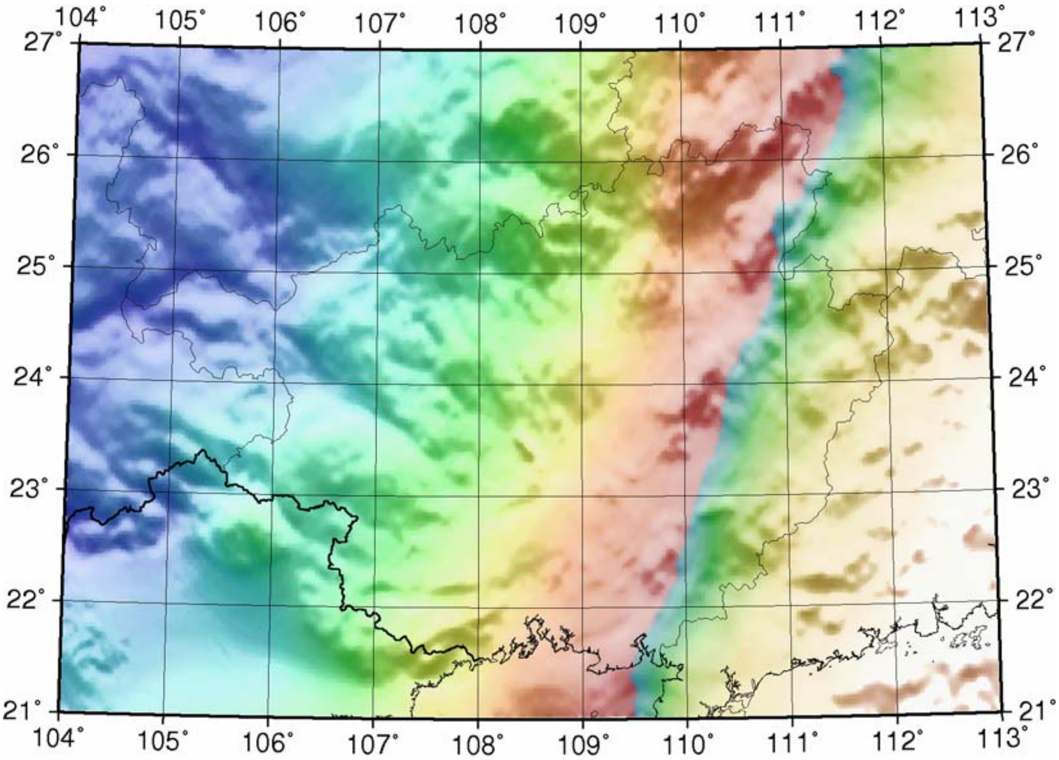

Figure 5 The 2′30″×2′30″ quasi-geoid of Guangxi province

Shanxi province：

Table 6 Comparisons between GPS leveling and heights of gravimetric quasi-geoid (unit: m)

Network	Number of points	Max	Min	Mean	Rms	Std
B order	119	0.114	-0.298	-0.102	±0.129	±0.078
		0.216	-0.196	0.000	±0.078	±0.078
C order	406	0.123	-0.305	-0.096	±0.125	±0.080
		0.219	-0.209	0.000	±0.080	±0.080

Table 7 Statistics of remnants between GPS leveling and heights of GPS quasi-geoid (unit: m)

Network	Number of points	Max	Min	Mean	Rms	Std
B级	119	0.102	-0.133	0.008	±0.043	±0.042
C级	406	0.112	-0.140	-0.004	±0.041	±0.040

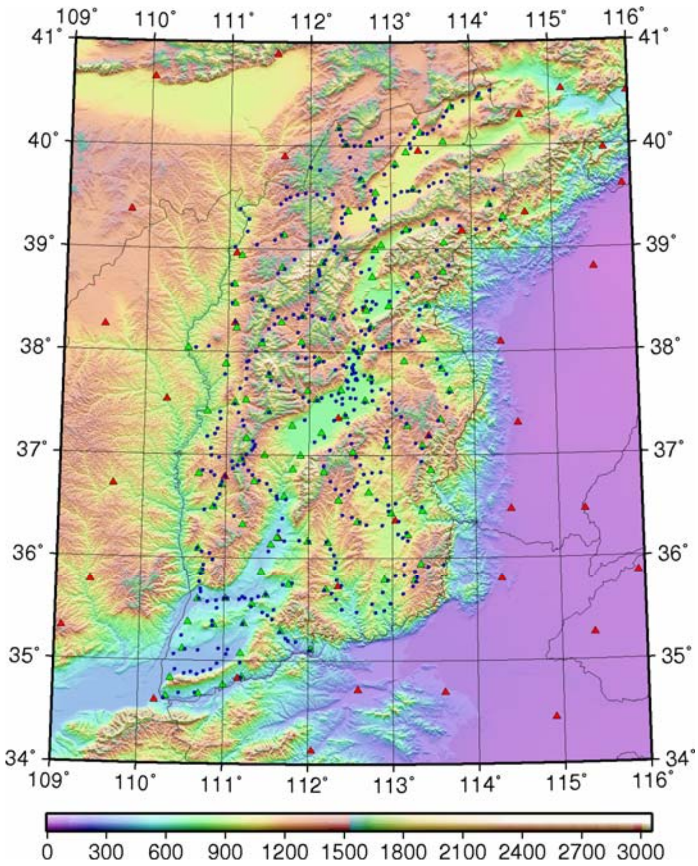

Figure 6 GPS leveling points in Shanxi province

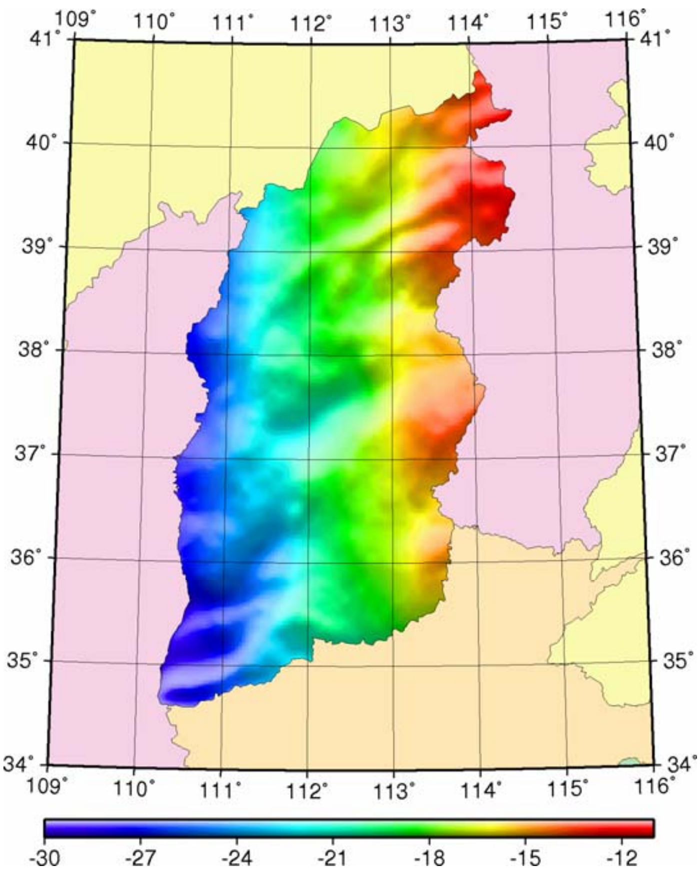

Figure 7 The 2′30″×2′30″ quasi-geoid of Shanxi province

Dongguan City:

Table8 Comparisons between GPS leveling and heights of gravimetric quasi-geoid (unit: m)

点数	最大值	最小值	平均值	均方根	标准差
64	-0.185	-0.247	-0.217	±0.214	±0.012
62	-0.189	-0.247	-0.214	±0.215	±0.012

Table 9 Statistics of remnants between GPS leveling and heights of GPS quasi-geoid (unit: m)

点数	最大值	最小值	平均值	均方根	标准差
62	0.014	-0.014	0.000	±0.006	±0.006

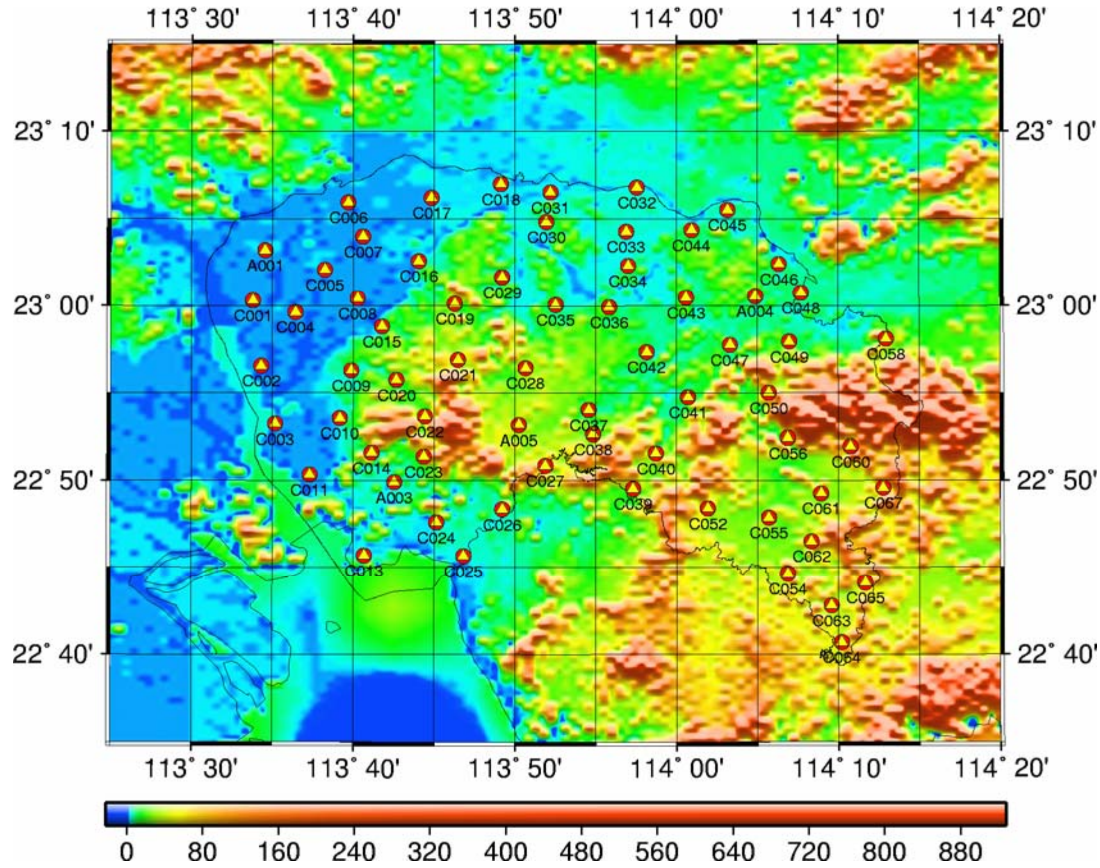

Figure8 GPS leveling points in city of Dongguan

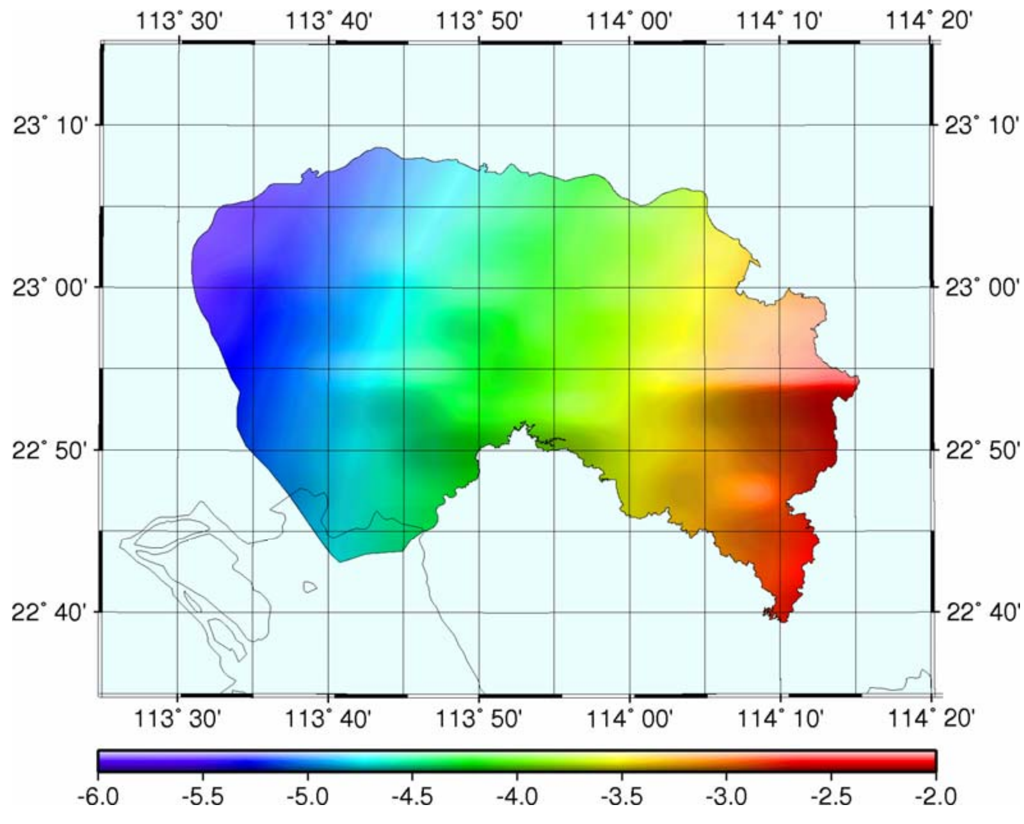

Figure 9 The 2′30″×2′30″ quasi-geoid of the city of Dongguan

V. CONCLUSIONS

In summary, a rigorous land-sea combined terrain correction algorithm, spherical cap harmonic analysis theory and the method with originality were applied in the research of the local geoid in China since 2004, and a number of key technique problems were solved, great-leap-forward development of the accuracy of the quasi-geoid for cities in China has been realized. Combined with global location techniques and 1 cm quasi-geoid, the demand of the second leveling could be satisfied.

To determine the geoid with centimeter level, the theories of geodetic boundary value problem should be studied further. The existing theories and methods for determining the Earth's geopotential field should be improved and unified, and the consistency of the definitions of the global geoid and global reference system should be investigated (e.g., permanent tide). At the same time, the terrain data, gravity data, GPS leveling, multi-satellite altimetry data should be studied, including the optimizing data federation of the global geopotential field model and the error model, in the aspect of data-processing. In the case of long wave band of the Earth's geopotential field, we should make full use of the combined solution of the satellite geopotential field model (combination of data derived from gravity satellites) and terrain gravity data, in order to get the information of the geoid in long wave band with high accuracy. In the case of medium wave band, the precise fast algorithm for gravity reduction should be formulated further in order to improve the accuracy of the numerical calculations for topographic-isostatic correction, and the interpolation and prediction method suitable for discrete geopotential field should be studied to guarantee that the accuracy of the mean grid gravity anomalies reach a new level. Because about 71% of the Earth's surface is covered by oceans, the new theories and techniques for recovering ocean gravity anomalies through multi-satellite altimetry data should be studied, and it is the key factor to obtain gravity anomalies at medium wave band with a high accuracy. In the case of the shortwave band, the kernel function for integrations should be improved, and the contribution of the terrain data with high resolution should be weighted. We should precisely calculate the all classes of terrain potential and effects of terrain gravitation in Helmert's second method of condensation, namely, the indirect effects of the remnant potential of the topography between potential of Newton terrain masses and the potential of the condensation layer, and the effects of the gravitations between the terrain masses and the condensation layer in Helmert gravity anomalies. At the same time, the corrections between quasi-geoid and geoid, the corrections of the normal gravity, the ellipsoidal corrections and the effect of the atmosphere, should be considered. In the combination of GPS leveling and gravimetric quasi-geoid with different data sources, the spherical cap harmonic analysis method which satisfies the Laplace equation should be used, in order to make the results of the geoid more rigorous.

In the efforts of the refinements of the local geoid in China these years, Chinese scholars have done a lot of work in exploring theories, methods and practical techniques in determining the local geoid. In general, the determined local (city) quasi-geoids have achieved the accuracy around centimeter-level with a resolution of about 5km. With the development of the theories and methods and especially the abundance of different kinds of data, the local geoid with 5km resolution and 5cm accuracy for the eastern part of China, local geoid with 10km resolution and 10cm accuracy for the western part of China could be hopefully realized in 5~10 years. On this occasion, the height measurement with centimeter level or decimeter level would be mainly completed based on the numerical model of the geoid and GPS altimetry, and the modernization of the height measurement could be realized primarily.

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THE PROGRESS OF THE EARTH'S GRAVITY FIELD IN CHINA

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Thanks to CHAMP and GRACE satellite systems, the accuracy of the medium-wave and long-wave components of the Earth's gravity field have been improved by 1~2 order in magnitudes and the accuracy of the corresponding geoid can achieve centimeter-level. These are great progresses in the gravity measurement and gravity field expressions in 21 century. Explorations on the methods for solving the high-accuracy global gravity models based on the observation data of the satellite systems (CHAMP, GRACE, and GOCE etc) have become the most attractive study projects in recent years. Chinese scholars have made efforts to work on this subject and published many research papers.

Due to the restrictions of physical geography and technical conditions, the measured gravity data in China are not distributed uniformly: dense in east and sparse in west in spatial resolution. Airborne gravimetry has become the top priority for improving this disadvantageous situation and refining the Chinese regional gravity field. Many experimental studies, which are preparing to actualize airborne gravimetry in China, have been carried out in recent years. In another aspect, the new progress in satellite gravity measurement will lay a solid foundation for realizing the global gravity field and geoid with an accuracy of centimeter level. However, challenges from quite a few theoretical problems should be faced, e.g., how to deal with the topographic masses above the geoid rigorously; how to determine the extension of the geoid from ocean to continent properly and accurately; how to evaluate the effect of lateral topographic density variations in the determination of the geoid with centimeter-level; how to solve the problems of the downward continuation of the gravity data; whether the spherical harmonic expansion series expressing the Earth's gravity field converges or not in the domain near the Earth's surface, etc. Chinese scholars have explored the problems mentioned above intensively and actively. Based on Bjerhammar's method, they presented a new method which has been tested by many experiments, and have achieved elementary results. There are also some progresses in other fields, e.g., the field of the frequency analysis of the Earth's gravity field, etc. The geophysical interpretations of the Earth's gravity field have been motivated by the new satellite gravity models with the accuracy of centimeter-level, especially, the time series of geopotential given by GRACE gravity models, which provide high time resolution (e.g. 10 days) for detecting the temporal variability of the Earth's gravity field. These models can be used to study the global changes of water storage closely related to the change of global climates, and can also be used to study the changes of the sea level, etc. The ocean geoid determined based on shipborne gravimetry and satellite altimetry with high accuracy provides a precise reference datum for the study of ocean currents and their changes. In these fields Chinese scholars have also achieved some meaning results. The relevant research work and progresses in China about the Earth's gravity field are generally summarized in this report.

I. THE STUDIES ON THE SATELLITE GRAVIMETRY

1. *The Development of Several Earth's Gravity Field Models Derived from CHAMP or GRACE Data*

(1) *The model XISM02*

XISM02 is a CHAMP gravity model developed by Xi'an Research Institute of Surveying and Mapping in 2004 (XU, YANG, 2005). This model is recovered based on 30 days' rapid science orbit and accelerometer data from CHAMP date center (Jan., 2002), using Energy Conservation Method, expanded to 50 degree and order. The mathematic model and differential arithmetic for calibrating the accelerometer data are presented, which can be used for estimating the scale, bias and bias drift parameter simultaneously and efficiently. Various comparisons between XISM02 model and other international models (e.g., EGM96, GRIM5C1, EIGEN1S and EIGEN2) are executed, and the results show that XISM02 is most closest to GRIM5C1. The assessment with the observations of arctic gravity anomalies is also made among these models. Table 1 and Fig.1 show the main results.

Table 1 Compsrison results among the measured gravity anomalies in the arctic pole area and the corresponding anomalies calculated by various models (unit: mgal)

Model	Mean	St.dev	.Max	Min
EGM96	-0. 035	23.833	218.864	-209. 511
GRIM5C1	-1. 581	25.447	219. 960	-211. 164
EIGEN1S	0. 306	23. 936	222. 776	-208. 119
EIGEN2	0. 145	23. 776	219. 473	-209. 295
XISM02	0. 093	23. 759	223. 826	-205. 148

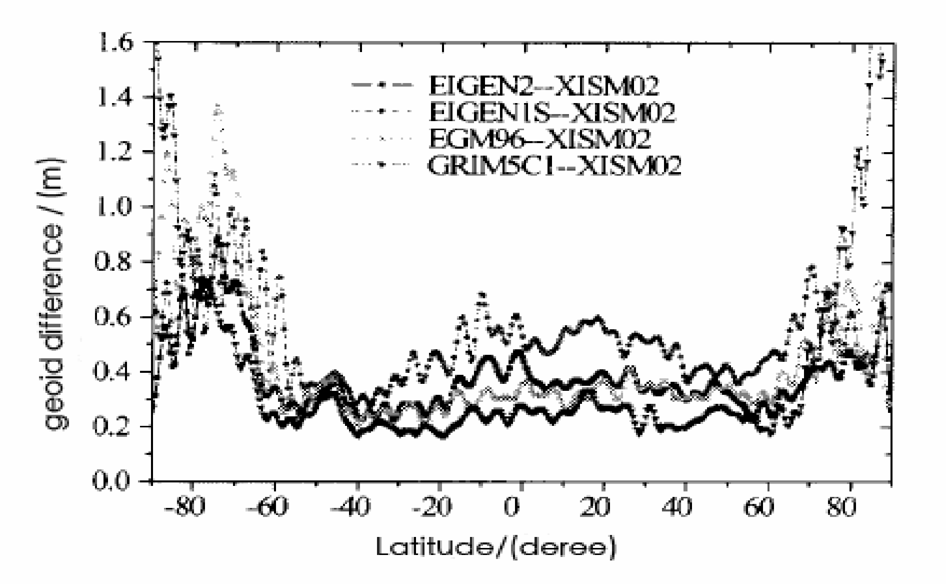

Fig.1 Geoid differences based on various gravity field models.

