Journal of Geodesy (2004) 78: 103–108
DOI 10.1007/s00190-004-0379-0

Journal of Geodesy

Integrated adjustment of CHAMP, GRACE, and GPS data

S. Zhu, Ch. Reigber, R. König

GeoForschungsZentrum Potsdam (GFZ), Department of Geodesy and Remote Sensing, Telegrafenberg, 14473 Potsdam, Germany
e-mail: koenigr@gfz-potsdam.de; Tel.: +49-8153-28-1353; Fax: +49-8153-28-1735

Received: 31 July 2003 / Accepted: 8 January 2004 / Published online: 21 June 2004

Abstract. Various types of observations, such as space-borne Global positioning system (GPS) code and phase data, accelerometer data, K-band range and range-rate data, and ground-based satellite laser ranging data of the CHAllenging Minisatellite Payload (CHAMP) and GRAvity Climate Experiment (GRACE) satellite missions, are used together with ground-based GPS code and phase data in a rigorous adjustment to eventually solve for the ephemerides of the CHAMP, GRACE, and GPS satellites, geocenter variations, and low-degree gravity field parameters. It turns out that this 'integrated' adjustment considerably improves the accuracy of the ephemerides for the high and low satellites, geocenter variations, and gravity field parameters, compared to the case when the adjustment is carried out stepwise or in individual satellite solutions.

Key words: CHAllenging Minisatellite Payload – GRAvity and Climate Experiment – Global positioning system – Precise orbit determination – Reference frame – Gravity field

1 Introduction

Dedicated low Earth orbiter (LEO) missions like the CHAllenging Minisatellite Payload (CHAMP) and the GRAvity and Climate Experiment (GRACE) are aiming at improving the accuracy and resolution of static global gravity field models and detecting temporal variations of the Earth's gravity field (Reigber et al. 1999, 2002; GeoForschungsZentrum Potsdam (GFZ) 2003; Tapley and Reigber 2001; University of Texas at Austin, Center for space Research 2003). For this goal, the CHAMP and GRACE satellites generate space-borne observations, namely accelerations, K-band range and range-rate and Global positioning system (GPS) data. Satellite laser ranging (SLR) data are provided by the International Laser Ranging Service (ILRS 2003) ground-station network. The most important data in the context of the following analysis are the measurements of the space-borne GPS receivers.

Precise orbit determination (POD) of LEOs based on space-borne GPS data has recently gained considerable attention from various geodetic groups because more and more satellite missions equipped with space-borne GPS receivers are scheduled for space deployment in the years to come. Therefore the 'IGS LEO Pilot Project' was set up by the International GPS Service (IGS 2003) as the CHAMP data became available. Quite a few participating groups contributed 'orbits' to the pilot project, where the orbit products contained positions of a satellite given at certain points in time or positions and velocities of a satellite given at any useful time interval, depending on the way of restituting the orbit. Comparisons and accuracy estimates of the contributed orbits are summarized in Boomkamp (2003).

The approaches to determine the orbit include dynamic, kinematic, and reduced dynamic methods. An introduction to the various methods may be found in Neumayer et al. (2003). The approach adopted in the following is the dynamic one, as it is the direct way to recover satellite-related parameters such as the orbit parameters, and at the same time Earth system parameters, such as the gravity field coefficients. In addition, the dynamic approach typically provides the following advantages as compared to the kinematic approach: it allows for the simultaneous recovery of position and velocity, it yields equally spaced ephemerides, and it can be based on any equal or non-equal data sampling.

At present, the 'two-step' approach is widely adopted for the restitution of LEO orbits from GPS data. In the first step, orbits and clock corrections of the GPS satellites are adjusted by using GPS ground-station data. In the second step, LEO orbits are estimated using GPS intersatellite tracking data from the LEO space-borne receiver only. The ephemerides and clocks of the GPS

Correspondence to: R. König

satellites enter this latter part of the overall process as fixed quantities or as ‘geometric reference points’.

