Geodetic Height Determination in 2005 Qomolangma Survey

DANG Yamin  CHENG Chuanlu  CHEN Junyong  ZHANG Peng

Abstract  Determining the geodetic height of Mount Qomolangma was one of the very important missions in the 2005 Qomolangma height survey. There were three GPS networks in the survey: regional GPS crustal deformation network, geodetic GPS control network, and GPS measurement on the mountain summit. Data collection and processing were introduced. The final data processing strategy and reasonable geodetic height were fairly determined based on careful data analysis.

Keywords  Qomolangma; geodetic height; GPS; measurement

CLC number  P228.41

Introduction

The first determination of the height of Mount Qomolangma above sea level by Chinese scientists was conducted by mountaineers in 1975[1,2]. That measurement is one of the best height determinations in history, since many geodetic techniques were employed, including astronomy, triangulation, leveling, and gravity. In addition, a meteorological balloon with an aerograph was also used to measure meteorological parameters.

In the next three decades, the height determination of Mount Qomolangma became a focus of scientists worldwide. The height of the peak has been a subject of controversy for decades[3-7], particularly with the development of new geodetic techniques, especially global positioning systems (GPS). Chinese scientists also conducted a survey of Qomolangma's height 3 times, in 1992, 1998 and 1999, some in collaboration with western scientists[4-9], and obtained significant results.

A new and authoritative height determination of Mount Qomolangma was conducted by the State Bureau of Surveying and Mapping (SBSM) in 2005. The highlighted technique employed at that time was GPS, which can offer remarkable accuracy of the location measurement. Although GPS itself could provide fairly high precision, bad weather on the summit of Mount Qomolangma made GPS measurements and data processing a very important technical issue for the 2005 Qomolangma height survey.

1 GPS measurement in 2005 Qomolangma height survey

There were three GPS networks covered in the 2005 Qomolangma height survey. The first network was the crustal deformation network in the area of the Tibetan plateau, the second was the GPS control network in the Qomolangma area, the third was the GPS measurement on the summit of Mount Qomolangma. Different surveying strategies were made for each of these networks, since their surveying environments
were quite different. The survey duration ranged from tens of hours to tens of minutes. The high precision GPS receivers, such as SHTECH Z-II and TRIMBLE 5700, all ensured the quality of the GPS data in the 2005 Qomolangma height survey.

1.1 GPS crustal deformation measurement in Tibet

One of the very important tasks of the 2005 Qomolangma height survey is the crustal deformation survey in Tibet, which was also the earlier fundamental survey task for the last Qomolangma height survey campaign. This deformation network consists of 30 GPS sites, the main purpose of which is for monitoring the crustal motion in this region. The geodynamical studies can be made based on these monitoring results (Fig.1). The network can also be regarded as a reference frame to some extent for the later GPS measurements. For earlier data availability of crustal deformation in this area, the GPS measurements of the GPS crustal deformation network were tied in with some other GPS networks, such as the Crustal Movement Observation Network China (CMONC) and the earlier Tibetan crustal GPS deformation network, etc. A total of 18 sites were included for this linked measurements.

The northernmost sites of the Tibetan crustal GPS deformation network are in Qinghai Province, most of these sites are located in Tibet, with some over the high altitude area. Field surveying work began on March 16, 2005 and ended on April 8, 2005. The 48-h continuous surveying strategy was adopted for all monitoring sites, while the synchronized multi-stations surveying model was employed in field surveying.

The tied-in measurements of 18 sites, which linked crustal deformation in the Tibetan area with the CMONC, and the earlier Tibetan crustal GPS deformation network, all involved surveying duration of around 8 h.

1.2 GPS geodetic control network of 2005 Qomolangma height surveying

After the surveying mission of the Tibetan crustal GPS monitoring network was accomplished, we needed to establish a GPS control network in the Qomolangma area for the last summit GPS campaign survey. The sites of these GPS control networks are used for comprehensive geodetic purposes, e.g., the sites can be used for GPS/leveling, and also for refining geoid in the area with the density of gravity data, which can be used for transforming the geodetic height to geoidal height or the height above sea level. In addition, the GPS control network would take the data provider role for the last summit GPS campaign (Fig.2).

The Qomolangma GPS control network consists of 32 sites, six of which are superposition sites. The field works began on May 9 and ended on June 4, with surveying time of around 8 h.

1.3 GPS summit measurement

The 2005 Qomolangma GPS summit measurement is the last but most important mission for determining the geodetic height of Mount Qomolangma (Fig.3).
On May 22, 2005, a team of Chinese researchers/mountaineers on a mission to remeasure the height of the mountain successfully performed the operations. The starting time was at 11:43:55 am and ended at 12:19:32 pm - the summit measurement process lasted around 35 min and 37 s.