(2) *The model WHU-GM-05 series*

WHU-GM-05 is a GRACE gravity model series including WHU-GM-05S and WHU-GM-05D developed by the School of Geodesy and Geomatics, Wuhan University in 2005 (Chao et al, 2005). The data used in establishing the model series can be clasified in four types: precise orbits, accelerometer, star camera and KBR. The precise orbit data consist of JPL dynamic orbit (from 1st Feb. 2003 to 1st Aug. 2004) and TUM reduced dynamic orbit and kinematic ones (from 1st June 2003 to 1st Oct. 2003); the others are GRACE data products of Level-1B released by JPL, and the sampling duration of these data classes is from 1st Feb. 2003 to 1st Aug. 2004. Based on the energy integral equation of satellite, some applied computation formulas for Earth gravity field recovery from satellite to satellite tracking data are presented, in which a strict expression of the difference of kinetic energy between two satellites on the same orbit in terms of KBR range–rate observation value is given instead of an approximate expression. In addition, the application of preconditioned matrix is proposed, the use of which can result in the convergence of the iterative solution for the normal equation effectively. Using GRACE data from the single satellite or both satellites and energy integral method the model WHU-GM-05 is established , which is named as WHU-GM-05S for single GRACE satellite and WHU-GM-05D for double ones respectively. The tests of WHU-GM-05 series are performed by multi-comparisons, in which the comparisons of the model geoidal heights with GPS leveling in the area of U.S. and China (some regions) are included. The GPS leveling (grade- A and B) networks (2723 points) in U.S. and the GPS leveling geoid heights from three local GPS leveling networks (307 points) in China are used for the comparisons. The test results show that the average accuracy of WHU-GM-05 series is near to those of the models used in the comparisons. Tables 2 and 3 show the results of the comparisons with GPS leveling.

Table 2 Tests by GPS leveling networks in China (unit: m)

model	degree	Sampling duration (day)	Mean	Max..	Min.	RMS
EGM96	360	-	-0.043	2.929	-3.163	0.660
EGM96	120	-	-0.058	3.086	-4.887	0.887
WDM94	360	-	-0.533	2.809	-5.277	0.639
GGM02S	160	363	-0.617	4.439	-5.732	1.943
EIGEN-GRACE02S	150	110	-0.260	3.157	-6.367	0.827
EIGEN-CHAMP03S	140	975	-0.838	4.657	-11.147	2.085
WHU-GM-05D- Ⅰ	120	60	0.567	3.339	-4.417	1.243
WHU-GM-05D-Ⅲ	90	30	-1.358	5.531	-8.054	2.406

Table 3 Tests by GPS leveling networks in U.S. (unit: m)

model	degree	Sampling duration (day)	Mean	Max..	Min.	RMS
EGM96	360	-	-1.062	1.668	-4.879	0.525
EGM96	120	-	-1.074	2.668	-5.739	0.798
WDM94	360	-	-0.775	2.068	-4.639	0.581
GGM02S	160	363	-1.077	2.358	-4.294	1.045
EIGEN-GRACE02S	150	110	-1.077	2.648	-5.169	0.760
EIGEN-CHAMP03S	140	975	-1.064	3.087	-6.049	0.896

WHU-GM-05D-Ⅰ	120	60	-1.092	2.588	-6.169	1.042
WHU-GM-05D-Ⅱ	120	30	-1.070	2.718	-6.329	1.061
WHU-GM-05D-Ⅲ	90	30	-1.035	4.058	-7.117	1.893

(3) *The IGGGRACE01S model*

IGGGRACE01S is a GRACE gravity model developed by Institute of Geodesy and Geophysics, Chinese Academy of Sciences and Shanghai Astronomical Observatory, Chinese Academy of Sciences (ZHOU et al, 2006). The model is derived from 141 days of GRACE tracking data, including KBR, accelerometer, and satellite orbit data. The model resolves the geoid with an accuracy of about 0.012m at a resolution of 500 km half-wavelength, it improves the accuracy of the gravity field model in the long to medium wavelength part (＜80 degree＝, which is higher than the accuracies of pre-CHAMP model. Comparing the coefficients of IGGGRACE01S, EIGEN-GRACE02S, EIGEN-CHAMP03S, and EGM96 models, the results show that the coefficients of IGGGRACE01S are close to those of EIGEN-GRACE02S, and much different from those of the other two models. Comparing the geoid undulations and gravity anomalies derived from the above mentioned models, the results indicate that the IGGGRACE01S solution is close to EIGEN-GRACE02S solution, and there exist large differences between IGGGRACE01S and EGM96 in Antarctica region. Comparing the gravity anomalies derived from IGGGRACE01S (72 degree) with NIMA gravity anomalies data (2.5°×2.5°), the standard deviation is 8.4mGal in China land region. Table 4 shows the results of the comparisons.

Table 4 Difference of gravity anomaly and geoid height.

	Gravity Anomaly(mGal)		Geoid(m)	
	IGGGRACE01S -EGM96	IGGGRACE01S -EIGEN-GRACE02S	IGGGRACE01S -EGM96	IGGGRACE01S -EIGEN-GRACE02S
Maxmum	28.3	-0.67	3.35	0.091
Minimum	-31.1	0.71	-4.68	-0.113
Standard Deviation	3.17	0.16	0.44	0.035

Average	-0.055	-0.0035	-0.021	-0.015

(4) *The CDS01S model*

CDS01S is a CHAMP gravity model developed by Institute of Geodesy and Geophysics, Chinese Academy of Sciences. (ZHOU et al, 2006). The model up to 36 degree is derived from the post processed science orbits and accelerometer data released by GFZ's CHAMP satellite center based on the theory of satellite dynamics. The model resolves the geoid with an accuracy of better than 4 cm at a resolution of 700 km half-wavelength. By using the differences of geopotential coefficients between the model CDS01S and the model EIGEN3P, EIGEN1S and EGM96 for comparing, the results indicate that the CDS01S coefficients are most close to EIGEN3P. Comparing the accuracy of the geopotential coefficients in these models, the result indicates that the accuracy of the coefficients in CDS01S is higher than that of the coefficients in EGM96. The geoid undulations of CDS01S and GGM01C up to 30 degree are calculated, and the results indicate that the standard deviation is 4.7 cm between them.

2. *The Precise Orbit Determination of Low Earth Orbit Satellites*

(1) *Precise orbit determination of GPS and CHAMP satellites with PANDA software*

Using PANDA (Position And Navigation Data Analysis) software developed by Wuhan University, the precise orbit determination of GPS and CHAMP satellites based on the data of 45 IGS stations in different conditions is obtained. Concerning the orbit determination, the comparisons between PANDA and the corresponding one provided by GFZ show that both of the accuracies are on the same level (ZHAO et al, 2005).

(2) *The compensations of gravity model errors in precise orbit determination of Low Earth Orbit Satellites*

Based on the orbit integration and orbit fitting method, the characters of the influence of the gravity models with different precision on the movement of Low Earth Orbit Satellites are studied. The way and the effect of the compensation of gravity model errors in the precise orbit determination of CHAMP and GRACE satellites by liner and periodical empirical acceleration model and so-called "psedo-stochastic pulses" model are also analyzed (GUO et al, 2006).

3. *The Error and Accuracy Analyses for the Solution of Satellite Gravity Model*

(1) *The effects of orbit and accelerometer errors of CHAMP on recovery of gravity field*

On the basis of energy conservation method, the effects of orbit and accelerometer errors on disturbing potential and the recovered gravitational field model are studied. The results show that the energy conservation method is more sensitive to velocity errors than to position errors and accelerometer errors. To obtain $1m^2s^{-2}$ in accuracy of the disturbing potential, the accuracy requirements for position, velocity and accelerometer are 10cm, 0.13mms^{-1} and 10^{-8}ms^{-2} respectively. Using one month CHAMP data to recover the gravity field model up to 50 degree and obtain 5°×5° mean gravity anomalies with accuracy better than 2×10^{-8}ms^{-2}, the mentioned accuracy requirements are 5cm, 0.1mms^{-1} and 10^{-8}ms^{-2} respectively (Xu and Yang, 2005).

(2) *Accuracy analysis of SST gravity field model in China*

Taking the region of China as test, using the satellite gravity technique, satellite-to-satellite tracking (SST), how to improve the accuracy of the regional gravity field model is studied. With WDM94 as reference, the gravity anomaly residuals of three models, the latest two GRACE global gravity field models (EIGEN-GRACE02S, GGM02S) and EGM96, are computed and compared. The causes for the differences among the residuals of the three models are discussed. The comparisons among the residuals show that, in the selected region, EIGEN-GRACE02S or GGM02S is better than EGM96 in lower degree part (less than 110 degree). From the analysis of the model gravity anomaly residuals, it is found that some systematic errors with periodical properties exist in the higher degree parts of EIGEN-GRACE and GGM models. The results can be taken as references in the evaluation of the SST gravity data (Luo et al, 2006).

(3) *Error analysis for recovery of the Earth's gravity field by HL-SST technique*

The effects of the orbital error and accelerometer's error on the potential coefficient recovery are analyzed by integral technique. The results indicate that the potential coefficient error induced by orbital error is great. Thus at most 40 degree coefficients can be recovered by use of orbital data with accuracy of 5 cm. However, the effect of the accelerometer random error is smaller than the effect of orbital error, even the potential coefficient error induced by 10^{-7}ms^{-2} accelerometer random error being smaller than the one caused by 3 cm orbital error. The effect of the accelerometer systematic error is serious, but the effect can be reduced if a method for the error estimate is used (XIAO et al, 2006)

4. *The Study on the Earth's Gravity Model Based on Satellite Gravity Gradiometry*

(1) *Least squares collocation in calculating potential coefficients with satellite gravity gradiometry data*

The covariance function about satellite gravity gradiometry data and gravitational potential coefficients is educed by space disturbance potential covariance. Least squares collocation is used to educe the function that can be directly used to compute gravitational potential coefficients by satellite gravity gradiometry data. The practicability of the function is analyzed (ZHANG, CHEN, 2005).

(2) *Regularization error estimation of spherical harmonic coefficients from SGG data*

Gravity gradient is the second order derivation of gravitational potential, which can be observed by satellite gradiometer. The spherical harmonic coefficients of the gravity field can be obtained from gravity gradients through regularization scheme. Based on the analysis of the regularization scheme, a method for estimating the error of regularization solution is presented The result of the study shows that the regularized approximate solutions of the geopotential coefficients have an asymptotic optimum if the regularized parameters are determined based on Tikhonov regularization method and Morozov bias principle, and the theoretical accuracy of the coefficients depend only on the observational accuracy of SGG. It also shows that Morozov bias is an optimal regularization method if a certain condition is satisfied (CHANG et al, 2006).

II. THE STUDY ON AIRBORNE GRAVIMETRY

1. *The Development of the Chinese Airborne Gravimetry System*

The Chinese airborne gravimetry system, named CHAGS, was realized in 2002. CHAGS is a damp platform system which comprises hardware system, including the following subsystems: gravity sensor, positioning sensor, altitude sensor, attitude sensor and data collecting system. The software system consists of five modules: the module for recording and saving of data collection, the module for filter and processing of observation data, the module for adjustment of air observing line network, and the module for downward continuation. The test of CHAGS was carried out in Datong region of Shanxi province in March-April, 2003. In the area of 14580km^2, 81 measurement lines are included, and 190 blocks of $5'\times5'$ grid mean gravity anomaly in space were formed. The standard deviation of discrepancy at crossover point is 6.5mGal before adjustment, and 3.3mGal after adjustment respectively. The standard deviation of the differences between the anomalies derived from terrestrial observed anomalies by upward continuation and air-anomalies is 3.6mGal, whereas the standard deviation of the differences between the terrestrial observed anomalies and the anomalies derived from air-anomalies by downward continuation is 4.2mGal (SUN et al, 2004).

2. *Wavelets in Airborne Gravimetry*

Three sets of continuous wavelets are constructed for the filtering processing of airborne gravimetry data. The continuous wavelet filters are used to perform the low-passing, first-order derivative and second-order derivative filtering at expected space (or time) scales for the airborne gravimetry data. Here we focus on how to construct the continuous wavelet filters and show their working principle. Particularly the technical parameters (window width parameter and scale parameter) of the filters are tested. The advantages of the continuous wavelet filters over the conventional digital filters are also discussed. We make some filtering tests, which show the feasibility and effectiveness of applying the continuous wavelet filters to airborne gravimetry (LIU, Xu, 2004)

3. *A Comparison of Different downward Continuation Methods for Airborne Gravity Data*

Four downward continuation methods for airborne gravity data are presented: the direct representation method, Tikhonov regularization, point-mass model and the spherical interior Dirichlet's harmonic solution method. The downward continuation computation for real airborne gravity data in the Datong region of China is performed by means of these methods. The accuracy, reliability and stability of different methods are evaluated based on the comparisons and analysis of downward continued results with terrestrial real gravity data. The numerical computations indicate that results obtained by using the first and second methods are more accurate and stable than using the third and fourth methods (WANG et al, 2004).

4. *Comparison of Determination of the Vertical Acceleration using GPS for the Airborne Gravimetry*

The vertical acceleration is one of the most important corrections in the airborne gravimetry. The accuracy of the vertical acceleration using GPS is first estimated based on analytical models, then three different approaches with GPS are analyzed and compared using the real data from one airborne gravimetry test, and some initial conclusions are drawn (SUN et al, 2004).

5. *Research on Space Covariance Function's Characteristic During downward Continuation of Airborne Gravity Measurement Data*

By the analysis of airborne gravity measurement data, the authors construct a space covariance function model with spatial characteristics. Using this model, the airborne gravity measurement test data are downward continued based on least squares collocation and are compared with known ground gravity data. According to the results of the comparisons, the effect of this model on the downward continuation of the airborne gravity measurement data is analyzed. Results indicate that this model can satisfy the characteristics of covariance function and can be used in local areas with satisfied precision (ZHANG et al, 2006).

III. THE EXPLORATION OF SOME THEORIES AND METHODS

1. *The Generalized Bjerhammar Method*

(1) *Method*

Influenced by Bjerhammar (Bjerhammar, 1964) as well as Heiskanen and Moritz (1967), the generalized Bjerhammar method, which is also referred to as the fictitious compress recovery method, was proposed by Shen (2004), aiming to pursue a precise, simple, and effective method for determining the Earth's external gravitational potential field. Further, taking into account the equivalent properties of the regular harmonic Newtonian potential field and a regular harmonic field, the generalized Bjerhammar's method is generalized to any regular harmonic field determination (Shen et al., 2005), provided that the boundary value is given, where the boundary could be the surface ($\partial\Omega$) of the Earth or the surface (∂S) corresponding to a satellite altitude. The main idea of this method is stated as follows.

Choose an arbitrary inner sphere $\mathrm{K_i}$ (or Bjerhammar's sphere, Cf. Bjerhammar, 1964), a sphere entirely located in the interior of Earth. On the boundary $\partial\mathrm{K_i}$ (the surface of the inner sphere $\mathrm{K_i}$), using the gravitational potential boundary value on $\partial\Omega$ (or ∂S) generated by Earth, i.e., along the radial direction taking the identity map between $\partial\mathrm{K_i}$ and $\partial\Omega$ (or ∂S), and based on Poisson integral one gets a regular harmonic solution $u^{*(1)}$ in the domain outside the inner sphere $\mathrm{K_i}$. Then, the solution $u^{*(1)}$ is taken as the first approximation of the Earth's real field u in the domain outside Earth, where one gets a residual field $\Theta^{(1)} = u - u^{*(1)}$, which has the value $\Theta^{(1)}|_{\partial\Omega}$ on the Earth's surface $\partial\Omega$. Again, taking the value $\Theta^{(1)}|_{\partial\Omega}$ as the boundary value on $\partial\mathrm{K_i}$ and using Poisson integral one gets a regular harmonic solution $u^{*(2)}$ in the domain outside the inner sphere and the second approximation $u^{*(1)} + u^{*(2)}$ of the Earth's real field u in the domain outside Earth. This procedure can be repeated until a series solution (satisfactory result) $u^* = \sum_{n=1}^{\infty} u^{*(n)}$ is achieved, which coincides with the Earth's real external potential field in the domain outside Earth (Shen, 2004).

(2) *Applications of the generalized Bjerhammar's method*

Various simulation experiments (Li, 2005; Shen et al., 2006a, 2006b, 2006c) supports the generalized Bjerhammar's method (i.e. the fictitious compress recovery method), which has broad applications in physical geodesy and geophysics. It can be used for determining the normal gravity field of a reference ellipsoid, for determining the fictitious gravity anomaly needed in Bjerhammar's method (Shen et al., 2005), for determining the shift of the geopotential constant on the geoid, for solving the convergence problem (Shen, 2005a) and downward continuation problem (Shen, 2005b), etc. It can be also say that the fictitious compress recovery method is the realization of Runge-Krarup theorem (e.g., Bjerhammar, 1964).

(3) *WGS84 normal field determination*

Given four basic parameters of a reference ellipsoid, the normal potential field generated by the ellipsoid could be determined by using conventional method. In another aspect, as an application example of the generalized Bjerhammar's method, based on four basic parameters of WGS84 reference ellipsoid, a fictitious harmonic field is determined, which is defined in the domain outside an inner sphere that lies inside both the geoid and the ellipsoid. Comparisons between the real field determined by conventional way and the fictitious field determined by the generalized Bjerhammar's method are provided in the domain outside the ellipsoid, showing that the fictitious normal field coincides with the real normal field in the domain outside the ellipsoid, under the millimeter-level accuracy requirement. That means, using the generalized Bjerhammar's method, one can also determine the normal field generated by a reference ellipsoid.

2. *Downward Continuation of Gravity Signals Based on the Multiscale Edge Constraint*

A new method to stabilize downward continuation of gravity signals is studied. The principle of multiscale edge detection by wavelets is presented, and the multiscale edges of the earth's gravity field are analyzed by using EGM96 model as an example. Based on the constraint of the multiscale edge, a method for the downward continuation is proposed and a simulation example is given. The results indicate that it is feasible to enhance the stability of downward continuation using the multiscale edge as a constraint. This method has a better effect in the case when the signal-to-noise ratio of observations is low (NING et al, 2005).

3.*Applications of Gravity Vector and Tensor in the Gravity Field*

It is established the mathematical model of solving the disturbing field elements of gravity field based on the gravity vector and tensor, of which it is derived out the Dirichlet and Neumann boundary value problems based on the gravity vector and tensor, and under the condition that the zero and first order terms are equal to zero, the two models coincide with each other. Under the condition that the gravity vector is given, either one of the two models could be used. Under the condition that the gravity tensor is given, it is constructed a new model of the Direchlet problem, where the constructed function $\rho^2\partial^2 T/\partial^2\rho^2$ is harmonic in the interested domain. either one of the two models could be used. of . With this new model, the information that reflects the fine structure of the Earth's gravity field could be effectively applied (LI et al, 2005).

4.*Deduction and Estimation of Innermost Zone Effects in Altimetry Gravity Algorithm*

Based on the analysis of the FFT algorithm for the inverse Vening Meinesz formula, the authors present a new method to compute the components of the vertical and a formula to estimate the innermost zone effects to improve the accuracy of altimetry gravity recovery. The results show that the innermost zone effects are related to the gradient of the vertical gravity in the area of the innermost zone, while the vertical gravity itself has no influence on the innermost zone effects. As an application of the derived formula, it is estimated the innermost zone effects of the gravity recovery from ERS-1 altimetry data for an area of $6^\circ \times 6^\circ$ in North Atlantic, and results of the estimation are analyzed (CHANG et al, 2005).

5.*Problem on Fitting the Marine Gravity Quasi-Geoid to Local Altimetric Quasi-Geoid*

This subject is to study the problem on extending the method for fitting terrestrial gravity quasi-geoid to GPS leveling quasi-geoid in the case of sea area near coast. In theory, it is proved that marine geoid can not coincide with the corresponding quasi-geoid if sea surface topography (SST) exists, and a formula is derived for calculating the difference between marine geoid undulation and corresponding height anomaly. The formulas are presented to calculate the normal height of mean sea surface (MSS) on a local vertical datum and altimetric quasi-geoid. Considering the fact that altimetric MSS could have the same accuracy level as that of GPS geodetic height, an extended method for fitting marine gravity quasi-geoid to altimetric quasi-geoid on a local vertical datum is proposed by using altimetric MSS data (WANG et al, 2005).