An alternative concept, which could be called the ‘one-step’ method, is what we like to call an ‘integrated’ adjustment, where the orbits of the LEOs and of the GPS satellites are recovered in one simultaneous least squares (LS) solution by processing all of the various observation types (i.e. GPS ground and space-based data, SLR data, accelerometer data, K-band range and range-rate data, attitude and thruster data, etc.) together. Moreover, when dealing with the dynamic method, the solution space can be expanded to Earth orientation parameters (EOPs), ground-station coordinates, geocenter coordinates, gravity field model parameters, etc. It can be predicted that the quality of the solution of an integrated adjustment will improve. However, some care is needed to have all possible systematic effects properly modeled. Especially when the a priori gravity field model is of poor quality, the LEO orbit is considerably affected with the risk of deteriorating the GPS ephemerides as well.

The improved quality of an integrated adjustment can not only be related to the effect of adding an ‘orbiting station’ which, by increasing the degree of freedom, inherently leads to improved accuracy and reliability of an LS solution. The major effect strengthening the solution may be attributed to the fact that with the dynamic method the LEO introduces strong algebraic correlations between its ephemeris throughout the arc and the GPS constellation and as well with the ground reference frame. Accordingly, the quality of the GPS orbits should also improve as well as the Earth system parameters, e.g. ground-station coordinates, geocenter estimates or gravity field parameters.

The International Earth Rotation Service (IERS 2003) invoked the SINEX Combination Campaign (IERS 2002), where normal equation matrices from different observation techniques are set up and finally combined to solve for relevant parameters such as EOPs. This concept, applied to the CHAMP-GRACE-GPS constellation, would mean a multi-step approach where, depending on the parameters included in the SINEX file, all or part of the algebraic correlations may be neglected. Noticably, for the SINEX Combination Campaign, Andersen (2002) proposed ‘combination at the observation level’, which probably has a similar meaning as the term ‘integrated adjustment’ used here.

Guided by the prospects of the integrated adjustment of CHAMP, GRACE, and GPS data, the EPOS-OC software of the GFZ Potsdam has been upgraded for the one-step or integrated solution capability. In the following analysis this upgraded software was used to generate representative test results in order to demonstrate the improvement of the quality of the solutions when applying the integrated adjustment approach.

2 Major functions of the EPOS-OC software

In the first place the EPOS-OC software is designed to dynamically compute precision orbits, gravity field coefficients and other dynamic parameters, station coordinates, EOPs and various other non-dynamic parameters. EPOS-OC can also run in the geometric (kinematic) mode for various GPS applications such as precise point positioning etc.

With EPOS-OC we can process a variety of tracking data types: SLR data, GPS data, Precise Range And Range-rate Equipment (PRARE) data, DORIS data, Doppler tracking data, and optical observations. These data types can be used individually or in combination in order to recover the orbit of a single satellite or the orbits of a number of satellites simultaneously. Altimeter heights, altimeter cross-overs, attitude, thruster, accelerometer, K-band data, and satellite ephemerides (e.g. GPS satellite positions and velocities) serve as supplementary data types. Adding one or more of these data to the basic tracking data can improve the quality of solutions substantially.

In order to carry out the analysis as given below, the following functions of EPOS-OC are needed.

1. Restitution of the orbits of GPS satellites from GPS ground tracking data.
2. Determination of the orbits of CHAMP and GRACE satellites from space receiver GPS data based on fixed GPS ephemerides and clocks from step 1. Attitude, accelerometer, thruster, or K-band data can be added if required. Gravity field coefficients can also be treated as unknowns. This constitutes the two-step approach for LEO orbit and gravity field determination.
3. Simultaneous determination of orbits of the GPS, CHAMP, and GRACE satellites and recovery of gravity field model coefficients, EOPs, and station positions from GPS ground and LEO space-borne data in the same solution. Attitude, accelerometer, thruster, and K-band data can also be added if required. This is the one-step or integrated procedure.
4. To the above solutions 2 and 3, SLR data can be added with some realistic weighting.