In addition to one GPS receiver at the peak of Mount Qomolangma, there were 8 GPS sites in the summit campaign, with the measurement duration of most of the sites at about 8 h. To get more available data on the summit, the collection sampling interval was set as 1 s.

2GPS data processing of 2005 Qomolangma height survey

As we had mentioned above, there were three GPS campaigns in the 2005 Qomolangma height survey. The GPS data processing strategies of these three GPS networks were set differently according to their data collection situations.

The GAMIT/GLOBK GPS processing software package was employed for GPS data processing of the 2005 Qomolangma height survey. At first, doubly differenced GPS phase observations from each day were used to estimate station coordinates, the zenith delay and the gradients of the atmosphere at each station, and orbital and Earth orientation parameters (EOPs) by applying loose a priori constraints to all parameters. In the second step, the loosely constrained estimates of station coordinates, orbits, EOPs and their covariance from each day were used as quasi-observations in a Kalman filter to estimate a consistent set of daily coordinates.

For each GPS network, the data processing scheme was different. The sampling interval was set at 30 s for the GPS crustal deformation network in Tibet, since the sampling interval of most International GPS Service (IGS) are 30 s. There were 17 IGS stations included in the 2005 Qomolangma survey.

The data processing sampling interval of the GPS control network was set at 15 s, since we have 15 s sampling GPS data in both the campaign measurements and continuous GPS stations in China, and there are about 13 continuous GPS stations included in this phase. As for the summit GPS measurements, since 1 s survey sample data are available in both the peak and GPS control networks around the Qomolangma area, the data processing experiments were conducted, and the 2 s sampling interval was set for the final summit GPS data processing strategy.

3GPS data analysis of 2005 Qomolangma summit GPS measurements

Since GPS data collection in the Qomolangma summit area was a difficult mission, the data collection sampling interval was set as 1 s in the summit GPS campaign. This makes the data processing strategy more flexible. As we all know, the most continuous GPS station, e.g., IGS stations, have their data sampling interval set at 30 s. Thus, the IGS stations could not be combined with the summit GPS data directly, or data combination enforced, since
most data would be lost. To ensure we have reasonable and satisfactory geodetic height determination results by using as much more data as possible, we designed some data processing schemes for the summit GPS campaign measurements. Especially, the IGS stations were excluded from the data processing, and the data from local continuous GPS stations act as reference stations in the summit data processing procedure.

3.1 Preprocessing and analysis of 2005 Qomolangma summit GPS measurements

The first preprocessing of the summit GPS measurements involved data processing using the software from the manufacturer. The result from this data processing will act as a reference to some extent for the later standard summit GPS data processing. Considering the bad environment on top of the peak, and that erecting a 2.5-meter-tall survey beacon will take some time, determining the exact beginning time of the summit GPS measurements became fairly critical for the final standard GPS data processing. The practical preprocessing was to select different start time points that will change from the first selected minute to the next, until the last 10 min surveying duration was satisfied. After all these computations are completed using GAMIT/GLOBK software, we then compare and analyze all results to determine the exact reasonable start and end time points of the summit GPS measurements. First, we determine the exact start time point, and these preliminary geodetic height results are listed in Table 1 (ITRF2000 reference frame, the epoch is 2005.315), where $N$, $E$, $U$ are RMS of summit GPS data processing in north-south direction, east-west direction, and vertical direction, respectively.

| Scheme | Geodetic height | $N$ | $E$ | $U$ | Start time | End time |
|--------|-----------------|-----|-----|-----|------------|----------|
| F343   | 8 817.348 3     | 0.056 24 | 0.173 86 | 0.097 62 | 3:43  | 3:53 |
| F344   | 8 817.830 1     | 0.049 81 | 0.150 52 | 0.085 16 | 3:44  | 3:54 |
| F345   | 8 818.292 2     | 0.049 26 | 0.151 71 | 0.085 31 | 3:45  | 3:55 |
| F346   | 8 820.987 6     | 0.034 42 | 0.109 18 | 0.063 95 | 3:46  | 4:01 |
| F347   | 8 820.901 8     | 0.049 54 | 0.155 41 | 0.089 55 | 3:47  | 3:57 |
| F348   | 8 821.102 3     | 0.048 23 | 0.149 89 | 0.085 94 | 3:48  | 3:58 |
| F349   | 8 821.473 1     | 0.048 27 | 0.146 42 | 0.085 99 | 3:49  | 3:59 |
| F350   | 8 821.453 4     | 0.047 88 | 0.143 91 | 0.085 01 | 3:50  | 4:00 |
| F351   | 8 821.443 1     | 0.049 36 | 0.146 22 | 0.089 14 | 3:51  | 4:01 |
| F352   | 8 821.461 7     | 0.048 11 | 0.145 06 | 0.086 07 | 3:52  | 4:02 |
| F353   | 8 821.486 2     | 0.047 78 | 0.142 47 | 0.085 45 | 3:53  | 4:03 |
| F354   | 8 821.473 2     | 0.047 59 | 0.139 97 | 0.084 90 | 3:54  | 4:04 |
| F355   | 8 821.434 1     | 0.047 62 | 0.139 00 | 0.085 13 | 3:55  | 4:05 |