6. *Frequency Analysis of Topography-Isostasy Compensative Gravity and Geoid Anomaly*

Expending geography, earth interior mass, gravity and geoid into sphere harmonic series, the authors establish topography-isostasy compensation gravity and geoid sphere harmonic series expression according to isostatic compensation theory of lithospheric flexibility. Then it is established the relationship among topography-isostasy compensative gravity, geoid and order and degree of sphere harmonic series and topography wavelength. Deducted topography-isostasy compensation gravity, geoid anomalies from observed free air gravity and geoid anomalies, isostatic gravity anomaly and isostatic geoid anomaly could be obtained. Isostatic geoid anomaly eliminates the gravity effect of shallow mass. Isostatic geoid anomaly reflects inhomogenity of the deep mass distribution of the earth. Isostatic gravity anomaly shows middle-short wavelength character, and reflects mass distribution imbalance and mass adjust dynamical character in crust and upper-mantle (FANG et al, 2006).

IV. THE INVESTIGATION ON THE APPLICATION OF SATELLITE GRAVITY MODEL AND TERRESTRIAL GRAVITY DATA IN GEOSCIENCES

1. *Study on Seasonal Variations of Global Ocean Mass*

Mean sea level variations are caused by the changes of sea water density and global ocean mass. It is an important context in studying global climate change. Using the data of gravity field parameter variations observed by GRACE and the mean sea level variations observed by satellite altimetry removed steric sea level changes calculated from the numerical ocean models, global ocean mass change is investigated. The results show that sea water mass changes estimated by the two methods have obvious seasonal characteristics, and the annual amplitudes and phases coincides with each other very well (Yin et al, 2005).

2. *The Steady Sea Surface Topography and Its Spectrum Characteristics Determined from GRACE Data*

Using GRACE gravity field model GGM01C it is calculated the new steady sea topography

with high accuracy and resolution. Based on the signal frequency spectral analysis method, it is analyzed the determined residual sea heights corresponding to different order of model GGM01C, and the results are compared with those determined by EGM96 gravity field model. The results show following conclusions: 1) the spectral structure of the sea topography is very stable, which consists mainly of long wavelength; 2) the middle wavelength occupies definite percentage; 3) longitude and latitude directions have different frequency spectral characters; 4) there exists obvious difference between two gravity models, which could explain why Tapley provided different sea circulation situations based on the above mentioned two models (Zhang, Lu, 2005).

3. *Monitoring the Seasonal Variations of the Waters Storage in Yangzi River Basin Using GRACE Gravimetry*

Based on the GRACE temporal gravity field covered 15 months starting from April, 2002, to

December, 2003, it is found that the global water storage has obvious seasonal variations. The water storage in Yangtze River is mainly analyzed. Results show that the annual average variation magnitude of the Yangtze River water could achieve 3.4 cm, and the maximum value appears in the Spring and Autumn. The inverted global water storage variations based on the GRACE temporal gravity field coincides with two currently best global hydrology models quite well, and the difference is less than 1 cm. Investigations also show that the modern spatial gravimetry technique has great application potential in detecting water storage variation in large river (e.g., Yangtz River), global water circulation, and atmospheric variations (Hu et al, 2006).

4. *Inversion of Gravity and Topography Data for the Crust Thickness of China and Its Adjacency*

The data of Bouguer gravity and topography are inverted to obtain the crust thickness of China. In order to reduce the effect of regional non-isostasy it is corrected the reference Moho depth in the inversion with regional topography relief, and multiple iterations are performed to make the results more reliable. The obtained crust thickness of China and its adjacency is plotted on a map in cells of $1^\circ \times 1^\circ$. Then it is analyzed the correlation between the Bouguer gravity anomaly and fluctuation of the Moho depth. A good linear correlation is found, with a correlation coefficient of -0.993. Different correlation coefficients, 0.96 and 0.91, are found for the data in land and ocean region, respectively. The correlation results also show that the boundary between land and ocean is generally along the bathymetric line of -800m. In order to examine the influence of the Earth’s curvature on the calculated result, two inversion models are explored: the inversion for the whole region and the inversion for 4 sub-regions. The difference in the crust thickness deduced from the two models is less than 5km. Possible explanation for the difference is investigated. After comparing results with those provided by other studies, it is concluded that with the method (Huang et al, 2006) the Bouguer gravity and the topography data can be independently inverted to obtain the crust thickness of China and its adjacency (Huang et al, 2006).

V. CONCLUSIONS

In recent four years, the research projects of the gravity field in China are mainly concentrated on satellite gravimetry, airborne gravimetry, local geoid determination with high resolution and accuracy, and fundamental theories and methods. The general goal is to further improve the resolution and accuracy of the China geoid, step by step realize the centimeter level geoid, and generalize the approach in determining the orthometric height based on GPS altimetry.

To improve the accuracy of the gravity field in middle and long wave length, Chinese research scholars make best efforts with very extensive studies in SST gravimetry technique and the will-being launched GOCE satellite system. Several gravity models have been established: two CHAMP models, i.e., XISM02 (50 degree/order) and CDSOIS (36 degree/order), two GRACE models, i.e., WHU－GM－05 series (90 degree/order，120 degree/order) and IGGGRACE01S (80 degree/order). Compared with newly published models, as well as GPS leveling network and ground gravity data, the models established by Chinese scholars achieved almost the same accuracy level with the recently published international models. It is also shown that, compared with EGM96, in the range of middle and long wave length, the accuracy of the satllite gravity model has raised a magnitude in one order, achieving centimeter level. The precise determination of a low orbit satellite is the foundation of satellite gravimetry. The determined CHAMP satelite orbit by PANDA software (it was developed by Wuhan University) has the same accuracy level with that provided by GFZ.

To improve the resolution and accuracy of gravimetry in middle and short wave length in China, the China government has begun to develop airborne gravimetry since the end of last century. In 2002, the first airborne gravimetric system CHAGS in China was successfully developed. In recent four years, the methods and techniques related to the airborne gravimetry have been extensively investigated, including wavelet analysis, downward continuation, vertical acceleration determination, spacial covariance function determination, etc. The achievements have played a important role in airborne gravimetry in China at present.

To meet the needs of massive engineering project requirements, in developing regions and cities of China, recently, the local geoids with high resolution (<5km) and centimeter-level accuracy in more than 10 of provinces and cities have been determined. The details are given in another report.

The realization of detemining the global centimeter level geoid needs developing and improving the conventional theories and methods about the geodetic boundary value problems. Chinese scholars put forward a generalized Bjerhammar approach, referred to as the fictitous compress recovery approach. The basic idea is constructing an iterative series solution by using identity downward operator and the rigorous Poisson upward integration. With this approach, the unstable problem of the downward continuation existed in the original Bjerhammar method is solved. This approach has been generalized to be suitable for solving the first and second kind of the boundary value problems. Various experimental tests show that this approach is valid and reliable in determining the gravity field, and it has extensive application potentials, e.g., dealing with the terrian masses above the geoid. In addition, it was put forward a new approach for the downward continuation of gravity signals based on multiscale edge constraints; the vector and tensor boundary value problems are intensively studied and their solution models are also presented; it was put forward the rigorous approach for fitting the ocean gravity quasi-geoid and the altimetry quasi-geoid, as well as the approach for estimating the inherent irregular value in altimetric gravity field calculations, etc. The research achievements of the above theories and methods might improve the results of determining the global centimeter level geoid.

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NATIONAL REPORT ON ABSOLUTE AND SUPERCONDUCTING GRAVIMETRY

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The Earth's gravity field contains abundant information on mass's distribution and movement among the Earth system, which directly reflects the basic properties of the Earth's spheres layers, namely the characteristics of distribution and its variation of density. It is know that the mass density is one of the most fundamental, direct and important quantities to studying varieties of environment changes and geodynamic features. In recent years, on the basis of international cooperation project such as the Global Geodynamic Project (GGP), the gravity cooperation in east Asia between China and Japan and the national key science project named monitoring network on crustal movement in China, the Institute of Geodesy and Geophysics, Chinese Academy of Sciences (IGG, CAS) has carried out a plenty of field and scientific investigations by using advanced FG5 absolute and GWR Superconducting Gravimetric (SG) techniques and achieved much excellent progress, which are summarized as below:

I. ABSOLUTE GRAVITY REFERENCE NETWORK IN CHINA MAINLAND

In the recent years, the establishment of the absolute gravity network and absolute gravity reference have been developed with FG5-112 absolute gravimeter. By the end of the year of 2006, measurements of absolute gravity at about 100 stations in China mainland are completed with the precision of 2~5μGal (1μGal＝10^{-8} ms^{-2}) in which repeat operations had been carried out at majorities of the stations (Zhang et al, 2005a; Zhang et al, 2005b). The results provided the national gravity fundamental network 2000 with gravity reference with precision of 5μGal (Qiu et al, 2004). As Wang et al (2004) mentioned, the establishment of the national network of the absolute gravity reference supplied important information for the national basic surveying and mapping, earthquake monitoring and studying on regional tectonics and geodynamics.

Combining with the repeat mobile observations of gravity, the image of gravity variation nowadays has been constructed firstly, which contributed to the important reference for middle and long term predictions of earthquakes events (Hsu et al, 2003). The monitoring on crustal movement and geodynamic study corresponding to the regional gravity change was carried out under the cooperation with Kyoto university in Japan. In this cooperation, the stations involved in our country were Wuhan, Shanghai, Kunming, Beijing, Nanning, Urumchi, HongKong, Lhasa, Xi'an, Xining and so on. Sun et al (2006b) investigated the comparison among the FG5 instruments of Kyoto

University, Geographical Survey Institute in Japan and IGG, CAS in China. Wang et al (2004) and Liu et al (2005) carried out the tests on gravity changes at three gorges region before and after the storage of the large amount of water mass, and established a regional absolute gravity network with μGal precision at tide gauge stations in southeast China coastal area, in Dianxi, Yunnan province and in Tibetan plateau in order to develop the research on ground sedimentation, crustal movement and plateau uplift. After several year of hard work, the absolute gravity reference and absolute gravity network had been improved one order of magnitude in precision than the reference network during the period of 8^{th} five-year project. Meanwhile, density of the gravity stations and the coverage rate had been increased significantly, which provided with more accurate parameters of ground based gravity field for the study of the gravity model constructing and the geoid refining.

II. RESEARCH ON GRAVITY VARIATION AND ITS MECHANISM

By analysing the repeat observations of high precision gravity network, the information of variations of absolute gravity field was obtained, which contributed to the earthquake prediction, studies on variation of sea surface and geodynamics with μGal precision. By analysing the results of the repeated absolute gravity measurements during the period from 1998 to 2004, Wang et al (2004) found the decrease trace of gravity field over the area of Tibetan plateau, which showed the uplift of Tibetan plateau with speed of 8.7 mm/yr. They found the decrease of gravity over north China region while increase over the coastal lines regions of the southwest China and southeast China. These phenomena were consistent with the leveling results that the crust over southeast China was descending, which reflected the characteristics of the vertical movements in Chinese continent. Zhu et al (2003) pointed out that the Ms8.1 earthquake in Kunlun mountain area occurred at the high gradient of maximum negative gravity change belt, which corresponded to the high strain area derived from GPS observations. And Wang et al (2004) also found the gravity change due to this earthquake. To study the crustal movement of coastal area in southeast China and variation of sea surface, Liu et al (2005) obtained the characteristics of horizontal displacement of coastal area in China relative to Europe-Asia frame and the characteristics of the vertical displacement relative to ITRF2000 using the gravity station and GPS co-site network constructed at 6 tide gauge stations, which contributed positively to monitoring the large scale crustal movement and tectonic deformation.

III. TIDAL GRAVITY AND LOADING EFFECTS OF ATMOSPHERE AND OCEAN TIDES

By comparing the gravity observation obtained with SG and FG5 gravimeters, the scale of SG gravimeter was accurately determined by Sun et al. Xu et al (2003) and Sun et al (2006a) developed the researches on Earth tides over China mainland, HongKong and Antarctic area. Tian et al (2005) and Ducarme et al (2006) synthetically analyzed the long term global SG observations in the GGP network and accurately determined the tidal parameters including the ones of long period tides. Xu et al (2004) investigated the global distribution characteristics of tidal parameters.

On the basis of the theory of elastic Earth's response to surface load and standard atmospheric model, combing the variation of the global atmospheric pressure and temperature, Luo et al (2005) studied the time-space and frequency characteristics of atmospheric load effect by numerical method, i.e. convolution of air pressure and atmospheric loading Green's function, which provided an atmospheric load correction model for high precision measurements of ground gravity, tilt, displacement and strain. Hu et al (2006) investigated the frequency dependence of atmospheric gravity signals utilizing long term global SG observations. With the latest global ocean tide models, Zhou et al (2005; 2006) calculated the load correction vectors for all the GGP network stations. Combing the local ocean tide models in China coastal area, this work improved significantly the correction precision of gravity and tilt observations. Sun et al (2005a; 2005b) synthetically investigated the adaptabilities of Earth's tide models and ocean tide models by using the global SG observations.

IV. EARTH'S FREE CORE NUTATION AND EXPERIMENTAL MODEL OF TIDAL GRAVITY

According to the characteristics of nearly diurnal resonance observed from gravity observations and stacking the long term, continous and high quality gravity observations obtained at 19 GGP stations distributing in different areas globally, the parameters including resonant period, resonant intensity and quality factor of Earth's Free Core Nutation (FCN) were accurately determined after effectively eliminating the effects of atmosphere, ocean and environment around stations. The results were in good agreement with the ones resulted from space geodetic techniques such as Very Long Baseline interferometry (VLBI). Sun et al (2003) and Xu et al (2004a) investigated the difference of the resonant period between determined and theoretical ones. By using gravimetric technique, that the realistic dynamic eccentricity of Earth's liquid core was 5% larger than the one derived under the hypothesis of hydrostatic equilibrium was proved by this study. Sun et al (2004) and Xu et al (2004a) studied the variation characteristics of the tidal gravity parameters and solved the parameters of nearly diurnal resonance of the Earth's tides and the dependent factors of amplitude factors on latitude (O_1 and M_2). The experimental tidal gravity models were constructed with considering of the free oscillation of the Earth's liquid core. Their results showed that the mean differences of the amplitude factors of four main constituents between the experimental Earth tide model and the ones obtained by SG observations were all small than 0.2%, which agreed well with the latest Earth tide model. The mean discrepancy of the amplitude factors was ±0.06% in which the diurnal results were in good agreement with Mathews' theoretical model (2001) and semidiurnal results were in better agreement with Dehant's model (1999). These results provided with accurate correction model for Earth tidal gravity for the ground and space based geodetic techniques.

V. DETECTION OF EARTH'S FREE OSCILLATION AND ITS INVESTIGATION

By synthetically analyzing the observations obtained with global superconducting gravimeters at five stations during Peru Ms7.9 earthquake, all the spherical oscillation modes were accurately detected by Lei et al (2005). And from analyzing the SG observations at Wuhan station during Sumatra large earthquake, many free modes of Earth's free oscillation including 50 harmonic modes were detected. It was the first time in China that the harmonic spherical modes series had been detected systematically by gravimetric technique, which could be used as new basic observational achievements for the research of the deep interior of the Earth. Additionally, the triplets of some modes were also found, which were very accurate especially for those of ${}_0S_2$ and ${}_0S_3$ modes (Park et al, 2005). By using global SG observations, during the period of the Sumatra large earthquake, Hu et al (2006) found the coupling toroidal modes and lower degree spherical spectral splitting phenomena, it could provide with the new important reference for the study of the Earth's deep interior.

Using the high quality of continuous SG observations at 13 stations globally in the GGP network, the possibility in the detection of long period core modes was investigated by Xu et al (2005), in which four globally spectra peaks with periods of 16.55, 15.79, 11.00 and 10.09 hour were found in the inter-tidal bands. The further analysis showed that these peaks possibly resulted from long period oscillation of the Earth's liquid core. Further more, 8 globally spectra peaks were found in sub-tidal band. Sun et al (2006c) studied the temporal variation features of these signals using wavelet technique. The researches by Sun et al (2004) and Xu et al (2005) showed that the Slichter mode was one of the possible sources of these signals. Of course, to get a definite conclusion, the more knowledge on structure of the deep interior of the Earth and improvement of dynamic research methods to Earth's liquid core are being expected.

VI. RESEARCH ON EFFECT OF POLAR MOTION ON GRAVITY

The effect of polar motion on gravity was investigated by using the global SG observations and Earth's rotation data provided by the IERS. The theoretical calculation showed that energy of product spectra of annual and Chandler wobbles concentrated at the periods of about 436.68 and 377.36 day while the one according to the observation concentrated at the periods of 438.60 and 362.32 day. Consequently, the differences between mentioned periods above are 0.4% and 3.9% respectively for Chandler and annual wobbles (Xu et al, 2004b; Yang et al, 2004). Meanwhile the gravity tidal parameters were obtained as 1.1613±0.0737 and －1°.30 ±1°.33 respectively for amplitude factor and phase lag, which was very close to the simulation using zonal tide theory by Xu et al (2004a). It was showed that the gravity change caused by polar motion could be effectively detected accurately by superconducting gravimetric technique.

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ON THE OBSERVATION OF CRUSTAL MOVEMENT AND ASTRO-GEODYNAMICS RESEARCH IN CHINA

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Abstract: This report reviews, very briefly, some observational and research works of astro-geodynamics by Chinese colleagues during 2003-2006, including: observations and study of the model of global and Chinese local crustal movement, the GPS applications on the meteorology and ionosphere study, the applications of VLBI on astrometry and geodesy, SLR observations and related research, the earth rotation variation and its relation with atmosphere, ocean and the interior Earth, and fluid dynamics study of planetary (such as the Earth and Jupiter) atmosphere and their interior physics.

I. CRUSTAL MOVEMENT

1. Global Crustal Movement and Global Plate Motion Model

As a realization of a conventional terrestrial reference system (CTRS), the ITRF2000 frame is found that it does not satisfied the no-net-rotation (NNR) condition and a new present-day global plate motion model NNR-ITRF2000VEL and a relative motion model RM2000 are derived from the Tisserand system constraint (Zhu et al. 2003a). Incorporating the geomagnetic anomaly data in the past 80 My., Jin et al (2004) determined the relative Euler vectors of global plates in the different ages, based on which the spreading, sliding and converging rates of adjacent plates could be obtained. Using a spectral analysis and a Multi-resolution wavelet analysis methods, Zhu et al. (2003b) study GPS time series in height component generated from nearly 200 continuously operating globally distributed GPS stations, and find that there are both annual and biannual vibrations of integrated expanding and contracting movements in the Earth and that the southern hemisphere is expanding compared with the northern hemisphere.

2. Crustal Deformation in the Chinese Continent Monitoring by GPS.

In the past four years, there are a lot of papers, the observations of the crustal deformation in the Chinese continent by GPS are reported intensively. For example, according to the unified velocity field in the Chinese mainland and the surrounding areas, which was composed of the velocities at nearly 1600 GPS stations in the Crustal Motion Observation Network of China (CMONOC), Wang et al. (2003) delineated 9 tectonically active blocks and 2 broadly distributed deformation zones for the Chinese continent, and the movement and the strain parameters of active blocks are also estimated and analyzed. These results indicate that all active blocks in the Chinese continent have a consistent E-trending movement component but its N-S component has an obvious difference. For the N-S seismic zone of China, the blocks in the western part have a consistent northward motion and the blocks in the Eastern part have a consistent Southward motion.

Zhu & Cai (2003) proposed a method to invert the viscosities in lower crust and upper mantle from temporal series of GPS measurements. It is shown that the inversion method is highly efficient and stable.

3. *Active Tectonic Blocks and Strong Earthquakes*

Zhang et al. (2003), Han et al. (2003), Li et al. (2004), Jiang et al. (2006) and else studied the relations between the active tectonic blocks and strong earthquakes in the China continent. The primary pattern of the late Cenozoic and the present tectonic deformation of China are characterized by relative movement and interactions of tectonic blocks. Active tectonic blocks are geological units that have been separated from each other by active tectonic zones. Most of tectonic activity occurs on boundaries of the blocks. Earthquakes are results of abrupt releases of accumulated strain energy that reaches the threshold of strength of the earth's crust. Almost all earthquakes of magnitude greater than 8 and 80%--90% of earthquakes of magnitude over 7 occur along boundaries of active tectonic blocks. This fact indicats that differential movements and interactions of active tectonic blocks are the primary mechanism for the occurrences of devastating earthquakes.

II. The meteorology applications of GPS

1. *Ground-base GPS/MET*

Zhu et al. (2004) introduced real-time monitoring of PWV from Shanghai GPS Comprehensive Applied Network(SGCAN) and its application in numerical weather forecast for Yangtz River Delta region. By using the Cressman method, GPS/PWV is interpolated to the grids of the initial field, and therefore, the humidity condition of numerical forecast model is optimized after and the accuracy of numerical forecast is improved (Song et al. 2004). At present, the PWV provided form SGCAN as day-to-day work have been applied in weather forecast service for Yangtz River Delta region.

Using slant water vapor(SWV) observations from SGCAN, Song et al. (2006) diagnosed the three-dimension(3D) water vapor structure over Shanghai area. Comparisons between tomography results and the profile provided by numerical model (MM5) show that the forecasted moisture field of MM5 can be improved obviously by GPS slant water vapor. Bi et al.(2006), also proposed a method of remote sensing of SWV, from which the SWV amount can be accurately retrieved and this method is also valid for nearly real-time remote sensing and detection of the atmosphere.