Due to the abundance of data and due to the large number of unknowns to be solved for, computation time rises steeply for the one-step solution. For example, processing of one day’s worth of data according to point 3 or 4 can take a full computation day on a SUN 750 MHz workstation. The EPOS-OC software is not yet optimized for substantially minimizing computation times of the integrated procedure. Therefore, in this paper, only a limited number of test results is given to demonstrate the importance of the concept and its benefits.

3 The roles of the basic space-borne observation types

Multiple types of data are available from the CHAMP and GRACE missions. As far as orbit restitution is concerned, the most important data type is the GPS data acquired by the space-borne BlackJack receiver. The quantity of data is very high (data interval 10 s, average number of GPS satellites observed per epoch 5–6 for CHAMP, 6–7 per GRACE satellite). This amount of data allows us to restitute the orbit by adjusting a large number of unknowns (geometric, stochastic, dynamic). Therefore even a pure geometric orbit restitution can be applied (the LEO is treated like a moving object), as described by Svehla and Rothacher (2003). In our study solely the dynamic procedure is considered. In this case, even without using accelerometer data, just by solving a large number of 'once-per-revolution' empirical parameters, CHAMP orbits can be restituted with a few centimeters' accuracy as demonstrated in Zhu et al. (2003). So, on the one hand, 'once-per-revolution' parameters can improve the orbit quality significantly but, on the other hand, these parameters can absorb the gravity information. Therefore their usage can be harmful to the gravity field recovery.

It can be debated at this point whether the dynamic approach with a large number of empirical parameters is no longer dynamic but rather reduced dynamic. The reduced-dynamic strategy, first proposed by Yunck et al. (1990), combines the dynamic and the geometric method by a filter approach, where the weight of the dynamic solution is controlled by appending process noise to the force models. In the cited case of Zhu et al. (2003), and in general in the EPOS-OC case, the nature of the empirical parameters is purely deterministic, therefore stating that it is a dynamic approach is still justified.

Accelerometer data are also very important for POD and gravity field recovery. Table 1 demonstrates GRACE POD results. In the first solution solely spaceborne GPS data were used. In the second one, accelerometer data were added. Their influence can clearly be seen in the improvement of the orbital fit of the K-band range, K-band range-rate and SLR observations in terms of root-mean-square values of the residuals. Adding K-band data leads to the third solution listed in the third row of Table 1. The K-band range and range-rate data obviously play a minor role for the absolute orbit accuracy, e.g. in position, of each of the two satellites connected by this observation type, but a major role for the relative accuracy, e.g. in range, between the two satellites. The SLR fit improves from 3.16 to 2.88 cm, which is a significant improvement at this accuracy level, but small in comparison to the improvement for the accelerometer data. In the end, K-band data are extremely important for the gravity field solution. Figure 1 shows the residuals of the K-band range rates in the solution when K-band data are given zero weight. The signal in the residual time series is the error of the

Table 1. Comparison of GRACE orbital fits for different observation scenarios

Observations used (yes/no)				Orbital fit (RMS)		
GPS	Accel-erometer	K-band	SLR	K-range (cm)	K-range rate (μm/s)	SLR (cm)
y	n	n	n	3.05	30.9	6.45
y	y	n	n	1.05	9.10	3.16
y	y	y	n	0.08	1.87	2.88
y	y	n	y	0.98	9.02	2.06
Number of observations:				61 233	61 233	85