To compare the effect of different surveying durations, we select 15 min duration this time for estimating the start time point. The results are listed in Table 2.

| Scheme | Geodetic height | $N$ | $E$ | $U$ | Start time | End time |
|--------|-----------------|-----|-----|-----|------------|----------|
| S343   | 8 819.660 4     | 0.030 62 | 0.095 14 | 0.053 54 | 3:43  | 3:58 |
| S344   | 8 819.963 9     | 0.028 74 | 0.085 25 | 0.049 14 | 3:44  | 3:59 |
| S345   | 8 820.530 8     | 0.028 57 | 0.087 74 | 0.050 50 | 3:45  | 4:00 |
| S346   | 8 821.006 5     | 0.029 34 | 0.087 12 | 0.051 49 | 3:46  | 4:01 |
| S347   | 8 821.270 5     | 0.027 22 | 0.082 61 | 0.048 95 | 3:47  | 4:02 |
| S348   | 8 821.351 2     | 0.026 58 | 0.081 75 | 0.047 82 | 3:48  | 4:03 |
| S349   | 8 821.493 7     | 0.026 44 | 0.079 32 | 0.047 36 | 3:49  | 4:04 |
| S350   | 8 821.489 5     | 0.026 41 | 0.078 46 | 0.047 12 | 3:50  | 4:05 |
| S351   | 8 821.472 2     | 0.027 24 | 0.079 47 | 0.048 25 | 3:51  | 4:06 |
| S352   | 8 821.431 2     | 0.027 37 | 0.079 23 | 0.048 42 | 3:52  | 4:07 |
| S353   | 8 821.423 2     | 0.028 25 | 0.080 17 | 0.049 26 | 3:53  | 4:08 |
| S354   | 8 821.419 2     | 0.029 38 | 0.080 66 | 0.049 93 | 3:54  | 4:09 |
| S355   | 8 821.390 4     | 0.030 59 | 0.081 66 | 0.050 80 | 3:55  | 4:10 |
From the above processing and analysis, the solution became stable and reasonable at start time 3:49, that is, after the solution of the scheme of F349, all results are consistent for determining the Qomolangma geodetic height. For reliability, we select 3:50 as our start time point for the final GPS data processing of summit GPS measurements.

Similarly, we select the end time point every one minute from the practical end time, since the start time point had been fixed, so the start time point is at 3:50 in the designed computation schemes. Results are listed in Table 3.

From Table 3, although several end time points were selected, the computation results are highly consistent, and the end time point of the 2005 Qomolangma GPS summit measurements was set at 4:19.

### Table 3  Preliminary geodetic height result and precision (sampling interval: 2 s) /m

| Scheme | Geodetic height | Nrms | Erms | Urms | Start time | End time |
|--------|----------------|------|------|------|------------|----------|
| F419   | 8 821.419 0    | 0.035| 0.024| 0.011| 3:50       | 4:19     |
| F418   | 8 821.416 9    | 0.036| 0.025| 0.012| 3:50       | 4:18     |
| F417   | 8 821.415 6    | 0.037| 0.026| 0.012| 3:50       | 4:17     |
| F416   | 8 821.413 3    | 0.039| 0.026| 0.013| 3:50       | 4:16     |
| F415   | 8 821.416 7    | 0.041| 0.028| 0.013| 3:50       | 4:15     |

### 3.2 Global IGS station-based GPS data processing of 2005 Qomolangma summit GPS measurements

As we had mentioned above, the data collection sampling interval was set as 1 s in the summit GPS campaign, and the efficient survey duration is about 29 min. To ensure the reliability of the final GPS data processing results, we took another data processing scheme - a global IGS station-based solution, i.e., we selected some global IGS stations, such as LHAS, DLHA, TASH, BAHR, IISC, and KIT3 as our reference stations, with data collection sampling interval set at 30 s, so the data sampling interval in our data processing was also set at 30 s. The data surveying duration is from 3:50 to 4:19. The Global IGS station-based data processing results are listed in Table 4.