2. *GPS Radio Occultation*

For atmosphere GPS radio occultation inversion, Yan et al. (2004) discussed the reflection effect in GPS/LEO observation. Hu et al. (2005) proposed a new inversion scheme which combines the geometric optics method and the full spectrum inversion method. It was applied to data processing with one GPS/MET radio occultation event data and one CHAMP event data, and successfully yielding atmospheric parameter profiles. Wang et al. (2005) presented a non-linear inversion method to retrieve water vapor profiles in the troposphere with radio occultation measurements. By analysis of these retrieved profiles, it was suggested that the present method could simultaneously retrieve both temperature and water vapor profiles and the corresponding error covariance. Guo et al. (2006) developed a computation procedure of GPS radio occultation data retrieval. The retrieved atmospheric profiles from CHAMP data were compared with the ECMWF analysis data. The calculation results fairly approved the potential of GPS occultation data that might become an extremely valuable data source for the numerical weather prediction (NWP) and long-term monitoring of the Earth's climate. Based on one dimensional variation (1DVAR) retrieval technique, Hong et al. (2006) proposed that the refractivity or the bending angle profiles from GPS/LEO occultation was possibly used to be assimilated into NWP model, and then the atmospheric temperature and water vapor profiles, as well as the surface pressures were retrieved. In order to avoid the error arising from horizontal refractivity inhomogeneity, the 2D ray-tracing mapping operator was developed to assimilate bending angle profile into numerical weather model.

Hu et al. (2006) discussed the principle and methods of estimating bending angles of the radio rays and atmospheric refractivity profiles with the mountain based GPS radio occultation data.

3. Ionosphere study with GPS

Using the dual-frequencies GPS data from the local GPS network SGCAN, Zhu et al. (2004) studied a small-scale ionosphere heterogeneity. By using VTEC data, the wave-motion appearing in the ionosphere on November 3, 2003 when a small solar flare happened was monitored and analyzed (Zhang et al, 2005). Ping et al. (2005) validated the Jason-1 dual-frequency nadir ionosphere TEC for 10-day cycles 1-67 using absolute TEC measured by GEONET or GEONET RIM.

On the inversion and tomography of ionosphere: Zeng et al. (2004) proposed, based on the assumption of the local spherical symmetric ionosphere, two inversion methods with which ionospheric density profiles are extracted from the dual frequencies and single frequency radio occultation data respectively. Wu et al. (2006) proposed an inversion algorithm, calibrated TEC method, to estimate the TEC above LEO using the data from the non-occultation portion of the satellite track. Xu et al. (2005) illuminated the principle and algorithm of time-dependent three-dimensional computerized ionospheric tomography with ground-based GPS network and occultation observations as well as reconstruction results based on real measurements.

III. ASTROMETRIC AND GEODETIC VLBI ACTIVITIES IN CHINA

With the promotion of Chinese lunar mission, A Chinese national VLBI network is completed. Additional to the two 25-m radio telescopes located near Shanghai and Urumqi, a mobile VLBI antenna (3m) has started to work in Kunming since 2000, and a new 50m antenna also started to work in Beijing in 2006. Meanwhile, the MK5A system is installed and related hardware/software correlator are rebuilt, and e-VLBI experiments are also successful (Zheng et al., 2005; Wei et al., 2004)

The research of VLBI applications in astrometry and geodesy during the last several years includes the following:

1. Data Analysis And Application Of VLBI/SLR/GPS Combination

The relative positions among co-located stations must be precisely determined. Shen et al. (2006) introduced the observation projects and the methods to determine the coordinates' difference. Zhu et al. (2005) derived a plate motion model called GVM1 by the integrated data of VLBI and GPS. Ding et al. (2005) assessd the frequency features in the solutions over various time-scales using time series of daily position solutions at eight co-located GPS and VLBI stations.

2. Analysis Strategies And Modeling

Zhang et al. (2003) deduced relativistic time delay model used in VLBI data-processing and presented a rigorous analyzed expression. Zhang et al. (2004) studied the modeling of residual clock behavior in VLBI observations, and they (Zhang et al., 2005) also studied the analysis strategies to solve the high-frequency variation of ERP from VLBI observations.

3. VLBI Application for Spacecraft Navigation

With the development of the lunar mission in China, a lot of related researches of VLBI application for spacecraft navigation have been carried on. Such as error analysis, data analysis and orbit determination using combination of VLBI and other range and range rate data etc. (Wang et al., 2005; Wang et al., 2006; Huang et al., 2006).

IV. SLR RELATED ACTIVITIES IN CHINA

1. Update Of The SLR Systems, Mobile Station And Related Works

In order to monitor the crustal movement of Chinese continent, two mobile SLR stations have been built by the Seismological Institution of Chinese National Seismology Bureau. With the support from Chinese Key Science Project, they have started to work in Beijing, Urumqi, Lhasa and other sites since August, 2000. Using these data, the geocentric coordinates of these sites are obtained in the frame of ITRF2000 with good precision (Feng et al., 2003).

Since 2001, Shanghai Astronomical Observatory (SHAO), Chinese Academy of Science, has collaborated with Czech Technical University to develop a Raman Laser system for multi-wavelength SLR and this system works very well (Hu et al., 2004). Furthermore, the laser system and the receiver system are improved and day-time SLR has been realized successfully.

2. The Pre-processing And Fast Service Of SLR Observations

In order to satisfy the request of the service for SLR observation, the SLR group in SHAO pre-process and analysis regularly the SLR raw data of all global SLR stations, evaluate their quality of the observations, calculate their systematic error and precision, and publish these results as bulletin in the website of ILS (ftp://cddis.gsfc.nasa.gov/reports/slreport) once a week.

3. Related Research Works From SLR Data

(1) Precise determination of the SLR satellites orbits

The precision of Lageos satellite orbit determination cab be reached at around 1 cm for 3-day pass, while the precision of the radial component of TOPEX/Poseidon is about 2-2.5cm (Feng et al, 2003).

(2) To study the gravity model and its temporal variation and the movement of geocenter

Both robust estimation and variance component estimation of the data set of Lageos2 from January 1996 to December 2000 are applied to study the geocenter motion with respect to ITRF2000, and it is found that there are annual and semiannual components in the geocenter motions, but, there is no significant long term (Qing & Yang, 2003).

An Earth's gravity field model IGGGRACE01S is derived from 141 days of GRACE tracking data, including K-band, accelerometer, satellite orbit data. The model resolves the geoid with an accuracy of about 0.012 m at a resolution of 500km half-wavelength, and improves the accuracy of the gravity field model in the long- to medium-wavelength part (<80 degree) than pre-CHAMP model (Zhou et al. 2006).

(3) Determination of EOP from SLR data

The possibility and precision of the determination of earth orientation parameters (EOP) from Chinese national SLR network (CNSN) are discussed. As an example, two data sets during 19 April – 30 May, 2001 and during 1 Sept. – 30 Oct., 2001 from SLR observation of Lageos 1 by CNSN are used to determine polar motion (PM) and LOD by SHORDE program, and the results are compared to the EOPc04 series of IERS. It is found that the uncertainties are 4-5 mas for PM and 0.32 ms for LOD, while they are 0.35 mas for PM and 0.03 ms for LOD if using all observations of Lageos 1 by global SLR stations (Zhu et al., 2003, 2006).

(4) Sea level change and oceanic geoid

Two ocean models and the altimetry data from TOPEX/Poseidon (TP) are studied, and it is found that the mass transfer within the oceans, specifically within the Pacific Ocean, contribute to at least part of the variation of the Earth oblateness (J_2) since 1997/1998, which may be from the variations of the steric effects (Hu et al., 2004).

The deflections of the vertical line in ocean areas are calculated from altimeter data by simple difference method. A covariance function to approach precisely the marine geoid from the deflections of the vertical line is presented, and a global marine geoid and dynamic ocean topography (DOT) are obtained from TP and ERS-1/2 altimeter data. (Peng et al., 2003).

V. EARTH ROTATION VARIATION AND ITS RELATION WITH ATMOSPHERE AND OCEAN

The atmosphere is the most important excitation source to the Earth rotation from intra-seaonal to inter-annual time scales. Zhou et al. (2006) improved the computation of the atmospheric excitation function (AEF) by considering the Earth's variable surface topography. The new equatorial AEF got generally closer to the observed polar motion excitation function, and it has been adopted by the Special Bureau for Atmosphere (SBA) of the Global Geophysical Fluids Center of the International Earth Rotation and Reference Systems Service (IERS). Ma & Han (2006a) found that time-variations of period lengths and amplitudes also exist in the seasonal oscillations of the axial AEF and are in good consistency with those of the seasonal LOD change.

The oceans are the secondary important excitation sources to the Earth's variable rotation, other than the atmosphere. Zhou et al. (2004) investigated the excitation of non-atmospheric polar motion by the migration of the Western Pacific Warm Pool (WPWP), and found the non-negligible effects of the WPWP on the annual polar motion. Zhou et al. (2005) analyzed and compared the oceanic contributions to the non-atmospheric polar motion excitations determined from different oceanic general circulation models (OGCMs). The results showed that due to different modeling schemes and methods, significant discrepancies could arise with respect to the quantity of modeling large-scale oceanic mass redistribution and current variation. Zhong et al. (2006) stated that the oceanic role in polar motion excitation should be further examined. Ma et al. (2006b) studied the atmospheric and oceanic excitations to LOD change, and concluded that the combined effects of the atmosphere and oceans can explain about 99% of LOD change on quasi-biennial time scales during the period of 1962-2005. Yan et al. (2006) evaluated the nontidal oceanic contribution to length-of-day (LOD) changes from two ocean models, and noted that the excitation of LOD by other sources, such as hydrology, might be also important.

There are quasi-periodic changes in the Earth rotation. Liao & Zhou (2004) obtained the mean values of Chandler wobble period and Q value by the wavelet transform technique. Liao et al. (2004) analyzed the statistical property of the Chandler wobble excitation function, and noted that the excitations from atmosphere, ocean, and hydrosphere are the main sources of the Chandler wobble, and the Chandler wobble excitation function is of a random normal property. Liu et al. (2005) presented the wavelet coherence analysis of LOD variations and El Nino-Southern Oscillation. There are obvious time-scale-dependent correlations and phase-shifts between the Earth rotation rate variations and the ENSO even within interannual scales.

VI. PHYSICS OF THE EARTH AND PLANETS' INTERIOR

1. Theoretical Studies on Earth Rotation

Generalized spherical harmonics function (GSH) and its application on geophysics are studied (Huang et al., 2003). A set of scalar differential equations of infinitesimal elastic-gravitational motion for a rotating, slightly elliptical fluid outer core (FOC) is derived in an explicit and ready-to-program format (Huang et al., 2004).

The coupling between the earth nutation and the electro-magnetic field near the core-mantle-boundary (CMB) is studied, and it is proved that the spheroidal and toroidal parts of the induced magnetic field by nutation are decoupled (Huang et al., 2005). Furthermore, from numerical integration approach and by using well-accepted electro-magnetic parameters near CMB, computation shows that this coupling may contribute to the retro-annual nutation at a certain level and maybe used as a candidate to interpret the difference between the theoretical model and the VLBI observation of the retro-annual nutation (Huang et al., 2006).

The first attempt to search for the inner core wobble (ICW) in Earth's polar motion data and gravimeter data was made with spectral method by Guo et al.(2005). By using the elliptic function solution, Wang (2004) tried to solve the exact rotation solution of triaxial Earth as motion of couple periods with an image decadal period longitudinally and Chandler wobble as transverse wave, and the periods and amplitudes of decadal wobble are calculated.

Both astronometric and gravimetric observations at Beijing Observatory, as well as in Yunnan Province and in north China area, are used to study the non-tidal variations in the deflections of the vertical (or plumbline variation, PLVs) and its relation with earthquakes. (Li et al., 2005, Li & Ding, 2005).

By using new geophysical data and the paleontological clocks data, It is estimated and compared luni-solar tidel dissipation, the Earth's momentum variation, the long-period variation of length-of-day and the length of synodic month in the passed 1500 Ma. (Gao, 2005).

2. On The Interior of Planets, Satellites And Comets

Radio Doppler data generated by the Deep Space Network (DSN) from the recent encounters of the Galileo space craft with the Galilean satellites have been used to determine the internal structure models and dynamical parameters of the four Galilean satellites (Zhang, 2003). Their Q values and their tidal contributions to the deceleration of Jupiter's rotation (Zhang & Zhang, 2004).

The linear wave phenomenon observed during the collision between Comet Shoemaker-Levy 9 (SL9) and Jupiter in July, 1994 are studied, especially the inertia-gravity waves are solved from fluid dynamics equations (Bao et al., 2004).

VII. FUNDAMENTAL RESEARCH OF THE FLUID DYNAMICS OF THE EARTH AND PLANETS, AND NUMERICAL SIMULATIONS OF MAGNETIC FLUID DYNAMICS

In the recent years, Chinese colleagues have conducted fundamental researches in fluid dynamics of the earth and planets and numerical simulations of magnetic fluid dynamics. As an example, some related works done by the group in Shanghai Astronomical Observatory since 2004 are reviewed very briefly in this section.

As to the Poincaré & Bryan problem of fluid motions in the form of inertial waves or inertial oscillations in an incompressible viscous fluid contained in a rotating spheroidal cavity, the first explicit general analytical polynomial solution of this classical problem valid for 0<(degree N and order m)<∞ have been found by a perturbation analysis in spheroidal polar coordinates, as well as for arbitrary eccentricity and satisfying a certain set of the boundary condition. Based on this solution, some unusual and intriguing properties of the spheroidal inertial waves or oscillation are discovered (Zhang et al., 2004a, 2004b).

Linear and weakly nonlinear thermal convection in a moderately thin spherical shell in the presence of a spherically symmetric gravity subject to a spherically symmetric boundary condition is systematically investigated through fully 3D numerical simulations. By starting with carefully chosen initial conditions, one is able to obtain a variety of nonlinear convective flows at exactly the same parameters near the onset of convection (Li et al., 2005).

Convection in a Boussinesq fluid in an annular channel rotating about a vertical axis with lateral rigid sidewalls, stress-free top and bottom, uniformly heated from below is investigated. Three different types of convection are identified when the channel is rotating sufficiently fast, and the corresponding weakly nonlinear problem describing differential rotation and meridional circulation is also examined (Liao et al., 2005a). Furthermore, a fully 3D numerical simulations of this nonlinear convection in such a Boussinesq fluid is conducted, It is found that the wall-localized convection mode is nonlinearly robust, that both directions of traveling waves are always present in the nonlinear solutions, and that It is the nonlinear interaction between the wall-localized modes and the internal mode that plays an essential role in determining the nonlinear properties of convection in a rotating annular channel (Chang et al., 2006).

The convective instabilities and differential rotation generated by the instabilities in rapidly rotating stars are investigated, using a new quasi-geostrophic approximation incorporating full spherical geometry and the equation of mass conservation, and this new approximation provides an exciting opportunity to analyze and compute convective flows in rapidly rotating stars with very small Ekman numbers (Liao et al., 2005b).

The problem how thermal-wind-type flow near the CMB in a stable layer (at upper core) could influence the geomagnetic field and the geodynamo using a very simple 2D kinematic dynamo model in Cartesian geometry is studied. Exact dynamo solutions are obtained for a range of parameters. Their earlier results that a stable, static layer can enhance dynamo action is confirmed. And it is also found that shear flows produce dynamo wave solutions with a different spatial structure from the steady 2 dynamos solutions. The stable layer controls the behavior of the dynamo system through the interface conditions, providing a new means whereby lateral variations on the boundary can influence the geomagnetic field (Liao et al., 2005c).

An asymptotic theory is presented to describe the possible mechanism for the excitation and maintenance of torsional oscillations in rotating convective stars and planets. It is demonstrated analytically that the torsional oscillations can be excited and sustained by global thermal convection (Liao & Zhang, 2006).

Furthermore, the asymptotic solutions of second-order accuracy taking account of the velocity boundary conditions imposed on the sidewalls are derived for wall-localized boundary-layer convection in a rotating fluid layer in the presence of stress-free or no-slip vertical sidewalls. Movoer, it is shown, through fully 3D numerical simulations, that the structure of the boundary-layer convectionis highly robust in strongly nonlinear regimes (Liao et al., 2006).

The core-mantle thermal coupling is studied by investigating non-linear convection in an annular channel rotating about a vertical axis, heated uniformly below with heat-flux anomalies on its sidewalls. It is found that the non-linear convection either exhibits complete locking onto the corresponding lateral heterogeneity on the sidewalls or becomes strongly time-dependent, interspersed with the intervals of no fluid motions (Zhan et al., 2006).

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GRAVITY AND GEOID DATA PROCESSING

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I. TECHNIQUE OF HIGH-RESOLUTION TERRAIN CORRECTION COMPUTATION

1.1 The mathematical model for the fast and precise computation of terrain correction using gridded spherical elevation data is established. For the internal 3×3~9×9 sub-blocks the precise prism integration method is applied and for the outside global areas the spherical approximation expansion method is applied.

The software for terrain correction based on the Fast Fourier Transformation (FFT) is created with accuracy better than ±0.2mgal compared with the precise prism integration at a same data resolution. And the integral fast computation of the 1′×1′ Gaussian Plane grid terrain correction of local area for the China territory is implemented.

1.2 The global integration technique for the global 5′×5′ terrain and isostatic corrections has be completed within 36 hours using the spherical approximated single or multi band FFT.

1.3 The frequency extraction for the global 5′×5′ terrain concerned computation, for which only the spherical harmonic series expansion to degree and order 2160 needs to be extracted, have been completed within 32 minutes. For isostatic correction, the land and ocean areas need to be processed using different methods.

1.4 The efficient computation for local 3″×3″ terrain related correction has been completed using equi-partitioned overlapping area summation, moving window and FFT techniques. For different devices and the 1GB limitation for Windows single process, the moving window can be set as 2°×2° or 2°×3°, which can be consistent with figures and is suitable for data combination. However, the time consumption for one computation on the global 3″×3″ data is staggering.

II. ESTIMATION METHODS OF 5′×5′ GRID MEAN GRAVITY ANOMALY IN GRAVITY GAPS

2.1 The isostasy-based global generalized potential model with equivalent resolution is set up and applied to fill the gaps. The method is applied for EGM96-originated observations. Iteration characterizes the method.

2.2 The gravity gap-filling method by removing high-frequency part followed by large-scale system error fitting and then restoring high-frequency parts has been implemented. For

UGM05-originated data the method is applied to estimate the global land 5′×5′ mean gravity anomaly.

2.3 The fitting and estimation method based on the zooming window of complete Bouger gravity anomaly has been implemented to fill the gravity gaps.

2.4 Using rich terrain data, firstly estimating vertical deflection then estimating unobserved gravity anomalies using the inverse Venning-Maniz formula, and then constituting residuals with observed gravity anomalies, finally estimations are derived by indirect fitting of the residuals.

2.5 With the above methods, a model of China's 5′×5′ mean gravity anomaly is constituted, with accuracy up to ±3~5mGal.

III. INTEGRATED ANALYSIS TECHNIQUE FOR GLOBAL LAND AND OCEAN GRAVITY DATA

Highest resolution reaches 30″×30″; land resolution reaches 3″×3″; numerical model UGM05.ΔG by piecing together global 5′×5′ gravity anomaly is obtained. The process has two steps.

Step 1. From $\Delta g \approx \delta g_I + \delta\Delta g$ and the theory of Isostasy, the global 5′×5′ δg_I s are estimated using the global 5′×5′ mean elevation and mean ocean depth data files, and then the global 30′×30′ mean gravity anomalies are generated using the EGM96-originated data, and by converting the δg_I into data of 30′×30′ resolution the 30′×30′ $\delta\Delta g$ can be computed and intensified into 5′×5′ resolution data via duo quadratic moving interpolation, and then the derived 5′×5′ $\delta\Delta g$ plus the 5′×5′ δg_I makes the estimated global 5′×5′ Δg , which shares the data source with EGM96 at a 30′×30′ resolution.

Step 2. The ocean areas between 72° south latitude and 72° north latitude are filled with the collected satellite altimetry mean gravity anomaly; the US area is filled with terrain-corrected gravity anomalies; and China area is filled with 5′×5′ Δg of 1978 edition minus 13.5mgal. Finally the integrated global 5′×5′ Δg file is generated, and is called UGM05.ΔG.

A land-and-ocean-unified Earth gravity field model UGM05 with degree and order up to 2160 is established, with a ±0.46m accuracy in consistently approximating China's geoid. Tests show that the model is stable for globally restoring geoid and gravity anomalies, including two poles. For ocean geoid approximation, the accuracy is better than 30cm for 5′×5′ grid; for US and China land geoid approximation, the accuracies are 30cm and 45cm respectively.

IV. ESSENTIAL IMPROVEMENT IN GLOBAL GRAVITY FIELD SOLUTION

The torus spherical/ellipsoidal harmonic analysis method is implemented, which can deal with not only the radial observations like gravity anomaly, but horizontal observations like global satellite gradiometric observations. Methods that have been developed make a faster and more accurate inverse solution of the Earth's gravity field. The modeling process for the global gravity field up to degree and order 360 and 2160 can be completed within 16 seconds and 16 minutes respectively.

For the restoration of the gravity field, the torus harmonic analysis method is more accurate than conventional harmonic analysis methods. The significant digital number is 4-6 for the torus method and 2-4 for conventional methods in that there is a smoothing factor which is hard to be accurately determined whereas the torus method overcomes the smoothing factor problem and gains better accuracy.