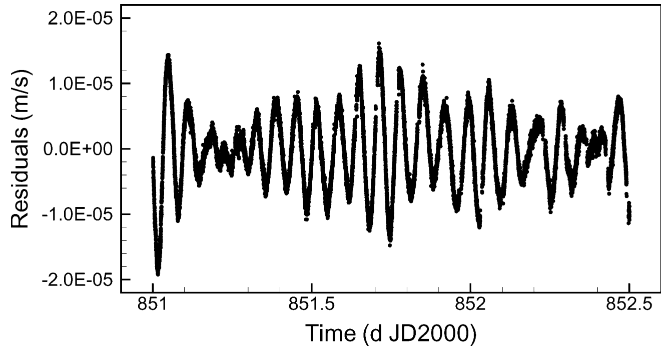

Fig. 1. Residuals of GRACE K-band range-rate data

relative along-track velocities between GRACE-A and GRACE-B. The 'once-per-revolution' signal can typically be attributed to errors in the gravity field model.

Although for the LEO satellites the amount of SLR measurements is relatively sparse, they are useful for independent checks of the orbit quality. Despite this usage, they may also be employed to identify possible systematic errors of the reference frame. In addition, by adding SLR data to the solution, the quality of the solution can also be slightly improved, as visible from the last row in Table 1.

From the above short description it becomes clear that various data types play different roles for different purposes. Only if they are carefully and properly combined can an optimized solution in terms of reliability and accuracy be achieved.

4 CHAMP, GRACE, and GPS POD and reference frame determination

From the point of view of the satellites involved, GPS satellites on the one hand and LEOs on the other fly at altitudes that differ by almost 20 000 km. Their sensitivity towards a given set of parameters is therefore quite different. So, if either solely GPS satellites or solely LEOs are utilized in a parameter adjustment process, advantages and weaknesses are introduced that are specific to either group of satellites. If, however, they are combined in the proposed one-step procedure, the weakness of either kind of satellite is compensated by the strength of the other. Thus it can be expected that the solutions will become more consistent and homogeneous.

From the point of view of the GPS receivers involved, GPS ground stations are located on the surface of the Earth and fixed to the Earth. Their coordinates are well known with accuracies of up to 1–2 cm or better. Spaceborne GPS receivers are the orbiting ones, their positions change quickly with time. However, the positions over the course of time are not random at all; certain dynamic models link them together. Furthermore, the ground tracks of a LEO cover the whole surface of the Earth, which in a sense simulates a homogeneous ground-station network that evenly covers the globe.

Accordingly, if the high orbiters, the LEOs, and the GPS ground stations are linked together, the overall

Table 2. GPS orbit quality of 1-day arcs

Arc	Orbit comparison differences (RMS)			
	2-step IGS (mm)	1-step IGS (mm)	JPL IGS (mm)	JPL CODE (mm)
1	70	37	24	36
2	64	41	34	37
3	66	36	26	35
4	55	34	25	34
Mean	64	37	27	36

Table 3. LEO (GRACE) orbit quality of 1.5-day arcs

Arc	Orbital fits					
	K-range		K-range rate		SLR	
	2-step (cm)	1-step (cm)	2-step (μm/s)	1-step (μm/s)	2-step (cm)	1-step (cm)
1	1.05	0.79	9.10	6.14	3.16	3.04
2	0.98	0.81	10.1	7.98	3.41	3.36
3	1.07	0.81	8.60	6.83	7.08	6.03
Mean	1.03	0.80	9.27	6.98	4.55	4.14

Table 4. Geocenter estimation quality with 1-day arcs

Arc	Geocenter estimates in Z-direction			
	Ground only		LEO added	
	Estimate (mm)	Standard deviation (mm)	Estimate (mm)	Standard deviation (mm)
1	16.2	13.0	−7.7	4.2
2	3.8	11.7	7.3	4.7
3	−39.4	13.1	−0.5	4.7
4	19.4	12.1	0.9	4.7
Mean	0.0	12.5	0.0	4.6

solutions will be more consistent and homogeneous. Each part, i.e. the GPS orbits, the LEO orbits, and the ground reference frame, should gain profit from this procedure. This asset is confirmed by the test results given in Tables 2, 3, and 4.