### Table 4  Geodetic height and precision on the snow peak of Qomolangma based on IGS stations (sampling interval: 30 s) /m

| Site  | Geodetic height | N   | E    | U    | Start time | End time |
|-------|----------------|-----|------|------|------------|----------|
| 000F  | 8 821.254 4    | 0.062| 0.143| 0.095| 3:50       | 4:19     |

### 3.3 GPS data processing of 2005 Qomolangma summit GPS measurements

The data collection sampling interval was set at 1 s in the summit GPS campaign, and the sampling interval of IGS stations was 20 s, preventing a direct processing of these two types of data together. Thus, we first combined GPS control network with the IGS station data, then used the GPS control network as reference stations to process the summit GPS measurements.

The data processing of GPS crustal deformation network in Tibet is a standard high precision GPS procedure using the GAMIT/GLOBK software package. There were 55 IGS stations included in the data processing under ITRF2000. The same scheme was employed for the data processing of 2005 Qomolangma GPS control network. Except for the IGS stations, some stations of the crustal deformation network were also constrained as some sort of reference stations.

The GPS data processing scheme of the 2005 Qomolangma summit GPS measurements was similar to the GPS geodetic control network, but the temporary continuous GPS stations (sites of Z001 and Z002) and some stations in the GPS control network were constrained. The final result of the geodetic height of the highest station on the earth (site of 000F in Table 5) was well estimated under ITRF2000, and listed in Table 5.
Table 5  Geodetic height and precision on snow peak of Qomolangma (sampling interval: 2 s)/m

| Site | Geodetic height | N  | E   | U   | Start time | End time |
|------|----------------|----|-----|-----|------------|----------|
| 000F | 8 821.401 6    | 0.019 9 | 0.045 8 | 0.030 3 | 3:50       | 4:19     |

4 Conclusions

From Table 1 to Table 5, it is apparent that precision became better along with the increase of data collection time. Our last computation scheme took the whole summit GPS measurements as one session, and the sampling interval of data processing was set at 2 s. The final geodetic height of the highest site 000F of Mount Qomolangma with reference to the snow surface is \((8 821.401 6 \pm 0.030 3)\) m, and the epoch is 2005.315. After a reliable determination of the depth of the snow layer, and new determination of the geoid under the summit of Mount Qomolangma, we thus recorded the final definitive height of Mount Qomolangma above sea level at \((8 844.43 \pm 0.21)\) m.

Acknowledgements

Thanks to all of those who worked for the 2005 Qomolangma Height Survey, the fieldwork and data processing work. Many thanks to Zhang Ji-Jiangqi, Chen Xianjun, Sun Zhanzi from the National Geomatics Center of China, and Yue Jianli, Chen Yongjun, Wang Xiaorui from Shanxi Bureau of Surveying and Mapping, who collected those precious GPS data. Special thanks go to the climbers who participated with enthusiasm in this difficult scientific experiment.

References

[1] Chen Junyong(1975)The height computation of Mount Qomolangma[J]. Bulletin of Surveying and Mapping, 12(4): 19-27 (in Chinese)
[2] Zhu Liang(1976)The height determination of Mount Qomolangma[J]. Science in China, 19(2): 74-84 (in Chinese)
[3] Zhang Chijun(2003)Relative problems and thoughts on Qomolangma elevation determination[J]. Geomatics and Information Science of Wuhan University, 28(6): 675-678 (in Chinese)
[4] Dang Yamin(2005)Investigation on the height repetition determination of Qomolangma Peak [J]. Science of Surveying and Mapping, 30(3): 101-103 (in Chinese)
[5] Chen Junyong, Pang Shangyi, Zhang Ji, et al.(2001)The height determination of Qomolangma Peak in China: review and analysis[J]. Acta Geodaetica et Cartographica Sinica, 30(1): 1-5 (in Chinese)
[6] Chen Junyong, Zhang Ji, Xue Zhang, et al.(1996) On the crustal movement in Qomolangma Peak and its adjacent area [J]. Chinese Journal of Geophysics, 39(1):58-67 (in Chinese)
[7] Chen Junyong, Pang Shangyi, Zhang Ji, et al.(2001) Height of snow top for the Mount Everest and global warming [J]. Advance in Earth Sciences, 16(1): 12-14 (in Chinese)
[8] Dang Yamin, Chen Junyong, Zhang Yanping, et al.(2002) Contemporary crustal motion in southern Tianshan by global positioning system measurements [J]. Science of Surveying and Mapping, 27(4): 13-15 (in Chinese)
[9] King R W, Bock Y(2002)Documentation for the GAMIT analysis software, release 10.0[R]. Massachusetts Institute of Technology, Cambridge, USA
[10] Herring T A(2002)GLOBK: global Kalman filter VLBI and GPS analysis program, version 10.0 [R]. Massachusetts Institute of Technology, Cambridge, USA
[11] McClusky S, Balassian S, Barka A, et al.(2000) Global positioning system constraints on plate kinematics and dynamics in the eastern Mediterranean and Caucasus[J]. Journal of Geophysical Research, 105(B3): 5695-5719