V. NORMALIZATION METHOD FOR GRAVITY VECTOR AND TENSOR MAKES A FASTER COMPUTATION

From the property that the derivative of potential function with respect to coordinates is still harmonic, we can prove that the series expansion of perturbing forces under the Earth-fixed coordinate system is harmonic. From the same point, gravity tensor has similar expressions. Therefore, the computations of gravity elements within the Earth-fixed coordinate system can be boiled down to summations of spherical harmonics. And the elements within local coordinate system are their projections.

VI. GPS-GRAVIMETRY THEORY BASED ON DISTURBING GRAVITY SET UP

The strict theory of fixed Boundary Value Problems (BVPs) with ground disturbing gravity as boundary value conditions is proposed. The point is proved that the frequency spectral characteristics of disturbing gravity is very close to those of gravity anomaly and that consistent results have been derived when both are used in gravity field elements computations. At the same time, the kernel of the Hotine Integration with disturbing gravity as input is simpler that that of the Stokes Integration with gravity anomaly as input, which can also be converted into convolution and thus facilitates practical applications. As the disturbing gravity contains the first degree information of disturbing potential, when global disturbing gravity is available, it can be applied to detect the displacement of coordinate system with respect to the geocenter. As the new theory makes full use of the rapidness and convenience of GPS positioning, it can be used to determine the coordinates and elevation of points on which gravimetry is implemented instead of conventional geometric methods, which results in a faster and more precise acquisition of the disturbing gravity.

VII. ESTABLISHMENT OF CHINA'S NEW GENERATION STATISTICAL

CHARACTERISTIC PARAMETERS OF THE GRAVITY FIELD

For the statistical characteristic parameters of the gravity field, including terrain categories, complete Bouger gravity anomaly, complete gravity anomaly and isostatic gravity anomaly,etc., the mathematical models, statistical methods, characteritic curves as well as the Least Square criteria for the determination of parameters have been studied scientifically and systemmatically. And the covariance, degree variance and commission error models of the complete free-air gravity anomaly, complete Bouger gravity anomaly and isostatic gravity anomaly corresponding to the six terrain categories of China are developed statistically. For the practical gravity field situation of China, the number of intensifying gravity points that need supplementary observations is estimated ahead of schedule, which is a guide for China's gravimetry.

CHINESE AIRBORNE GRAVIMETRY SYSTEM

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I. SYSTEM DESCRIPTION

Conventional gravity measurement, by ship at sea or by stationary measurements on land, is time consuming and expensive as well as logistically difficult in many remote regions, such as virgin forest, swampland, desert and open sea. To determine the gravity field of these inaccessible areas, airborne gravimetry is a desired and practical method.

The Chinese research program in airborne gravimetry began in 1998. The first Chinese Airborne Gravimetry System (CHAGS) broken into success in 2002. CHAGS is a damped platform scalar system, which includes hardware part and software part (Xia et al., 2004). The constitutes and the functions of the hardware part are in follows.

- Gravity subsystem

A LaCoste&Romberg air/sea gravimeter, which used to measure the total acceleration (called specific force).

- The positioning subsystem

Five sets of GPS receiver, of which two are mounted on the fuselage and three are set on the ground.

- Altimeter subsystem

A laser altimeter is used to determine the height of the aircraft above the ground.

- Attitude subsystem

An array formed by four electronic compasses.

- Data-logging subsystem

All time-related signals are logged in the unit, which consists of a laptop computer and attached communication units. All data are precisely time-tagged with GPS time as fundamental time frame. Data are logged on a PCMCIA harddisk and „mirrored“onto a high-capacity drive in the logging PC.

The software part includes five modules:

- Position and velocity determination

Determination of the position and velocity of the aircraft by GPS observations.

- Data-editing

Outlier's detection and elimination, Data division and interpolation according to flight-lines.

- Filtering and processing

Calculation of various corrections and raw airborne gravity disturbance, filter design and implement.

- Adjustment

Systemic errors verification and compensation, random errors reduction.

- Downward continuation

To downward continue the airborne gravity into ground or geoid.

Two tests of CHAGS have been done in 2002 and 2003: one in Datong and the other in Harbin. Two missions have been completed in 2005 and 2006.

II. DATA PROCESSING METHOD

1. Lowpass Filter Design

Lowpass filtering is very important for the airborne gravimetry. In general, the amount of filtering to apply is a trade-off between spatial resolution and accuracy. A short filter yields a good spatial resolution on the expense of much measurement noise and vice versa. Based on the spectral windows for the airborne gravity and the internal accuracy under different filter length, we design the finite impulse response (FIR) filter and the cascaded Butterworth filter that can be suited for various operation conditions (Sun, 2004; Sun and Xia, 2000).

2. Precise Determination of the Vertical Acceleration

The main factors that impact on the precise determination of the vertical acceleration using GPS are the residual atmospheric and orbit errors, multipath errors, measurement noise and the errors due to changes in the satellite constellation. The effects of these factors are analyzed in detail in frequency domain, and the results demonstrate that in the bandwidth 0.00005 to 0.0008Hz are dominated by residual atmospheric and orbit errors, but their effects are smaller, in the bandwidth 0.008 to 0.02Hz are dominated by multipath errors, measurement noise and their effects are larger. Moreover, the errors due to changes in the satellite constellation have notable effects on the GPS acceleration determination. The accuracy of the velocity can be reached mm/s level using ours GPS software, and the accuracy of the vertical acceleration is better than 0.5mGal when the filter length is 200s (Sun, 2004; Sun et al., 2004; Xiao and Xia, 2003).

3. Recalibration of the Beam Scale Factor (K- Factor)

K-factor is the most important parameter that characterized the linear property for the LaCoste&Romberg airborne gravimeter. The K-factor is recalibrated by minimizing the difference between airborne data and upward continued surface data (external calibration) and by minimizing the errors at line crossings (internal calibration) respectively. The numerical results show that the accuracy of the airborne gravity disturbance is improved about 0.2~0.4mGal by using of the new K-factor. Also, the dependence of the K-factor on the amount of the filtering applied to the data is discussed. It is shown that the gravity sensor may be a nonlinear system, namely the K-factor is seen to be dependent on the beam velocity. It decreases with increasing beam speed at the ends of the greater beam velocity and varies slowly in the middle parts of the beam velocity (Sun, 2004).

4. Recalibration of the Coefficients of the Cross-Coupling (CC)

The CC corrections for the L&R airborne gravimeter are computed as a linear combination of 5 so-called cross-coupling monitors, the weight factors (coefficients) determined from marine gravity data by factory are obviously not be optimal for airborne application. These coefficients are recalibrated to minimize the difference between airborne data and upward continued surface data (external calibration) and to minimize the errors at line crossings (internal calibration) respectively. An integrating method to simultaneously recalibrate the above mentioned coefficients and the K-factor is also presented. Numerical results show that the systemic errors in the airborne gravity anomalies can be greatly reduced using any of the recalibrated coefficients. Since the internal calibration requires only the survey to be well structured, with a large and well-distributed number of line crossings, and it doesn't require any of external information, it will be useful and valuable (Sun, 2004; Sun et al., 2006a).

5. Downward continuation

The accuracy, reliability and stability of four methods are evaluated with respect to the comparison and analysis of downward continued results with terrestrial real gravity data. The four methods are regularization method, the direct representation method, point-mass model method and the spherical interior Dirichlet's harmonic solution method (Shi and Wang, 1997; Shi and Sun, 1999; Wang et al., 2004b).

The accuracy of regularization method is better than the one of least squares method almost in one times, which shows that the regularization parameter can reduce the observation errors effectively for an ill-posed equation. But it is noted that incorrect regularization parameter would cause larger systemic error since the regularization method is a biased estimator. In order to improve the accuracy of downward continuation results, the effect of topography should be considered in downward continuation progress because the regularization method not only reduces the observation errors but also the high spectrum signals (Wang et al., 2004a).

The direct representation method is convenience, reliable and accurate. Furthermore, it abundantly uses detail topography data and its calculation progress is rather easy. Since no margin effect exited, it is not affected by the shape or area of the surveying region, but detail topography data are needed.

It is easy and facilitative to perform downward continuation by used of point-mass model method, but the accuracy of results is worse than others results. The main reason is that the progress is unstable, and regularization cannot be performed for less prior information of point mass model. Besides, the method is affected heavily by margin effect, so it is not suitable for small region.

The spherical interior Dirichlet's harmonic solution method is that terrestrial gravity anomalies are deduced by directly integrating the aero-gravity anomalies, namely directly integrating outer data to yield the inter data, and the margin effect is notable, so it is unstable in theory. The real results indicate that its result is not ideal, so its application is not favorite in practice.

III. TESTS AND CAMPAIGNS

1. Datong test

The test area belongs to medium mountain, the range is about 1°40′×2°00′. The terrain undulation is steeper in the eastern and the highest altitude is 2800m. In the western are highland, the average height is 1000m. The maximal difference of the height in the whole area is 2100m. The change of the gravity anomalies in the flight altitude is -50~80mGal.

Two kinds of flight lines were designed to test the achievable resolution of the airborne gravimetry. One is high lines, which was flown at an average height of 3400m and covered the whole area. Another is low lines, which was flown at an average height of 2800m and covered only the northwest area. The line spacing was 5′ for high lines and 2.5′ for low lines. The survey was performed using a medium-size, pressurized cabin aircraft. The mean ground speed of the aircraft during the operation was around 360km/h. All flights were done at 7 am and 12 pm local time. It was just the windy periods, so the flight conditions were quite turbulent and bad. This survey included 16 flights and consisted in 81filght-lines, in which parts were used to verify the repeat accuracy.

In Datong survey, the standard derivations of the crossover errors at the flight level of 3400m and 2800m are 5.8mGal and 5.5mGal respectively with a half-wavelength of 10km; the accuracy of the repeat lines is 3.8mGal at the same resolution. The standard derivations of airborne 5′×5′ mean gravity anomaly computed from the measured values at the high lines and those at the low lines are 3.6mGal and 2.8mGal respectively, an accuracy of 5.1mGal can be obtained for the airborne 3′×3′ mean gravity anomaly computed from the measured values at the low lines. Compared with ground gravity, the rms difference of the downward continued 5′×5′ mean gravity anomaly is about 4.2mGal.

2. Harbin test

This area is a plain, which size is about 1°20′×1°30′. The maximum terrain undulation is 170m. The change of the gravity anomalies in the flight altitude is 5~20mGal. The survey was performed using a small-size, unpressurized cabin aircraft, and consisted in flying 12 north-south lines and 12 east-west lines at a barometric altitude of 1200m. Average flight velocity for all flights was 230km/h. All flights were done at 8 am and 15 pm local time. The ground temperature was under -10°C generally, the flight conditions were little turbulent.

In Harbin survey, the standard derivation of the crossover errors is 2.0mGal with a half-wavelength of 10km; the external accuracy of the airborne 5′×5′ mean gravity anomaly compared with reference gravity is about 1.7mGal (Sun, 2004; Sun et al., 2006b).

3. Campaign A

The area belongs to medium mountain, the range is about 20 000km^2. The height of the terrain in this area varies from 100m to 1800m. The total flight-lines were 48 at an average height of 3190m, in which 12 were in east-west direction and 36 were in north-south direction. The aircraft is medium-size and has pressurized cabin. The mean ground speed of the aircraft during the operation was around 424km/h. The aircraft was equipped with two GPS receivers; one GPS antenna was mounted on the cabin roof, the other one on the top of the head. There were three GPS ground stations located in the whole area. All GPS receivers were operated at a sampling rate of 1sec. The flight conditions were medium to quite turbulent.

The number of the crossover was 242. The rms of the crossover errors was 5.0mGal after removing the outliers using robust estimation model (Yang, 1994). After adjustment using the same robust model, the rms value became 4.0mGal. The accuracy of the repeat lines is 5.0mGal. Compared with ground reference, the RMS difference of the downward continued 5′×5′ mean gravity anomaly is about 6.2mGal. Considering the accuracy of the reference is about 3.0mGal, the accuracy of the downward continued 5′×5′ mean gravity anomaly could be reached 5.5mGal.

4. Campaign B

The surveyed area is also a medium mountain, its range is about 50 000km^2. The height of the terrain in this area varies from tens of meter to 2000m. The total flight-lines were 48 at an average height of 2600m, in which 24 were in east-west direction and 24 were in north-south direction. The line spacing for all adjacent lines was 5′. The aircraft is small-size and hasn’t pressurized cabin. The mean ground speed of the aircraft during the operation was around 280km/h. The collocation of the GPS receivers was similar as campaign A, but all GPS receivers here were operated at a sampling rate of 5sec. The flight conditions were little or medium turbulent.

The initial results indicated that the standard derivation of the crossover errors was 6.48mGal (total 576 points). After removing the outliers using robust estimation model, the rms of the crossover errors became 2.79mGal. Since no ground reference was obtained in this area, the external comparison couldn’t be made. The optimal processing of the survey is also underway.

IV. APPLICATIONS

1. Determination of the local Geoid

To determine the local geoid from airborne gravity, it is usually necessary to downward continue the airborne grid gravity anomalies into ground. However, different continuation methods may be effects on the determination of the geoid. As example, the data from Datong test were used to analyze. Compared with ground reference, the rms differences of the 5′×5′ mean gravity anomaly that downward continued by point-mass model method, the direct representation method and regularization method were 5.91mGal, 5.21mGal and 4.25mGal respectively (Wang et al., 2004), while the rms differences of the corresponding geoid undulation were 0.031m, 0.034m and 0.033m respectively (Sun, 2004). Obviously, the downward continuation methods had distinct effects on the estimation of the gravity anomalies, but had fewer effects on the determination of the geoid. The accuracy of the local geoid determined by airborne gravity with 3cm could be obtained by all three downward continuation approaches, but the direct representation method may be optimal since it isn’t limited by the observed area and has little edge effect.

2. Determination of the Deflections of the Vertical

The two components of deflections of the vertical were estimated and compared with ground references using Datong data. The standard derivations of the deflections estimated by the airborne gravity are 0.5 and 0.4 arc seconds for meridian and prime component respectively. Considering the accuracy of the reference is about 1.5 arc seconds, the accuracy of the deflections estimated by airborne data was better than 2.0 arc seconds (Sun, 2004).

V. CONCLUSIONS AND FUTURE WORKS

We have summarized some tests and campaigns of the CHAGS. General speaking, the accuracy of the CHAGS can be achieved 2~7mGal at 5~15km resolution under the conditions of moderate turbulence. CHAGS will play an important role in filling the gap between ground-based and spaceborne gravity measurement techniques. It remains a challenge to combine of the relative information from airborne gravimetry with other sources of information about the gravity field. We'll effort in this direction.

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MODES AND ALGORITHMS FOR GEOPHYSICAL GEODESY JOINT INVERSION AND THEIR APPLICATIONS

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Based on the geodetic observation signal with combining the geological, seismic and geophysical data, the aim of geophysical geodesy joint inversion or joint inversion of geodesy mainly focus on inverting kinematics and geodynamics model parameters, modifying and proposing new geodynamics model using the priori geodynamics model from the geophysical research, discussing the geodynamic mechanism of crustal movement. It also could be used to invert the movement parameters of active faults and blocks from the surface observation data, discuss relationship between the crust motion and earthquake and make the prediction and forecast on seismic and geological disaster.

During the last four years, significant advances have been made in the study of modes and algorithms for geophysical geodesy joint inversion and their applications.

I. MODES FOR GEOPHYSICAL GEODESY JOINT INVERSION

Xu et al. (2003, 2005) developed the split-block and multi-fault joint inversion mode based on the half space, homogeneous and elastic dislocation theory and active block Euler parameters theory considering the rich GPS observation data from the Crustal Movement Observation Network of China (CMONOC). This inversion mode could simultaneously study the block motion in large scale and the fault characteristic in small scale.

Considering the spherical visco-elastic structure, the post-seismic deformation inversion mode had been constructed based on the visco-elastic earth model by Li et al.(2005) ,they also developed the inversion mode based on the post-seismic fault dislocation model considering the crust-stratified structure and applied to real cases. The inverted results show that the inversion mode could well invert out the fault dislocation parameters and could be better settle down the inversion work to the practical seismic fault co-seismic inversion problem. There is also an important that one could not use the minimum of $V^T PV$ as the only rule to judge the inversion result whether good or not when the mode is not obvious. One should find other ways to make a supplement judge.

Geodetic inversion system includes function model and stochastic model. Because of the model created approximately in the process of practical inversion, error is often brought into function and stochastic models.

The researchful results show that error can be transformed each other between function and stochastic models and that the inversion result is influenced seriously by these two kinds of model errors.

Theoretic fundamental formula, estimation formula and testing method in the case that the model error is absent in inversion were deduced by Zhang (2006), and the method for choosing the best model of inversion system was put forward as well. These are different from those given by the existing literature for resolving the same kind problem.

II. ALGORITHMS FOR GEOPHYSICAL GEODESY JOINT INVERSION

Xu et al. (2003) put forward the Cyclic-Bayesian searching method, which has two obvious advantages：one, is of wide searching space for unknown parameters with Cyclic searching method and the result can act as initial value for Bayesian method，and the other is of considering prior information about unknown parameters with Bayesian method. It is useful for inversing problems which are short of prior information with cyclic-Bayesian searching method.

LI Shuang et al. (2003) discussed the algorithms for estimating parameters of dislocation model, especially an Interval Algorithm for finding all global minimization of a constrained nonlinear function with several variables. This algorithm can solve the global nonlinear constrained optimization problem and is very suitable to solve optimization problem. It can find all global optimums and all global optimizers of the problem, and the inclusion interval of optimizers is output. By these intervals, the approaching errors can be gotten easily. This can’t be done easily by the others algorithms.

To accelerate the speed of computation of interval algorithm, it is combined with simulated annealing method and called interval simulated annealing method（ LI Shuang et al.，2004). The combination accelerates the computation speed and makes algorithm reliable and exact. This is a hybrid of stochastic search and exhaustive search.

Semi-linear inversion method was put forward by Zhang (2006). The method conquers the disadvantages of nonlinear method that is not able to appraise inversion result and linear inversion depending on original model very much. Nonlinear least square algorithm based on 5-node numerical differential coefficient was derived out, which is different from searching methods. A sequential joint algorithm with self-adaptation weight ratio was also put forward, which is unbias and does not use lots of memory and calculate complicated matrices.

III. APPLICATIONS OF GEOPHYSICAL GEODESY JOINT INVERSION

The surface contraction and uplift rates in the Himalaya zone based on fault dislocation models and GPS velocity field were discussed with the cyclic-Bayesian searching method by Xu et al.

(2003). The results show that the surface contraction rate is 13.22mm/yr to 20.38mm/yr crossing the Himalaya zone, and that the uplift rate is 8.25mm/yr to 9.34mm/ yr in the Himalaya zone.

Models for crustal movement and strain of blocks were derived by Xu et al. (2003). On the basis of simulative data, the parameters for crustal movement and strain of blocks were inverted. In the light of unbiasedness and validity of model, they identify the rigidity rotation model and rotation with strain model. The result showed that the rotation with strain model for active block was more reasonable and applicable than the rigidity rotation model. Lastly, using the GPS velocity field coming from Crustal Movement Observation Network of China (CMONOC) and North China GPS network, they have identified the models for crustal movement and strain of blocks in North China.

In terms of its tectonic information, China continent is divided into irregular grids. Based on the bi-cubic Bessel spline function method, Xu et al.(2005) inverted the present-day crustal horizontal velocity field and deformation field in China continent by combining with GPS velocities obtained by high-precision GPS network adjustment, seismic moment tensor data and fault slip rates. By this velocity and deformation field model, they analyzed the necessity of crustal deformation correction for the geodetic network observations in the joint adjustment of geodetic network and GPS2000 network. From the results, they conclude that crustal deformation correction for the geodetic network observations, i.e. arc and azimuth can be neglected; the geodetic coordinates had changed and should be corrected, however, they can also be disregarded in the joint adjustment; so the crustal deformation correction for about 300,000 observations of geodetic network can be neglected. They inverted the strain rate field, strain energy density rate field, then calculated the shearing strain rate field, area strain rate field and analyzed the relationship between the strong seismic activity and strain rate fields. The results reveal that in the middle and west of China continent, tectonic activity is stronger, particularly along the boundary zone of Himalayan block, in Chuandian area of Qinghai-Tibet block and Tian Shan area of Xingjiang block, shearing strain rate is larger, the shearing strain rate fields are in correspondence with the tendency of present-day tectonic movement; from the distribution of principal axes of tectonic stress field, we can infer that present-day movement of active blocks in China continent is mainly caused by posthumous movement. The continent of China deformation has not only the strike-slip faulting and block’s transverse slip feature but also the crustal shortening and thickening feature, it doesn’t support the continental eastward escape theory of high-rate of slip.

Tan Kai et al. (2004) inverted co-seismic dislocation parameters of 2001 Kunlun earthquake with geodetic data, they adopt the simulated annealing algorithm and segmented fault dislocation model to do inversion.

Combining GPS data with leveling data makes it possible to inverse several parameters simultaneously. The inverted results are accord well with the results of the field investigation.

The co-seismic displacement field of the 2001 west of Kunlun Mountain pass earthquake is also obtained through the analysis of GPS data measured before and after the earthquake and leveling data measured in 1979 and 2002 by Wan et al. (2004). They inverted the co-seismic slip distribution along the seismic fault adopting these data, constrained by detail surface rupture data measured after the earthquake. The result shows that the depth of rupture lower limit is 14.2-21km (with 70% confidence level), with 17km as the optimal value. The result also shows that left-lateral strike slip of 2-3m exists in the area between the Sun Lake segment and the west end of the main rupture zone, although surface rupture is not observed there. This is consistent with the result of InSAR data analysis. The released seismic moment estimated by geodetic data and surface rupture surveying is $6.1\times10^{20} N.m$, consistent with the result inverted by seismic wave records.