Orbit tests are performed using GPS space receiver data from CHAMP, GRACE, and GPS data from 40 globally distributed GPS ground stations. The solutions are carried out by employing solely GPS measurements. SLR and K-band range and range-rate data serve for external quality assessment only. They are included into the processing with zero weight in order to obtain their measurement residuals. The arc length used for orbit recovery is equal to 36 hours, or 1.5 days, as adopted for gravity recovery solutions at GFZ. Three arcs in total are processed, with observations covering the period 1 to 6 May 2002.

In Table 2 the GPS orbits are compared to the final IGS orbits as an external reference for quality assessment. As the IGS orbits are 1 day long, the three 1.5-day arcs are cut to four 1-day arcs for the orbit comparison in Table 2. Two procedures are compared. The first one is solely based on the data from 40 ground stations. In the second set of solutions the data from the same ground stations as before were augmented by CHAMP and GRACE GPS–SST measurements (integrated method). No ambiguity fixing was applied. Although in the latter case the amount of data increased by $3/40 = 7.5\%$ only, the orbit accuracy improved by almost 40%. This means that adding three LEOs is of higher importance than adding three ground stations. This is due to the fact that a dynamically moving LEO has some useful properties for a terrestrial network without having the disadvantages of a ground station. For instance, at the LEO altitude the effects of the atmosphere on GPS tracking signal propagation are negligible. Therefore, tropospheric correction parameters do not need to be estimated for a zenith tracking GPS receiver on a satellite. Thus a parameter subset that would exhibit high correlations with station heights and the radial component of the orbit will not persist. For the same reason, we can drop any zenith angle limitations and observe down to almost zero-degree elevation, which significantly strengthens the solution. The comparisons of the JPL final orbits with those of the IGS are also listed. The ground only solutions presented in Table 2 look worse than the JPL (or the CODE or the GFZ IGS Analysis Center) final orbit products for the IGS, since the beginning and end of the orbit are not cut. Within the IGS, usually multi-day orbits are recovered and then the middle day is cut out as a final product in order to remove the parts with lower accuracy. It should also be mentioned that the GFZ IGS Analysis Center final orbits, for example, are based on 150 ground stations. More elaborate analysis would be needed on how many more ground stations in addition to the 40 of the integrated procedure would be required in order to achieve the IGS solution accuracy. And it is not only the number of ground stations but also the procedure of generating a one-day orbit product, for example cutting out the middle day, etc. that is important. The tests reported here therefore serve as a relative comparison only.

Now let us discuss the quality of LEO orbits. Table 3 shows a comparison of the residual fits of the three 1.5-day GRACE orbits. The left-hand side compiles the result of the routinely used two-step solution. A bias of approximately 200 kilometers for K-band range data was removed from the residuals. The residuals of the K-band data represent the differential along-track orbit errors of the two satellites. Since the GRACE twin satellites are separated by about 220 km only, they experience more or less similar model errors. Therefore the relative orbit errors indicated by the K-band range residuals are smaller than the absolute orbit errors indicated by the SLR residuals. The experimental one-step procedure results are given on the right hand side. It is clearly visible that the one-step method reduces the K-band residuals by 20–40%. For the SLR residuals, the improvement is not as dramatic, but still perceptible. It should be noted that the magnitude of the improvement could vary depending on various treatments of ambiguity resolution and GPS orbit recovery procedures.

For the geocenter of the reference frame, the one-step procedure is also superior to the ground-station-only solution, especially in the z-component. A test was conducted with four 1-day arcs starting on 1 May 2002. The 1-day arc cut was chosen in order to ease the assessment of the results by having four solutions instead of only three from the three 1.5-day arcs. The estimated geocenter z-component variation results are given in Table 4. For the x- and the y-components, the one-step method improves the internal precision by 10–20% compared to the ground-station-only case (not shown in Table 4), but for the z-component the improvement is 70% (i.e. a reduction of standard deviation from 12.5 to 4.6 mm). The peak-to-peak values are 58.8 mm and 15.0 mm, respectively.