On the basis of the point source model, Chen Shaoxu et al.(2004) inversed the seismogenic parameters of Nantou Mw7.6 earthquake occurred in Taiwan in 1999 with GPS displacement data observed in Fujian-Taiwan area. They also compare and analyze the inverted results with the real earthquake source parameters.

On the basis of the velocity field results of horizontal crustal movement obtained from GPS measurements during the periods of 1993-1999，1999-2001 and 2001-2003 in the northeast margin of Qinghai-Xizang block，and by the inversion of negative dislocation model for the elastic block boundaries, Zhang Xi et al(2005) provided a qualitative analysis and quantitative description for the difference of motion and deformation between the tectonic blocks and their boundary faults，time-space distribution of tectonic strain field, and locations with highly accumulated strain energy and correlative intensity. Furthermore, taking the regional tectonics and block strain into full consideration, they investigate the common features of background precursors relating to location prediction for $M \geq 6$ earthquakes.

Huang Jianping et al. (2006）inversed of gravity and topography data for the crust thickness of china and its adjacency. In order to reduce the effect of regional non-isostasy they corrected the reference Moho depth in the inversion with regional topography relief, and performed multiple iterations to make the result more reliable. The obtained crust thickness of China and its adjacent was plotted on a map in cells of $1^\circ\times1^\circ$. Then they analyzed the correlation between the Bouguer gravity anomaly and fluctuation of the Moho depth. A good linear correlation is found, with a correlation coefficient of -0.993. Different correlation coefficients，0.96 and 0.91，are found for the data in land and ocean region，respectively. The correlation result also shows that the boundary between land and ocean is generally along the bathymetric line of -800 m. In order to examine the influence of the Earth's curvature on the calculated result，they tried two inversion models, the inversion for the whole region and the inversion for 4 sub-regions. The difference in the crust thickness deduced from the two models is less than 5 km. possible explanation for the difference is discussed. After comparing our result with that of other studies，they suggest that with their method the Bouguer gravity and the topography data can be independently inverted to obtain the crust thickness of China and its adjacency.

The exponential density models of crust are inverted from Bouguer gravity anomalies in central Tibetan Plateau，combined with Moho boundaries derived from seism in Yadong-Golmud GGT by Ke et al.(2004). The Moho depths of Qinghai-Tibet plateau are inversed from gravity data with exponential density model (Ke et al., 2004). The inversion results demonstrate that the Moho depths of Qinghai-Tibet plateau are shallow around the edges and deep at the center. The gradients at the edges are steeper than at the center. The variable density model is more suitable for inversion with Moho depths structures than constant density model by comparison of Moho depth from seismic inversion.

On the basis of geological data，the three-dimensional geometric model and the segmentation model of the spatial distribution of the Zhuanglanghe faults and the northern marginal fault of Maxianshan were established by Zhou et al.(2005) .With the constraints of slip rates of some studied thoroughly faults，the inferred GPS velocity from the project "Crustal Movement Observation Network of China" was simulated by using" Three-dimensional Deep-fault Dislocation Model", the current sliding rates of some other faults were calculated with the inversion method. Those inverted results are in accordance with the geological results. The GPS station velocities predicted by the model are consistent with the observed velocities as a whole. It is therefore assumed that these results are all in the reasonable extent predicted before. For the faults with relatively low slip rates and on which the conventional geological methods are difficult to apply，e.g. the Zhuanglanghe faults and the Maxianshan fault，the inversion based on the GPS observations is an effective ancillary means.

Zhang et al. (2006) inversed of 3-D slip velocity of Qilianshan Fault with GPS data. The results show that the velocity in dip of Qilianshan fault is larger than those in strike slip and tension and the distribution of velocities along the fault are uneven.

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PROGRESS OF GEODETIC DATA PROCESSING IN CHINA

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I. ROBUST ESTIMATION

Within the last four years the research of the robust estimation theory is mainly on the establishment and improvement of the equivalent weight function which is very important in robust estimation. The equivalent weight function is usually constructed based on the statistics of normal distribution. The critical values are often fixed by experience. Factually the statistics employed in the robust weight function can be replaced by other statistics, for example, the statistic of *t* distribution may be applied, which can reflect the measurement errors more reliable. The differences between the statistic of normal distribution and the *t* statistic are discussed. It is demonstrated that the results obtained from the equivalent weight function constructed by *t* distribution with its critical values determined by the significance level which has relations with observation errors, the design matrix and the number of redundant observations, are more efficient and robust than those resulted from the constant critical values (Yang and Wu, 2006). Furthermore, the common used equivalent weight functions are compared and their robustness properties are analyzed (Wu F, 2006).

The influences of inaccurate prior parameters and the measurement outliers are taken into account by using the robust M-M sequential adjustment (Wu S, 2006). A method of robust estimation that combines the linear programming and least squares estimation is researched, since the least squares (LS) estimation is sensitive to gross errors. At first the residuals of observations are given by linear programming which are used as the initial variables of equivalent weight. In this way the residuals reflect the error values more accurately, and the corresponding robust estimation results can be improved (Qiu, 2003).

The Bahadur-Type linear representation of the basic vectors including the observational vector, residual vector, estimated vector of the unknowns and the adjusted observational vector are derived based on the M-estimation. The asymptotic variance-covariance matrix of the basic vectors for statistical analysis is further derived and determined by the three nuisance parameters. For L_q-norm estimate, the three nuisance parameters and the corresponding variance covariance matrix are derived respectively based on the normally distribution. For the least squares estimate, residuals are respectively independent of the estimator of the unknown parameters and the adjusted observations, statistically. For L_q-norm estimate with errors being normally distributed, the covariance matrices between the residual vector and the estimated vector of the unknown parameters, as well as the adjusted observational vector are not zeros. However, if the errors are distributed in L_q-norm and the corresponding L_q-norm estimation method is also employed, the covariance matrices between the residual vector and the estimated vector of the unknown parameters, as well as the adjusted observational vector are zeros (Peng et al., 2004).

A new method of parameter estimation based on the possibility theory is studied which is called Maximum Possibility Estimation. At first the principle and the optimal criterion of maximum possibility estimation using *p* parabola as a consult function are given. The least absolute value sum estimation and least square estimation when p=1 and p=2 can be obtained respectively. Then the general method of determining weight is given (Wang and Shi, 2003). The parameter estimation of p-norm distribution is obtained based on the moment method of estimation. The moment method of estimation and the maximum likelihood adjustment are combined to calculate the parameter estimates. The new method is effective and the estimated values are nearer to their theoretical ones than those by the moment method or the maximum likelihood adjustment (Sun and Pan, 2003).

The applications of robust estimation have been paid much more attention than the theory. The robust estimation has been applied in the project of “2000’ National Gravity Control Network of China” (Guo et al., 2005). The robust estimation for correlated observations (RECO) has been applied in the projects of “2000’ National GPS Control Network of China” and other GPS network adjustment, for example, the combined adjustment for the first-order and second-order GPS networks of China. The numerical results demonstrate that the new RECO method can effectively control the influence of outliers to the parameter estimates (Zhao, 2004). In order to control the outlier effects of the observational outliers on the deformation analysis, the robust estimation method has been applied in strain parameter estimation, the corresponding error influence function is given. The strain estimates obtained from robust parameter estimation are effective and reliable (Sui and Xu, 2005). A robust spectral analysis method was put forward. It combines the robust estimation and spectral analysis, and the method was applied in the time series analysis of geocenter motion from the 5-year GPS data of about 120 IGS stations. The results showed that the geocenter motion had different principal periods in different directions (Guo et al., 2003). The robust collocation is applied in height fitting of GPS-leveling. The fitted heights are more stable and accurate (Yang and Zhang, 2005).

II. OUTLIER DETECTING AND RELIABILITY THEORY

Detection of gross errors has been a very active research field in geodesy. A multiple outlier detection method by using the partial correlation coefficients is proposed, and test statistics is composed by the compound correlation coefficients. By computing the correlation coefficient repeatedly, the outliers of multi-dimensional outliers can be located more accurately (Tao et al., 2004). The relationship between gross error detectable and identifiable ability and the correlation coefficients is discussed. It proves that, if the gross errors in the observations cannot be identified based on the judgment matrix, they cannot be identified by the correlation coefficients.

Furthermore, the gross errors detectable ability and identifiable ability analyzed by the judgment matrix are more convenient and simple than by the method based on correlation coefficient (Gu et al., 2005). An algorithm for searching, judging and determining multi-dimensional gross errors simultaneously in geodetic network based on the development of data snooping method is studied. It can simultaneously locate and evaluate the multi-dimensional gross errors (Zhang et al., 2003).

Two approaches to detect the gross errors are described. The first approach is that the gross errors are treated as parameters to be estimated, and the idea of “Quasi-Stable Adjustment” for solving rank deficient problem is adopted. The second approach is that part observations are selected as accurate observations, the principle of partial least-square estimation is used, and then the residuals of the other observations are treated as suspected gross errors. The results obtained by these two approaches are the same as “Quasi-accurate detection of gross errors” (QUAD), and the observation with gross error no longer affects the adjustment results (Liu et al., 2005). By applying the QUAD, a method for detecting and repairing the gross errors and cycle slips is researched by taking the differences of LEO-based GPS phase observations in different epochs as the observations. The characteristics of gross errors and cycle slips are analyzed with emulating LEO-based GPS phase observations (Kong et al., 2005). By applying the Boolean matrix and the judgment matrix, the maximum number of detectable gross errors and the maximum number of locatable gross errors in observations in a surveying system are formulated. The test indicates that the current methods of detecting gross errors, i.e. iterated data snooping and iterated weight methods, cannot wholly correctly locate the gross errors if the gross errors exist in the correlated observations (Cen et al., 2005). It is found that the gross errors provided by the L_1-norm estimation are almost completely projected onto the corresponding residuals, thus the gross errors can be correctly located by the L_1-norm estimation. According to the residuals and their variances, the Baarda test statistic based on the L_1-norm estimation is constructed, and the reliability is discussed. As compared with the reliability of the L_2-norm estimation, the reliability of the L_1-norm estimation is less affected by the variation of the redundancy component (Peng，2005).

The current techniques and theories for detecting gross errors are based on the mean shift model or based on the variance inflation model, which have their individual characteristics and are restricted to certain fields of application, since they do not consider nor make use of the potential prior information of the unknown parameters. A Bayesian approach for gross-error detection was put forward when prior information on the unknown parameters is available (Gui, Gong, Li and Li，2006). First, based on the basic principle of Bayesian statistical inference, the Bayesian method—posterior probability method for detection of gross errors is established. Secondly, taking surveying adjustment practice into account, the computational formula of posterior probability is given for mean shift model and variance inflation model respectively under the condition of unequal weight and independent observations. A modified Bayesian method for gross error detection is also proposed based on posterior probability of observation errors (Gui et al., 2007).

The outlier detection methods in Kalman filter (Song, 2006) and in semi parametric model (Ding and Tao, 2005) are researched. Measures of statistical diagnosis and gross error test for the semi parametric model are constructed.

III. ILL-CONDITIONING DIAGNOSTICS AND REGULARIZATION

1. Ill-Conditioning Diagnostics

A new method based on condition index and variance decomposition proportion (CIVDP) is proposed to diagnose the presence, number and composition of multicollinearities existing among the columns of the design matrix in Gauss-Markov model (Gui, Yao, Gu and Guo, 2006). Since ill-conditioning is concerned with the sensitivity (or insensitivity) of a given relation to perturbations in underlying data, a new diagnostic technique was developed based on the sensitivity analysis of the inverse matrix of the normal matrix (Guo and Gui, 2004). In surveying adjustment, how to find and appropriately deal with multicollinearity is a very important problem. A method named as influence ratio is proposed to detect multicollinearity influential observations based on the theory of matrix disturbance (Gui, Yao, Ma and Gu 2006). To mitigate the ill effects and obtain more accurate and stable solution of the model parameters, the so-called truncated singular-value decomposition method was introduced by modifying the small (nonzero) singular values of the coefficients matrix (Gui and Guo 2005). The proposed method directly disposes the ill-conditioning observation equations, which differs considerably from the traditional normal equation method.

2. Biased Estimation

It is well known that one of the major consequences of ill-conditioning of the normal equation on the LS estimation is that it produces large variances for the estimated unknown parameters in linear model, which in turn leads to highly unstable LS estimated solutions. To circumvent this problem, lots of biased estimations, such as ridge estimation (RE), principal components estimation, combining ridge and principal components estimation, and combining ridge and shrunken estimation etc., have been proposed and have been successfully applied in geodesy in recent years.

The condition of regularization solution is superior to LS solution on the basis of the MSE principle was deduced. A statistic for testing this condition is constructed. If the null hypothesis is accepted with a significance level, it indicates that regularization solution is superior to LS solution, which also verifies that the determined regularization matrix and regularization factor are reasonable. On the contrary, if the null hypothesis is rejected, it means that the regularization method is unreasonably used. Since the regularization matrix and regularization factor may be changed, we can modify their values until the null hypothesis is accepted. The derived condition and the proposed statistic are fit for all kinds of Tikhonov regularization methods (Xu and Yang, 2004).

The problem of selection and comparison between the biased estimators, e.g. the ordinary ridge estimator, the principal components estimator and the combining ridge and principal component and LS estimator in Gauss-Markov model was studied. Firstly, the conditions to show the superiority of each of the three biased estimators over the LS estimator are obtained by using the criterion of mean squared error. Then, the conditions are tested hypothetically by using the hypothesis testing approach or Monte Carlo simulation (Gui, Li and Ou, 2003; Gui, Han, Gong, Yao and Li, 2005).

The advantages and disadvantages between Tikhonov regularization and truncated singular value decomposition (TSVD) were discussed (Gu, Gui, Bian. and Guo, 2005). At first, with the singular value decomposition of coefficients matrix, the ordinary LS solution of linear equation is expressed by decomposition of pseudo-inverse of the matrix. Then, through the analysis of the parameters, the similarity and difference between the two methods are declared theoretically.

A new method, L-curve method to determine the ridge parameter is studied. Its basic theorem is locating the point of the L-curve where the curvature is maximum. First, according to Hansen’s theory, the formulae of locating the point with maximum curvature in L-curve is derived and the algorithm is realized. Then, the method to determine the ridge parameter is applied in surveying data processing. After that, the L-curve method with the ridge mark method and the general cross validation (GCV) method are compared (Wang and Ou, 2004).

When the multicollinearity and gross errors exist simultaneously, the biased estimators and robust estimators are all ineffective. In order to combat the influences of both outlier and multicollinearity on geodetic adjustments, two robust-biased estimation methods are proposed by combining outlier identification with biased estimation or by grafting robust estimation technique into philosophy generalized shrunken estimation (Gui, Li and Ou, 2005a; Gui, Li and Ou, 2005b; Gong et al, 2006). From a new point of view to solve this coexistent problem, a method called outlier detection based on ridge estimation, which combines the advantages of the ordinary ridge estimation and outlier detection was studied. At first, it regards the ordinary ridge estimation as LS estimation with pseudo-observations. Then, the outlier and the corresponding statistic in the meaning of the ordinary ridge estimation are discussed in detail by using the LS outlier detection technique. Numerical examples illustrate that the new method can not only overcome the ill-conditioning effectively, but also detect the outlier successfully (Li et al., 2006).

A robust Tikhonov regularization method is developed. The only difference between the robust regularization estimator and the classical one is that the original weight matrix of observations is substituted by the equivalent weight matrix. The influence function of the new robust regularization estimator shows that it can efficiently control the influence of the outliers (Xu and

Yang, 2004). The solution expressions of several kinds of adjustment methods were unified in form based on the analysis and comparison of several mathematical models in surveying adjustment. The unified formula of these solutions could be derived based on the principle of Tikhonov regularization. Due to the inspiration of quasi-stable adjustment, the new idea is put forward to solve ill-posed problems, that is named "fitting method by selection of the parameter weights" (Ou, 2004).

3. Applications of Biased Estimation and Regularization

The applications of biased estimation or regularization mainly appear in the GPS data processing and satellite gravimetry data reduction. It is noted that, when only using several-epoch single frequency carrier-phase data for GPS rapid positioning of a short baseline based on the common DD (double difference) model, there exist severe multicollinearities among the columns of the design matrix in the DD model. They not only reduce the precision of the float solution, but also have a bad influence on the search efficiency of the integer ambiguities and the accuracy of the fixed solution. Two algorithms of GPS rapid positioning are proposed, namely the partial ridge estimator (PRE) (Gui and Guo, 2004) and the double-*k*-type ridge estimator (DKRE) based on the structure characteristics of the multicollinearities of the normal equation matrix in the DD model (Gui, Han, Wu, Gu and Wei, 2006). The LAMBDA method is improved by using the cofactor matrix computed by the PRE or DKRE replacing that computed by the least squares estimation (LSE). Another regularization method is studied for the rapid positioning using single frequency GPS receivers. First, an appropriate regularizer is chosen to weaken the ill-condition of the normal equation based on Tikhonov regularization method, according to the characteristics of the normal equation formed by DD phase observations of single frequency GPS receivers. The float ambiguity solutions calculated by the new approach are much closer to the correct integer ambiguities than those calculated by LSE, and the corresponding mean square error matrix (MSEM) is obtained. Then, combined with LAMBDA method, the new approach can fix the integer ambiguities correctly and quickly using MSEM instead of the covariance matrix. The comparisons are made between the new approach and LSE, RE and TSVM combined with LAMBDA method in fixing the integer ambiguities, respectively (Wang Z et al., 2005).

The application of GPS is often needed to transform coordinates, which often leads ill-posed problem, because the translation parameters and rotation parameters are high correlated, if the transformation parameters are solved with the GPS data in a small area. In this case the precision of transformation parameters may be very poor, and regularization solution is an efficient method in dealing with ill-posed model, which can improve the precision and extend the application range of the solved transformation parameters (Shen et al., 2006). The model and algorithm are verified with 500 numerical simulated examples; and the results show that the precision of the transformed coordinates in peripheral area can be significantly improved by regularization; and will linearly decrease as the extension of extrapolating distance.

A mathematic model for merging surface and airborne data based on regularization method is given. In spectral domain the reasons causing instability of downward continued results are analyzed and a computation method of regularization is successfully applied. (Wang X et al., 2004).

IV. SEMIPARAMETRIC REGRESSION AND NONLINEAR ESTIMATIONS

1. Semi-parametric Regression

The semi-parametric regression and its applications are still got some attention in geodesy. Under the principle of penalized least squares with a positive definite regular matrix, the method for getting the values of the unknown parameters of the semi-parametric model was researched. Based on the statistic characteristic of random errors, the mathematical expectation, variance and mean square error of the parameter estimator getting from this method are discussed in detail. The difference between the parameter estimates obtained by semi-parametric models and by general least squares are compared. It is shown clearly that the method of semi-parametric adjustment is better than that of least squares if the smoothing parameter takes a suitable value. The choice for the reasonable value of the smoothing parameter and its influence on the precision of the mathematic model are described (Sun and Pan, 2004). The systematic errors contained in observations are always complicated and they are varying with some variables. They can be expressed by using natural cubic spline, which is nonparametric component in semi-parametric regression model, thus the semi-parametric regression model and the penalized least squares technique can be applied which can more effectively separate systematic errors from observations compared with the parametric model and the least squares technique (Wu Y et al., 2004). The same problem is also studied by (Ding and Tao, 2004). According to penalized least squares, the penalized item is formed by using cubic natural spline. The choice of smoothing parameter can be automatically obtained by using generalized cross-validation function.

There are two crucial steps in resolving semi-parametric model. One is to choose the regularizer, and the other is to determine the smoothing parameter. A new method for determining smoothing parameter, L-curve method, is investigated. On the basis of analyzing the basic theorem of L-curve, semi-parametric model is solved and applied in the mitigation of systematic errors. Furthermore, the L-curve with different methods to resolve the semi-parametric model are compared (Wang Z et al., 2004). According to the kernel estimation theory of nonlinear semi-parametric model under the least squares principle, the structural formulae of the estimation of parametric nonparametric components and the direct formulae of kernel estimation considering the second order items were given, which can be applied in least squares kernel estimation of nonlinear semi-parametric models (Zhang and Zhang, 2006).

2. Nonlinear Estimation

A new fast different iterative solution model is proposed to apply in geodetic adjustment by least squares method with multi-type, multi-precision, multi-source dynamic and nonlinear data, which can avoid computing derivatives completely and reduce calculation of Jacobian matrix, at the same time, a matrix sequence, which can approximately substitute for second-order partial derivative matrix by recurrence method, is constituted to make the rate of convergence of the algorithm model faster. This creates a new solution to solve the generalized nonlinear least squares parameter adjustments (Ning et al., 2005). By using the difference to replace the derivative, the likelihood function in the nonlinear model is transformed into the product of the model space likelihood function and the orthogonal complement likelihood function. By using the orthogonal complement likelihood function, the general, rigorous and simplified estimator of variance and covariance components is derived. The common used iteration formulae for estimating the variance and covariance components can be obtained as the special cases of the above formulae (Wang and Zhu, 2005). On the basis of the superiority of genetic algorithms, the nonlinear least squares estimation can be used to overcome the disadvantage of classical least squares. The 6 essential factors related to genetic algorithms and its precision evaluation of the nonlinear estimation have been studied (Wang S, 2006).