The sensitivity of the satellite trajectory to the geocenter variations is proportional to a/r, where a is the radius of the Earth and r the radial distance of the satellite from the geocenter. Therefore, the CHAMP and GRACE trajectories are approximately four times more sensitive to the geocenter variations than the GPS satellites. The reduction of the peak-to-peak values and the standard deviations is roughly of this size and therefore the one-step result is much more reasonable.

5 CHAMP, GRACE and GPS ground station data for gravity recovery

In additional tests, the data from CHAMP and GRACE are combined for a simultaneous adjustment of the orbits of the three satellites and a full 20 × 20 gravity field. One 1.5-day arc, the one starting on 1 May 2002, is used as test arc. Figure 2 gives the estimated precision of these gravity field solutions in terms of cumulated geoid height errors. At first, the orbits of the GPS satellites are fixed. As the K-band observations between the GRACE satellites are not used at first, this scenario in a sense combines the data of three LEOs of CHAMP type. Open diamonds in Fig. 2 denote the solution with 30 s data (signified 'LEO GPS 30s' in the legend), the right-looking filled triangles denote the solution with 10-s data (signified 'LEO GPS 10s'). In the latter case the amount of observations increases by a factor of three and the sampling along the satellite path is more dense. Therefore the precision shows a large improvement. When the K-band data are added to the solution, keeping the GPS 30-s data rate, the solution error reduces tremendously, as can be seen from the open rectangles in Fig. 2 (signified 'LEO GPS 30s + KB'). In the final test solution, GPS data from 40 ground stations have been added to the previous run (signified 'LEO + Gr GPS 30s + KB'). Still a perceptible improvement can be seen if the scale of the height axis is expanded, as done in Fig. 3 for the last two cases.

An independent assessment of the improvement resulting from the integrated adjustment is made by comparing the gravity solutions deduced without and with GPS ground-station data to external gravity field models. For this, the EGM96 gravity field model (Lemoine et al. 1998) and the EIGEN-GRACE01S gravity field model (Reigber et al. 2003) are chosen. The EGM96 is a well-known, high-resolution combination model that serves many purposes, for example geoid representation or POD. The EIGEN–GRACE01S is a recent model deduced from GRACE data only, the claimed accuracy of which is probably 50 times higher than that of pre-CHAMP satellite-only gravity fields. The test arc of our analysis is not part of the EIGEN–GRACE01S solution, so the compared solutions are still independent. Figure 4 compiles the difference degree variances of the comparisons in terms of geoid heights. A considerable improvement can be noted by the

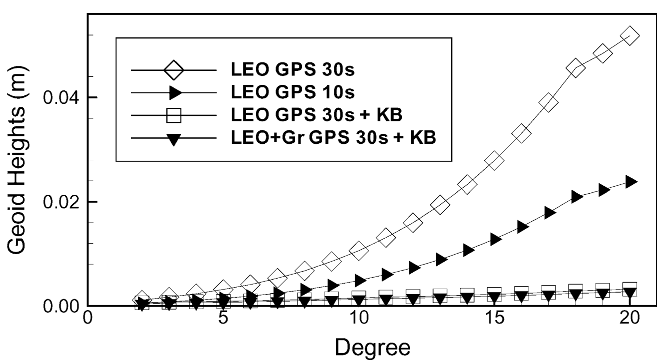

Fig. 2. Accumulated error degree variances of gravity field parameters derived from different data bases

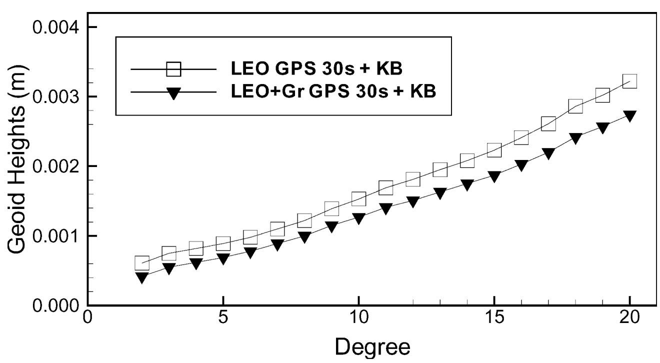

Fig. 3. Accumulated error degree variances of gravity field parameters derived without and with GPS ground data

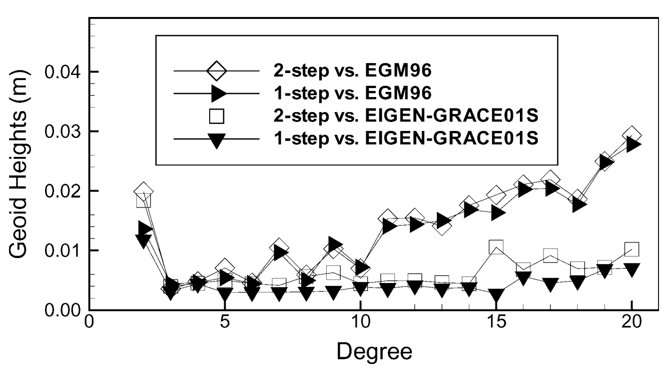

Fig. 4. Difference degree variances of gravity field parameters derived without and with GPS ground data versus independent gravity field models

integrated method for degree two. For the higher degrees the improvement is small, but visible.

Although ground GPS measurements themselves have almost no direct contribution to the higher-order gravity parameter estimation, it should be noted that the integrated method reduces the relative along-track position and velocity errors as shown in Table 3. Thus K-band data can efficiently be employed to separate the gravity signal.

6 Conclusions

GPS orbits (highest layer), CHAMP and GRACE orbits (middle layer), and the terrestrial reference frame (lowest layer) all benefit from the integrated processing procedure, which combines data from all three layers in one consistent solution. The procedure integrates a variety of observation types, such as space-borne GPS code and phase measurements from the CHAMP and GRACE receivers (high to middle layer), highly accurate K-band inter-satellite ranges between the two GRACE satellites (middle to middle layer), laser ranges from ground stations to the CHAMP and GRACE satellites (low to middle layer), and GPS ground-receiver code and phase observations (high to low layer). The observations are rigorously adjusted for the solution of GPS, GRACE, and CHAMP satellite ephemerides, geocenter variations and low-degree gravity field parameters. With the onboard GPS receiver data, the LEO orbits are tracked almost continuously and the restitution of the orbits becomes accurate. The space-borne accelerometer data are important for LEO POD and gravity field recovery. The GRACE K-band data mainly serve the purpose of high-accuracy and high-resolution gravity field recovery. In POD they strengthen the relative accuracy of the GRACE satellite ephemerides. For LEOs, SLR measurements are distributed sparsely in time and space, however they can be used for quality control of LEO ephemerides derived from the other data sources or to enhance the quality of POD, geocenter, and gravity field recovery solutions. So, each data type plays its role in reliable and accurate solutions.

The GPS and LEO satellites show different sensitivity to certain parameters. The integrated processing procedure compensates the weakness of either kind of satellite by the strength of the other. Therefore more accurate GPS ephemerides, more accurate LEO ephemerides, and more reliable geocenter estimates result. With the integrated procedure even the GPS satellites are more efficiently employed for gravity field recovery, because the simultaneous usage of GPS ground and space-borne data allows a better relative accuracy for the LEOs and therefore magnifies the effect of the K-band observations.

Acknowledgments. This study has been supported by the German Ministry of Education and Research through the Geotechnologies Programme grants 03F0333A/CHAMP and 03F0326A/GRACE.