After analyzing the two common linearization methods, a new linearization method for the nonlinear Kalman filter system is proposed. The error of linearization is similar to extended Kalman filter. Furthermore, the linear observation equation is the same as that in the least squares method. Thus the comparison between Kalman filter and least squares adjustment can be done during the data processing, which is helpful to the precision analysis and quality control of the positioning. Especially the linear filter equations for GPS positioning are listed (Sun and Li, 2004). It has been realized that there are a lot of constraints in application of the extended Kalman filter (EKF) for solving the nonlinear systems, for its hard implementation and intractability. A new estimation method is proposed, which takes the advantage of the Unscented Transformation method thus approximating the true mean and variance more accurately. The new method can be applied to nonlinear systems without the linearization process which is necessary for the EKF, and it does not require the assumption that the errors follow Gaussian distribution. Furthermore, the implementation is easier and estimates are more accurate, which makes the method easy to be applied in numerical experiments of satellite orbit simulation (Cai and Zhao, 2006).

V. OTHER RESEARCH ACHIEVEMENTS IN GEODETIC DATA PROCESSING

A super nationwide geodetic network adjustment project was finished in China in 2003. Aiming at the difficulties of solving the adjustment problem for super large-scale geodetic network, a new fast method for solving partitioned adjustment, on the basis of Cholesky decomposition principle was proposed. The large-scale geodetic network is partitioned into several sub-networks, the corresponding error equations are decomposed into sub-equations and connected equations, and then the reduction processes of inversing normal matrices are replaced by soling reduction processes. The coefficients of the connection error equations are avoided. Thus the computation time of the adjustment process for the large-scale geodetic network is tremendously reduced. By using a personal computer, Pentium IV, an integrated three-dimensional adjustment of the nationwide geodetic network with about 50 thousand stations and 180 thousand unknown parameters has been successfully carried out within about 3 hours (Song and OuYang, 2003). Furthermore, the non-zero structure decomposition of symmetric matrices for solving large-scale normal equation and error equation is introduced. The seats and numbers of non-zero elements of triangular matrix are then determined, so that the store places are distributed in advance, and the numerical solution can be calculated on the seats of non-zero elements (Liu et al., 2005). In the synthetic geodetic network of distance and angle measurements, the height anomaly correction is needed. A formula for average height anomaly correcting in measurement area calculated from residuals of distances was derived, and iterative calculating method was proposed. This method is simple and practical in computation that does not need the support of astronomy, gravity or space measurements. It improves the accuracy of the positions by the adjustment of geodetic networks (Song and Liu, 2005). The combined adjustment project of the national astronomical geodetic network and the 2000 national GPS network was accomplished (Yang et al., 2005).

In the GPS data processing, a least squares (LS) collocation method has been applied in GPS network adjustment. The formulae of parameter estimation and precision estimation based on LS collocation are provided. The influences of prior coordinate constraints and prior precision constraints have been studied. A general principle on the choice of prior constraints in adjustment is discussed (Yao and Tao, 2003). Some tactics for choosing the IGS stations in the GPS data processing was discussed from three aspects of geometrical significance, the statistical significance and the physical significance (Sui and Xu, 2003). On the basic adjustment model of GPS control network, the effect of GPS correlation between baselines on the adjustment result has been analyzed theoretically and the formulae have been derived (Ding et al., 2006).

There exist inevitably model errors in the functional models of adjustment due to the various systematic errors, which affect the quality of adjustment results in some extent. In the data processing, the functional model errors have to be compensated or controlled. The optimum seeking criteria of the adjusted functional model errors is given. Then the criteria for judging the functional model errors and the practical estimation schemes are provided. Furthermore, the formulae for evaluating the standard deviation of the functional models are given (Tao, 2003). The influences and mitigation between stochastic model errors and functional model errors are discussed (Zhang and Tao, 2005).

On the basis of Helmert variance component estimation formula, a sequential algorithm for joint adjustment of various observations is put forward (Zhang, Tao and Shi, 2005). This method avoids using a lot of memory and complicated matrix calculating.

A new method for centralized modeling for time series is proposed (Pan, 2005). Dynamic model and static model are compared based on AR model. It is shown that the forecast precision by the new method is high and static model is suitable for interposition.

An immune algorithm is overviewed, and the main principium and the characteristics of immune algorithm based on clone selection principle were discussed. The applications of immune algorithm in geodetic data processing were analyzed (Wang and Xu, 2006). The principle of information diffusion and information diffusion estimation (IDE) was introduced (You and Wang, 2003). The observation distribution can be estimated easily with IDE. Once the observation distribution is determined, the parameters can be estimated with the maximum likelihood. The diffusion maximum likelihood (DML) estimation is studied which is free from any supposition of observation distribution.

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ACHIEVEMENTS OF THEORIES AND METHODES RELATED TO GPS DATA PROCESSING IN CHINA

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I. GPS DATA PREPROCESSING

Data preprocessing is very important in GPS positioning, and it mainly involves cycle-slip detection and repairing, multipath elimination and clock error correction etc.

Since the character of the cycle-slip is similar to that of gross error, the method for detecting gross errors, such as the QUasi-Accurate Detection (QUAD) method, can be extended to detect the static and kinematic cycle-slips [2,8]. The idea of this method is that the statistical indices of the normal observations, named Quai-Accurate Observations (QAOs), are selected as standards and the estimators of the real errors are calculated under the condition that the norm of the QAOs is minimal. The cycle-slips may be judged according to the "hive off" phenomena of the estimators of the real errors. The key of the method is how to select the QAOs, and a preliminary selection and fine selection scheme for selecting the QAOs has been established. The virtue of the QUAD is that multiple gross errors can be detected simultaneously. Xiong et al put forwards a wavelet-based cycle-slips detection method. In this method, GPS phase observations are decomposed using the wavelet firstly, and then the cycle-slips can be detected according to the character of high frequency cycle-slips being enlarged [33].

It is sometimes very difficult to eliminate the multipath errors. To cope with this issue, a moving average method to reduce multipath effect on coordinate domain of the short static baseline is put forwards [37].

II. GPS SYSTEMATICAL ERRORS PROCESING

Recently, non-parametric and semi-parametric models have been employed to mitigate the systematic errors effects in high-precision GPS positioning. By adding stochastic constraints on the unknowns whose a priori information are understood accurately named "Quasi-Accurate Parameters", the selected group fitting method is used to separate the systematic errors in GPS observations. The key of the method is how to select the Quasi-Accurate parameters, and a circular selection method is designed [17]. To estimate real time systematic errors for medium-long baselines in network RTK, a three-step method is proposed based on the selected weight fitting method. Research results indicate that the precision of coordinate estimators of baselines varying from 10km to 1000km is the order of centimeter or decimeter after the systematic errors are removed [15]. Based on partial continuation model with exact finite measurements and a windowing technique, a new procedure is presented to mitigate the impact of systematic errors on DD GPS measurements [7]. A semi-parameter smoothing method by adding non-parameter item to absorb dynamic model error is proposed, where both the precision and the reliability of POD of LEO can be ensured [14].

III. DATA PROCESSING IN RAPID GPS POSITIONING

The key issue of rapid GPS positioning is OTF ambiguity resolution. The difficulty is that the float ambiguities and their covariance matrix are inaccurate because the normal equation of phase observations in this case is seriously ill-conditioned or rank-deficiency, namely ill-posed, which usually result in unreasonable ambiguities resolution. To obtain a more reasonable solution related to the ill-pose problem, a unified formula of the parameter resolutions based on the principle of Tikhonov regularization and the fitting method by selection of the parameter weights is presented by referencing the idea of Quasi-Stable adjustment. The new method emphasizes that if the a priori information of some parameters is known accurately, the ill-posed problem can be solved by adding a realistic weight matrix or a restricted condition about these unknown parameters [16]. In this way, the added constraint has the specific physics meaning. For instance, if the coordinate component is comparatively accurate in rapid GPS positioning, the float ambiguities and their covariance matrix may be greatly improved by adding the restricted condition about the coordinate component, thus the success rate is increased [12-13,19,27,34].

Based on the return calculating sequential conditional least squares technique and the upper triangular Cholesky decomposition algorithm, the return calculating LAMBDA approach to resolve GPS carrier phase integer ambiguity is proposed. It has a different objective function and a different search space from LAMBDA approach [56]. Based on the Bancroft numerical algorithm, a closed form extended kalman filtering method for the nonlinear algebraic solution is presented by separating the spatial parameters from temporal parameters of GPS dynamic positioning [52].

IV. ADAPTIVE KALMAN FILTERING

The reliability of the kalman filtering is based on the accuracy of the state model and the observation model. Some adaptive kalman filtering methods based on the quality control theory are therefore developed. For examples, YANG et al puts forward the synthetically adaptive robust filtering for controlling the effects of both abnormal GPS observations and abnormal dynamic models on the parameter estimators in determining precise orbit of a low orbit satellite. The implementation of the method is divided into two cases: the orbital parameters are estimated using the sage filtering when the low orbit satellite has no maneuver, otherwise, using the robust adaptive filtering [35]. An adaptive kalman filtering by selection of the parameter weights is put forward by OU [18,22]. According to the observations and a priori information about the state parameters, the state parameters are divided into two kinds: normal and abnormal. The equivalent weight factor is zero for the abnormal state parameter or one for the normal state parameter, and then the equivalent weight matrix is constructed by combining with the predicted weight matrix. The reasonable result can be resolved using the original kalman filtering program as long as the equivalent weight matrix replaces the original weight matrix. An adaptive kalman filtering is also proposed for controlling the abnormal observations and abnormal states simultaneously. At first, the gross errors of observations are detected with the QUAD method and removed, and then the covariance matrix of the state parameters is determined adaptively using the sage filtering [2]. YANG et al. proposed an adaptive kalman filtering for eliminating the systematic errors in the observational and kinematics models by using the residuals of both observations and predicted states within a chosen time window [36]. The square root information filtering and smoothing on orbit determination of LEO satellites using onboard GPS data is studied [55].

V. REPAIRING, MONITORING AND INVERSING ON IONOSPHERIC DELAY BASED ON GPS

In order to improve the precise and reliability for extracting ionospheric delay from dual-frequency data, a static scheme on calibration of instrumental bias in GPS observation has been proposed by Yuan, which can be utilized to eliminated the systematic error of the satellite and receiver biases [39, 46-47]. Taking into local characteristics of ionosphere account, a method of constructing large range (regional and global) high accuracy grid ionospheric model, namely the Different Area for Different Stations (DADS), is put forward [42]. The DADS method can improve the estimation precise of the large range and high precision ionospheric model, and it has been applied to establish a real time grid ionospheric correction model of China [38, 43,46]. A method of correcting ionospheric delays for the ground-based single frequency GPS users under typical adverse conditions, called the Absolute Plus Relative scheme (APR-I), is investigated [40]. The APR-I scheme has relatively better correction effectiveness for WAAS's users under different abnormal conditions. Other regional ionospheric models in China are also discussed with different GPS observations and methods, and the related precision is analyzed [1,10,25,53]. By establishing the ionospheric eclipse factor (IEF) of the ionospheric pierce point (IPP) and its ionospheric influence factor (IFF), a new method of modeling high-precision ionospheric delay using GPS data, named ionospheric eclipse factor method (IEFM), is discussed in detail[45]. The IEFM can effectively select the proper ionospheric models to model the total electron content (TEC) with different changes corresponding to annual, seasonal and diurnal variations [54], and can improve the correction precision of ionospheric delay which seems to be close to that of using L3 GPS observation to directly correct the corresponding ionospheric delay [46].

A generalized ionospheric model based on a set of trigonometric series functions is developed, and the generalized trigonometric series functions (GTSF) method not only can fit diurnal variation properties of normal ionosphere very well but also has good monitoring ability to ionosphere [44].

A new theory of monitoring random signal and its application for monitoring random ionospheric disturbance using GPS, the Auto-Covariance Estimation of Variable Samples (ACEVS), is presented, and the ACEVS-based framework scheme can be applied to monitoring ionospheric random variations using a static or kinematic dual frequency GPS receiver [41]. The ionospheric evolution and disturbance are investigated using GPS observation [11,50-51,58]. The high-order ionospheric delay correction on GPS modernization is studied [32].

The two-dimensional ionospheric models based on single-layer concept are inherently insufficient for investigating the vertical structure of the ionosphere. For resolving this limitation, a GNSS-based platform for imaging the three-dimension structure of the ionosphere is developed at the institute of geodesy and geophysics. The platform uses a voxel-based function to discretize the ionospheric region in order to assimilate different types of data associated with ever increasing number of GNSS and low-orbit earth observation satellites, and then a set of new methods are adopted to solve the ill-posed problem in ionospheric tomography system [28-31,48].

VI. DATA FUSION OF GPS WITH OTHER TECHNIQUES (SUCH AS INS, DR)

Data fusion of GPS with other techniques is studied widely in recent years. This involves the airborne gravity determination and MMS using GPS/INS, the navigation and azimuth determination with GPS/DR etc. One of difficult problems in data fusion of GPS/INS is that the noise of the INS is very big when dynamics model of the vehicle is complex. In this aspect, GUO et al apply the Butterworth low-pass filter to inertial navigation system (INS) original data processing [6]. The Extended Interval Kalman filtering (EIKF) is established for the nonlinear integration system according to the interval character of the time correlation constant in modeling the INS error [9]. SUN et al present an integrated method to perform data fusion of GPS double difference carrier phase and Doppler/ INS after single epoch GPS ambiguities are resolved [24]. In integrated GPS/DR, because the precision of DR is very low usually, the position errors accumulate more quickly than the velocity errors. In view of this, CHAI et al put forwards a data fusion method in which the weight matrix of the position errors is different from that of the velocity errors [3].

VII. OUTLINE OF NEW METHODS FOR GEODESIC DATA PROCESSING

In the last several years, some new adjustment methods have been developed for geodetic data processing. For the inequality-constrained least squares (ICLS), Peng et al proposed that the aggregate constraint method of non-linear programming by converting many inequality constraints into one equality constraint [21]. Zhu et al put forward a method that the ICLS can be solved using Bayesian estimation by converting linear inequality constraints into aprior information on the parameters with a uniform distribution, and applied it to GPS positioning [57]. The L_1-Baarda test statistic constructed from the residual and its variance based on the L_1-norm estimation is investigated, and its reliability is discussed [20]. Zhang et al studied the stochastic model of multi-difference GPS carrier-phase data [49]. Wang et al introduce the immune algorithm into geodetic data processing [26]. A method for calculating transformation parameters by way of integrating GPS data observed in different periods is presented [23]. For the case that ill-conditioned issues and outliers exist simultaneously, Gui et al proposed a new robust-biased estimation by combining the QUAD method with Bayesian estimation [5].

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STUDY ON SATELLITE ALTIMETRY AND ITS APPLICATIONS

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I. INTRODUCTION

Satellite altimetry is further studied and widely used in China during the last 4 years because of its high precision and resolution. New technology was developed by Chinese geodesists to process multi-satellite altimetry data for sea surface height with higher precision and accuracy than before. Refined methods were investigated to estimate gravity anomaly from sea surface observation, and combined with geophysical data and gravity field model, the results of satellite altimetry were employed in the inversion of ocean geological and geophysical characteristics and the research of geodynamics. Combined with in-situ observation and satellite gravity observation, satellite altimetry was used to refine geoid model and investigate the mode of ocean flow and ocean circulation. In order to improve the result, new technology was developed for the waveform retracking of satellite altimetry, which extended the ocean of altimetry into inland waters and desert surface.

II. DATA PROCESSING OF SATELLITE ALTIMETRY

Multi-satellite altimetry data were processed in China for more observations and waveform retracking was implemented to improve the accuracy.

China got the altimetry data of multi-satellites by international cooperation such as Geosat, ERS-1, ERS-2, T/P, EnviSat, and Jason-1. These data are in different levels, such as Geosat, which include GDR data, WDR data and SDR data. The transformation of reference ellipsoids and reference frame was studied for the combination of the multi-satellite data. Chinese Academy of Surveying and Mapping combined the Geosat, ERS-1 and T/P data to compute the mean sea level height over Chinese near coastal sea (Hu et al., 2004). Chinese Academy of Surveying and Mapping analyzed the empirical orthogonal functions of the sea level anomaly time series derived from ERS-2 and TOPEX altimeter data (Wen and Zhang, 2006).

The main achievement in altimetry data processing in China lies the waveform retracking. Waveform retracking was first used in the coastal sea surface measurement. In the last several years, this technique was extended to the measurement of inland lakes and rivers, and even to the desert surface measurement. Different algorithms were developed by Chinese geodesists according to the characteristics of waveforms. And these algorithms yielded good results. To solve the problems of low precision over coastal sea, Wuhan University investigated the waveform retracking in open sea with SGDR waveform data of ENVISAT (Chu et al., 2005). Wuhan Institute of Geodesy and Geophysics offered a group of concrete formula to reset wave combined with T/P waveform data (Bao et al., 2004).

Chinese academy of Surveying and Mapping, Wuhan University and Xuzhou Normal University developed their own algorithms to retrack the altimetry waveform (Chang et al, 2006). Based on the existing waveform retracking algorithms, coastal waveforms are studied by Chang and Li and a multi-threshold multi-leading-edge waveform retracking algorithm is developed based on the waveform leading edge recognition. This algorithm detects the possible waveform leading edges, and creates several sub-waveforms according to the detected waveform leading edges. Then distinguishes the real waveform leading edge according to the external sea surface reference, and calculates the distance corrections corresponding to the tracking gate. Finally, they transform the retracked sea surface heights into gravity anomaly to compare with shipborn gravity for the validation of the retracker. As an example in the East China Sea, they retracked the waveform of Phase E and Phase F mission of ERS-1 satellite and Geosat waveform, and computed the gravity anomaly according to the retracked sea surface heights by the least square collocation method. Compared with the shipborne gravity anomalies, their result has higher precision, success rate, and less standard bias than other retracking methods.

In addition, some on-going projects on land waveform retracking are implementing in Chinese Academy of Surveying and Mapping cooperating with Taiwan Chaotong University and China University of Geology. Wuhan University is in efforts for waveform retracking in Antarctic.

III. ALTIMETRY GRAVITY ANOMALY RECOVERY

The main algorithms of altimetry gravity recovery, including the least square collocation method and inverse Vening-Meinesz formula method, were investigated and analyzed in the past 4 years in China. Tianjin Institute of Hydrographic Surveying and Charting used new method to resolve local and global crossover adjustment problems in the integrated altimetry data processing, and then used inverse Vening-Meinesz formula method developed by Hwang C at Taiwan Chaotong University to compute the gravity anomaly (Huang et al., 2006).

Chinese Academy of Surveying and Mapping and Wuhan University designed appropriate formula to compute the deflection of the vertical, and remove/restore procedure is employed in the computation of gravity anomaly (Chang et al., 2005). For the least square collocation method, they focused on the methods of how to compute the covariance function. For the inverse Vening Meinesz formula method, a formula to estimate the square innermost zone effects in the FFT algorithm is deduced to improve the accuracy of altimetry gravity recovery. The result shows that the innermost zone effects are related to the gradient of the vertical and the area of the innermost zone, while the vertical itself has no influence on the innermost zone effects. According to the real computation example, the innermost zone effects could be up to level of hundred μGal, which should not be neglected in high accuracy gravity recovery. As an application and verification, they also use the least square collocation method to recover the gravity and compare the result with that of the inverse Vening-Meinesz formula method and the shipborne gravity.

In addition, Wuhan Institute of geodesy and Geophysics and Information Engineering University studied the problem of satellite altimetry gravity through finite approximation, and designed a new solution for the problem (Yu et al., 2005). According to their study, the solution of the problem of satellite altimetry gravity can be transformed into a linear system of equations with variants of the coefficients of spherical harmonic series. And the linear system of equations is separated with the orders and degrees of spherical harmonic series.

IV. ALTIMETRY APPLICATIONS TO OCEANOGRAPHY, GEOPHYSICS AND GEODYNAMICS

Satellite altimetry is an important technical method to obtain high resolution high accuracy sea surface height and ocean gravity anomaly, which opens up a broad prospect for oceanography, geophysics, and geodynamics.

In the application to oceanography, Dalian Naval Academy processed T/P altimetry data for the inversion of tidal parameters (Xu et al., 2006). According to their study, seasonal sea level change from satellite altimetry is mainly from the error of the tide model. Wuhan University calculated the mean sea surface topographic model using T/P data, and based on the SST model of EGM96, CSR and Levitus they analyze the mean ocean circulation mode (Wang et al., 2004). Peking University extracted the information of the global SSHA rising and annual and semiannual fluctuations of the SSHA variations by wavelet technique from 10 years T/P data (Fu et al., 2006). And the SSHA fluctuations of each ocean are analyzed. Wuhan Institute of Geodesy and Geophysics used high precision gridded sea surface height anomaly data based on more than ten years multi-satellite altimetry observations, associated with EGM96 sationary sea surface topography model, to derive time varying sea surface topography in the South China sea, and calculated the upper level circulation fields at different times (Bao et al., 2005). According to their study, the upper level circulation can reveal some meso-scale characteristics of circulations and eddies over South China Sea. Chinese Academy of Surveying and Mapping separated the precise mean dynamic ocean topography from altimeter-derived mean sea surface from T/P, Jason-1 altimetry data and GRACE geoid model and WHU-GM-05 gravity model model (Wang et al., 2006). In addition, Chinese Academy of Surveying and Mapping studied the tsunami wave heights by T/P altimetry observation (Wen and Zhang, 2005).

In the application to geophysics and geodynamics, Chinese academy and Wuhan University build the full resolution gravity anomaly spectrum, part of which under degree 360 are form the spherical harmonic coefficients of the gravity field model, and 360 degree above is from the satellite altimetry.

In the study, they analyzed the relationship between the gravity anomaly and its correction items and computed the degree components of the gravity anomaly, and then discussed the possibility of replacing gravity anomaly corrections with spectral components of the gravity anomaly. On this base, the lower mantle, upper mantle, and crust components of the full resolution gravity anomaly spectrum were analyzed, and the geodynamics background and mechanism in the ocean areas of east China were studied. According to their study, gravity anomaly of different degree in the ocean areas of east China is mainly due to mass distribution of different depth, and the dynamical imbalance from the geopotential imbalance is the source of the global dynamics activities, which changes the lithosphere structure through mantle circulation.

V. SUMMARY

As a method to measure the sea surface height, satellite altimetry is more and more widely used in each field of ocean development and research, and extend its measurement to the land surface and further applications. Satellite altimetry has higher resolution in the gravity anomaly recovery than satellite gravity.

During the last 4 years from 2003 to 2007, geodesists in China made rapid progress in the study on satellite altimetry. Their works focus on the technology to improve the accuracy and precision of the satellite altimetry and its applications to many fields of geo-science. They obtained much denser sea surface observations by multi-satellite data processing, and extended their study area of satellite altimetry from deep open ocean to the coastal sea, inland waters, and even the desert surface by waveform retracking. The study and application of satellite altimetry in China is not only to the sea surface height and geoid model, gravity anomaly and oceanography, but also to the geophysics and geodynamics by inversion of gravity anomaly.

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REGIONAL QUASI-GEOID DETERMINATION IN CHINA

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Abstract. This paper introduced the technique method and design principia of quasi-geoid project in China by the State Bureau of Surveying and Mapping with the cooperation with local surveying bureau from 2003 to 2006. The gravity measurements, GPS/Leveling data, digital elevation model (DEM), and the Earth's geopotential models were employed in the computation. Some techniques used in this project, such as the design of GPS/Leveling network, the accuracy requirements for the GPS measurements and optical leveling, etc. are discussed in this paper. The methods for incorporating gravimetric quasi-geoid and GPS/Leveling derived quasi-geoid are also described. The resolution and accuracy of the quasi-geoid in China are estimated and the potential applications of the quasi-geoid are discussed.

I. INTRODUCTION

At the present time, the cm level quasi-geoid is very requirement on the topographic map surveying in the city and the economy developing area of the China. Height surveying of the tradition mode is changed recently because the normal height could get from the cm level quasi-geoid integrates form geodetic height by GPS survey, which could satisfy the urgently demand of various mapping in different scales ranging from 1:10,000 to 1:5,000 or even larger, speeding the construction of "digital city", "digital province" and "digital China". The cost cut by GPS surveying is very significant; however, it is the efficiency that attracts the coastal area of China (Guangdong province, Dalian, Hangzhou, Chengdu, Qingdao and Dongguan city) with economy growing rapidly. Driven by the economy growth, the need for high-precision quasi-geoid increases. The techniques used by the State Bureau of Surveying and Mapping (SBSM) of China for the regional quasi-geoid improvement campaign had been proposed out in the unification datum and specification to step the ZheMinGan (Zhejiang, Fujian and Jiangxi province)local area quasi-geoid determination from 2003-2004, and the North China area(Beijing, Tianjing city, Hebei and Shanxi province) quasi-geoid determination from 2004-2005, and the East and Middle China area (Shanghai city, Jiangsu, Henan, Anhui, Hunan, Hubei, Shanxi and Shandong province) quasi-geoid determination from 2005-2006 by the cooperation with the local Surveying Bureau. The above quasi-geoid area is below the 15 provinces and cities together with an area of 1,900,000 square km, covering 19.8% of Chinese territory.

II. LOCAL QUASI-GEOID DETERMINATION

The technique used at the above area is firstly remove-restore method to get the regional gravimetric quasi-geoid according the Molodensky's formula using the gravity and DEM data and high degree geopotential model. Then using the high order leveling observation on the GPS bench mark to make the GPS/level net to get the height anomaly net is used to computation the GPS/level quasi-geoid. The final quasi-geoid would be got by fitting the two quasi-geoids into one curve surface using the least square adjustment method.

1. Gravimetric Quasi-geoid Computation

The gravimetric geoid or quasi-geoid is estimated using Stokes'/Molodensky's formula with gravity anomalies. Before applying Stokes' formula, the gravity anomaly must be reduced by the remove step of the remove-restore technique.

1) First Remove-restore

The first remove-restore is to compute the averaged free-air gravity anomalies in grids. The procedures are illustrated as follows:

In order to represent the quasi-geoid variations in terms of grid values, it is required to correct the discrete surface gravity measurements. The DEM data is utilized in the computation of the free-air, plate, topographic and isostatic corrections. These results in highly smoothed isostatic topographic gravity anomalies, which are further predicted or interpolated to form the base grids of the averaged isostatic topographic gravity anomalies.

The restore process is to recover the average free-air gravity anomalies in the grids, which is carried out by utilizing the high resolution DEM through reversed-correction procedures. That is, to subtract the plate correction, the topographic correction and the isostatic correction from the averaged isostatic topographic gravity anomalies that is obtained in the remove process.

2) Second Remove-restore

The second remove-restore procedure is to compute the height anomalies and thus the quasi-geoid. Firstly, the averaged free-air model gravity anomalies are computed through the geopotential coefficients from WDM94 or EGM96. The WDM94, a geopotential model complete to degree and order 360, was derived by combining global (including the area of China) 30′×30′ mean free-air gravity anomalies and the GEM-T2 Earth's geopotential model[1]. The results in the model gravity anomalies have the same resolution with the base grids. Removing the model gravity anomalies from the surface gravity anomalies gets the residual gravity anomalies that are carried out by applying the local topographic corrections.

Applying the Molodensky integral with the residual Faye gravity anomalies delivers the residual gravimetric height anomalies using the Fast Fourier Transform (FFT) technique in the computation. The height anomaly from geopotential model is then added back to the residual height anomalies to get the gravimetric quasi-geoid.

2. Quasi-geoid from GPS/Leveling

If a benchmark is observed using GPS, the height anomaly at this point can be derived from the normal height H_n and the geodetic height H_g. The normal height H_n could be directly measured by leveling. The difference between normal height and geodetic height is the height anomaly, whose accuracy is corresponds with the accuracy of GPS and leveling observation. As the accuracy of the geodetic height by GPS observation could get the cm level, the accuracy of the deduced height anomaly is about cm level too. It can be seen that the height anomaly and consequently the quasi-geoid may be determined from enough GPS and leveling measurements in some area.

3. The Fits Gravimetric Quasi-geoid and GPS/Leveling Derived Quasi-geoid

Thus far, we have two quasi-geoid estimations. One is from the surface gravity measurements with the aid of high resolution DEM data, which is based on Molodensky's theory for determination of height anomalies. Another quasi-geoid is derived from the GPS survey on level benchmarks. It is required to fit these two quasi-geoids with one surface. The surface fitting is carried out by using the least squares adjustment. The high resolution of the gravimetric quasi-geoid and the high accuracy of the GPS/leveling derived quasi-geoid are combined to provide a quasi-geoid with high accuracy and high resolution[2].

III. NETWORK DESIGN AND ACCURACY REQUIREMENTS

The refinement of local quasi-geoid is as important as the national height control network, and therefore the following factors should be carefully considered to design the GPS/Leveling network[3].

1. Geodetic Datum Update

Geocentric coordinate systems have been adopted in more and more countries for their geodetic coordinate systems. The Chinese geodetic datum has been developing to cope with the technology advancement. It is also considered in China to use geocentric coordinate system. The 1980 Xi'an geodetic coordinate system has been used for many years in China. The joint adjustment between astro-geodetic network and the "GPS2000 geodetic control network" was completed in 2004, which provides the geocentric coordinates of stations in astro-geodetic network. The adjusted results will play a key role in the adoption of geocentric coordinate system in China. Up to now, there are fewer points in the GPS2000 geodetic control network compared to that in astro-geodetic network. SBSM is now trying to update the geodetic datum in China. It is designed that the GPS measurements obtained during this project may also be used in the establishment of geocentric coordinate system in China. Therefore, the design for national GPS geodetic control network and the re-leveling of high-order leveling network in China were considered in the design of GPS/Leveling network.

2. Planning and Constructing the Local Basal Surveying Control net

To developing the regional quasi-geoid work it need enhance the fund and planning all to construct a well local basal surveying control net.

The aim of the local basal surveying control net construction is to establish the GPS C order net with some density and enough accuracy and set the third (or second) leveling route with the definition density to satisfy the local economy construction.

3. Fully Using the Presented Data

After the long economy construction the dense gravity measurement had been constructed in many area by surveying, oiling and geology exploring bureau, especially the geology exploring bureau had made national geology general investigation with some area made the scaling 1:200000 gravity investigation. The scaling with 1:50000 DEM had been finished by SBSM with the resolution 25 meter (about 0.75").

It needs fully using the above data to refine the regional quasi-geoid work.

4. Correspondence with the Aim of National Quasi-Geoid Determination

Refine the quasi-geoid is a long term work in China. It should be considered entirely the regional quasi-geoid should be one part of national quasi-geoid with the high accuracy and resolution in future. For this reason the regional quasi-geoid should be done area by area with the uniform specification and standardization to providing the full result file, which could be made the good foundation for the future national quasi-geoid refinement.

5. The Achieve Accuracy and Resolution

The regional quasi-geoid refinement should be taken place the lower leveling using the GPS technology to satisfy large scale topographical map surveying. The designed accuracy of quasi-geoid is:±5.0cm~±8.0cm in cities and plane areas to satisfy the requirements of engineering construction and 1:2000 scaled (or larger) topographical map surveying, better than ±15.0cm in mountainous areas to satisfy the requirements for 1:5000 scaled (or larger) topographical map surveying. The resolution of the regional quasi-geoid refinement should be 2.5′×2.5′.

6. The Distribution of the GPS/Levelling Points

To get better results, the GPS/Leveling network should be designed by considering the distribution of height anomalies and gravity measurements. Without considering the error in gravity measurements, the distribution of GPS/leveling points could be estimated from the distributions of height anomalies, gravity measurements, and the representative error of gravity measurements (reference 4). The distribution of GPS/Leveling points is listed in table 1, 2 and 3 respectively, according to different resolution λ of gravity anomalies (2.5′, 5′ and 15′ respectively), and the accuracy of height anomalies m_ς is ±0.05m, ±0.08m and ±0.15m correspondingly.

Table 1. The distribution of distances (in km) of GPS/Levelling points for m_ς =0.05m

	2.5′	5′	15′
Plane area	41	29	17
Hill area	27	19	11
Mountainous area	20	14	8
High Mountainous area	15	10	6

Table 2. The distribution of distances (in km) of GPS/Levelling points for m_ς =0.08m

	2.5′	5′	15′
Plane area	66	47	27
Hill area	44	31	18
Mountainous area	33	23	13
High Mountainous area	24	17	9

Table 3. The distribution of distances (in km) of GPS/Levelling points for m_ς =0.15m

	2.5′	5′	15′

Plane area	125	88	51
Hill area	83	59	34
Mountainous area	62	44	25
High Mountainous area	45	31	18

In most area, the resolution of gravity measurements is about 15′×15′, while the resolution in large part of the eastern China is 5′×5′ even some area is better than 2.5′×2.5′ with the statistics.

7. Measurement Accuracy Requirements

To get the design quasi-geoid accuracy the distribution of GPS/Leveling points should satisfy the requirements listed in table1, 2 and 3. The accuracy requirements for GPS control network and leveling are as follows:

The horizontal accuracy between two adjacent points is better than ±5mm, with a vertical accuracy being better than ±10mm for A-order GPS points.

The horizontal accuracy between two adjacent points is better than ±8mm, with a vertical accuracy being better than ±15mm for B-order GPS points.

The horizontal accuracy between two adjacent points is better than ±10mm, with a vertical accuracy being better than ±30mm for C-order GPS points.

One sigma per km is ±0.45mm, with a total sigma being ±1.0mm for first-order leveling.

One sigma per km is ±1.0mm, with a total sigma being ±2.0mm for second-order leveling.

One sigma per km is ±3.0mm, with a total sigma being ±6.0mm for third-order leveling.

IV. THE RESULTS OF THE REGIONAL QUASI-GEOID DETERMINATION

1. The First Regional Quasi-Geoid Determination in ZheMinGan Area

The quasi-geoid determination was carried out in three provinces in eastern China (ZheJiang, FuJian and JiangXi province) from 2003 to 2004. This work had been finished by SBSM on 28/2/2005.

1) The construction of the basal control net

GPS net establishment

In this area, 96 A-order GPS points, 1552 C-order GPS points had been constructed with 904 GPS/Leveling points among them. The A-order GPS point had been chosen in the jointed point of the first and second leveling line. The survey mark is set the new designed type with the forced centering mark. The C-order GPS point is established at uniform distribution by the province. The GPS point density and the length of each point could be seen in the below table:

Table 4. The distribution of GPS point and its average distances (in km) of each province

Area	Square （km^2）	A-oder	C-order	Total	Average length(km)
Zhejiang	100000	26	469	495	15.6
Fujian	120000	30	475	505	16.5
Jiangxi	160000	40	606	646	16.9
Total		96	1550	1646	

The levelling network establishment

The reconnaissance and rebury the benchmark work had been completed to the second leveling line in this area. 923.5km length of the first-order leveling, 10645km length of the second-order leveling and 11830km length of the third-order leveling had been finished in this area. The specified work could be seen in the below table

Table 5. The statistics of the distribution of leveling line in each province

area	First order（km）	Second order（km）	Third order（km）
Zhejiang	238.8	4524.1	3759.6
Fujian	180.8	2979.3	3267.9
Jiangxi	278.1	3587.6	4802.7
Total	697.7	11091	11830.2

2) The data collection and application

Over 140,000 gravity measurements were used in the quasi-geoid computation, including the density gravity observation in national geodesy data bank with 70000 points and the collected 72432 points in these provinces. The DEM of different resolution (3″×3″, 30″×30″ and 2.5′×2.5′) were derived from 1:50000 scaled digital elevation model at the north latitude area from 22 degree to 34 degree and the east longitude from 118degree to 123 degree, while the oceanic area data is used the satellite altimetry data.

3) The accuracy of regional quasi-geoid[5]

The accuracy after fitting was ±5.4cm in plane area, ±6.5 cm in hill area, and ±5.4 cm in mountainous area respectively with the resolution of 2.5′×2.5′ grids.

About 56 GPS/Leveling points were used to estimate the accuracy of local quasi-geoid among which, 20 points located in plane area, 18 in hill area and 18 in mountainous area. Each checking point had some length with the GPS/leveling point. After the computation to the checking points, the root mean square of differences is ±6.2cm.

2. The regional quasi-geoid determination in North China area

The quasi-geoid determination was carried out in four provinces in northern China area (Covered Beijing, Tianjin cities, Hebei and Shanxi provinces) from 2004 to 2005. This work had been finished by SBSM on 18/4/2006.

1) The construction of the basal control net

GPS net establishment

In this area, 319 A-order and B-order GPS points, 1317 C-order GPS points had been constructed. The A-order and B-order GPS point had been chosen in the jointed point of the first and second leveling line. The survey mark is set the new designed type with the forced centering mark. The C-order GPS point is established at uniform distribution by the province. The GPS point density and the length of each point could be seen in the below table:

Table 6. The distribution of GPS point and its average distances (in km) of each province

Area	square（km^2）	A and B-order	C-order	Total	Average length(km)
Beijing	16800	34	218	252	8.77
Tianjin	11300	28	208	236	7.44
Hebei	188000	136	227	363	24.45
Shanxi	156600	116	664	780	15.23
Total		314	1317	1631	

The leveling network establishment

The specified leveling network work could be seen in the below table

Table 7. The statistics of the distribution of leveling line in each province

area	First order（km）	Second order（km）	Third order（km）
Zhejiang	2076.4	1473.4	2147.2
Fujian	1601	4652.2	
Jiangxi		5800	551
Shanxi		5200	3482.9
Total	3677.4	17125.6	6181.1

2) The data collection and application

Over 120,000 gravity measurements were used in the quasi-geoid computation, including the gravity observation in national geodesy data bank with 75474 points and the collected 46289 points in these provinces. The DEM is used the 1:50000 scaled digital elevation model.

3) The accuracy of regional quasi-geoid[6]

The inner fitting accuracy of regional quasi-geoid is ±4.1cm, while the accuracy was ±3.8cm in plane and hilled area, and ±4.5 cm in mountainous area respectively with the resolution of 2.5′×2.5′ grids. The accuracy of each province is: ±2.8cm in Beijing area, ±2.2cm in Tianjin area, ±4.4cm in Hebei province and ±5.0cm in Shanxi area.

About 58 GPS/Leveling points were used to estimate the accuracy of local quasi-geoid among which having the different points in plane area, hill area and mountainous area. Each checking point had some length with the GPS/leveling point. After the computation to the checking points, the root mean square of differences is ±5.2cm while the Beijing and Tianjin area is ±2.6cm.

3 The regional quasi-geoid determination in East and Middle China area

The quasi-geoid determination was carried out in eight provinces in eastern and middle China area (Covered Shanghai city and Jiangsu, Anhui, Huebi, Shandong, Henan, Hunan, Shanxi provinces) from 2005 to 2006. This work will be finished by SBSM in March, 2007.

1) The construction of the basal control net

GPS net establishment

In this area, 765 A-order and B-order GPS points, 5300 C-order GPS points had been constructed. The A-order and B-order GPS point had been chosen in the jointed point of the first and second leveling line. The survey mark is set the new designed type with the forced centering mark. The C-order GPS point is established at uniform distribution by the province. The GPS point density and the length of each point could be seen in the below table:

Table 8. The distribution of GPS point and its average distances (in km) of each province

Area	square（km^2）	A and B-order	C-order	Total	Average length(km)
Shanghai	5800	13	105	118	7.53
Jiangsu	100000	84	472	556	14.41
Henan	160000	108	745	853	14.72
Anhui	130000	89	833	922	12.76
Hunan	210000	125	575	700	18.61

Hubei	180000	117	778	895	15.24
Shanxi	190000	119	297	416	22.96
Shandong	150000	110	1495	1605	10.39
Total		765	5300	6065	

The levelling network establishment

The specified leveling work could be seen in the below table

Table 9. The statistics of the distribution of leveling line in each province

area	First and Second order（km）	Third order（km）
Shanghai	2561	3237
Jiangsu	2119	360
Henan	3573	16700 (including infrared traverse)
Anhui	4302	6900
Hunan	5118	6600
Hubei	5636	4840
Shanxi	5220	7425
Shandong	3804	15970
Total	32333	62032

2) The data collection and application

Over 459,622 gravity measurements were used in the quasi-geoid computation, including the gravity observation in national geodesy data bank with 277,329 points and the collected 182,293 points in these provinces. The DEM is used the 1:50000 scaled digital elevation model

3) The accuracy of regional quasi-geoid

All the GPS and leveling observation work had been checked in 2006. The data procedure is been working. According to the distribution of GPS/leveling point, the estimated accuracy of the regional quasi-geoid should below ±6.0cm at the Middle and East China area.

V. CONCLUSIONS

At the tenth five years planning, the regional quasi-geoid work had provided the precious experience completed by SBSM cooperated with local surveying bureau. The feature could be seen at below:

The regional quasi-geoid determination work had been combined with the national modern surveying datum construction during its design work. It proved that it could save construction time, decrease the investment and ensure the local province surveying basal control net under the uniform datum, accuracy and performance specification.

Combing the national basal surveying project with the local basal surveying work and sharing the regional quasi-geoid result is another significant feature. The project is implemented uniform design and executed by each province. After the project is finished, the GPS A, B and C order control net results would been provide fully to the local surveying bureau by SBSM, with the second, third levelling results and regional quasi-geoid determination result providing all. The mode with the project construction by national and local government could assemble the fund, technology, human power and device use and supplement, which promotes the survey achievement sharing and application early.

Pay more attention to the surveying basal facility construction and reform the survey mark and bench mark is the other feature of regional quasi-geoid determination in China. The survey mark is the facility to collect data and the main reference to multidiscipline study and analyse. In this project the new type survey mark and bench mark had been buried according the modern geodesy demand.

Using the more density gravity measurement and the newer GPS/levelling observation data is the feature of the project. The gravity data is to decide the shape of geoid., which will display the key roll to get the high resolution geoid, while the high accuracy density GPS/leveling points would directly promote the accuracy and resolution of regional quasi-geoid.

The high accuracy regional quasi-geoid results got would realize the aim using the GPS technique to instead the lower order leveling. After the determination of local quasi-geoid, the normal height derived by combining the GPS geodetic heights with quasi-geoid may be used in the survey of large scaled maps, such as 1:1000、1:2000, etc. The GPS C-order net set in Beijing and Tianjin cities proved that the density and uniform points with observation long time could get the more accuracy quasi-geoid results.

Besides the above features, the straight work team of SBSM had learned and made communication each other with local surveying team, which promoted the technology of each unit.

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