References

Andersen P (2002) IERS SINEX combination campaign: FFI proposal. Available at: http://alpha.fesg.tu-muenchen.de/iers/sinex/sinex_campaign. html, accessed 4 December

Boomkamp H (2003) The CHAMP orbit comparison campaign. In: Reigber Ch, Luehr H, Schwintzer P (eds) First CHAMP mission results for gravity, magnetic and atmospheric studies. Springer, Berlin Heidelberg New York, pp 53–58

GeoForschungsZentrum Potsdam (2003) CHAMP—GFZ's challenging minisatellite payload for geophysical research and application (CHAMP) home page. Available at: http://op.gfz-potsdam.de/champ/index_CHAMP.html, accessed May

International Earth Rotation Service (2002) SINEX combination campaign, call for participation. IERS message no. 27. Available at: http://www.iers.org, accessed 28 May

International Earth Rotation Service (2003) IERS home page. Available at: http://www.iers.org, accessed May

International GPS service (2003) IGS home page. Available at: http://igscb.jpl.nasa.gov, accessed May

International Laser Ranging Service (2003) ILRS home page. Available at: http://ilrs.gsfc.nasa.gov, accessed May

Jet Propulsion Laboratory (2003) NASA Jet Propulsion Laboratory home page. Available at: http://www.jpl.nasa.gov, accessed May

Lemoine FG, Kenyon SC, Factor JK, Trimmer RG, Pavlis NK, Chinn DS, Cox CM, Klosko SM, Luthke SB, Torrence MH, Wang YM, Williamson RG, Pavlis EC, Rapp RH, Olson TR (1998) The development of the joint NASA GSFC and the National Imagery and Mapping Agency (NIMA) geopotential model EGM96. NASA Tech Paper NASA/TP-1998-206861, Goddard Space Flight Center, Greenbelt, MD

Neumayer KH, Koenig R, Reigber Ch, Zhu SY (2003) Aproaches to CHAMP precise orbit determination. In: Reigber Ch, Luehr H, Schwintzer P (eds) First CHAMP mission results for gravity, magnetic and atmospheric studies. Springer, Berlin Heidelberg New York, pp 78–84

Reigber Ch, Schwintzer P, Luehr H (1999) The CHAMP geopotential mission. Boll Geof Teor Appl 40: 285–289

Reigber Ch, Luehr H, Schwintzer P (2002) CHAMP mission status. Adv Space Res 30: 129–134

Reigber Ch, Schmidt R, Flechtner F, König R, Meyer U, Neumayer KH, Schwintzer P, Zhu SY (2003) First EIGEN gravity field model based on GRACE mission data only. Available at: http://op.-gfz-potsdam.de/grace/-results/grav/g001_eigen-grace01s. html, accessed 24 November

Svehla D, Rothacher M (2003) CHAMP double-difference kinematic POD with ambiguity resolution. In: Reigber Ch, Luehr H, Schwintzer P (eds) First CHAMP mission results for gravity, magnetic and atmospheric studies. Springer, Berlin Heidelberg New York, pp 70–77

Tapley BD, Reigber Ch (2001) The GRACE mission: status and future plans. EOS Trans 82(Suppl): G41C-02

University of Texas at Austin, Center for space Research (2003) GRACE—gravity recovery and climate experiment. Available at: http://www.csr.utexas.edu/grace/ or http://op.gfz-potsdam.de/grace/index_GRACE.html, accessed May

Yunck TP, Wu SC, Wu JT, Thornton CL (1990) Precise tracking of remote satellites with the global positioning system. IEEE Trans of Geosci Rem Sens 28: 108–116

Zhu SY, Neumayer KH, Massmann F-H, Shi C, Reigber Ch (2003) Impact of different data combinations on the CHAMP orbit determination. In: Reigber Ch, Luehr H, Schwintzer P (eds) First CHAMP mission results for gravity, magnetic and atmospheric studies. Springer, Berlin Heidelberg New York, pp 92–97