Chapter 2
Improvement in GPS Orbit Determination at GFZ

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Abstract Precise orbits of the GPS satellites are required at GFZ for generation of Earth's gravity field models, precise determination of baselines between Low Earth Orbiters (LEOs) such as TerraSAR-X and TanDEM-X, for processing of various LEO radio occultation data as well as in research following the integrated approach where ground and space-borne GPS data are used together to estimate parameters needed for determination of a geodetic terrestrial reference frame. For this GFZ has implemented many GPS modelling improvements including GPS phase wind-up and attitude model, improved ambiguity fixing, absolute antenna phase centre offsets and variations, global constrains for the terrestrial reference system, frame transformation according to IERS Conventions 2010, higher order ionospheric corrections and improvements in the parameterization of the solar radiation pressure model. In this paper the influence of all these modelling improvements on the accuracy of the GPS orbits is presented. It is shown, that the application of the new models reduced the mean 3D difference of our orbits from 7.76 to 3.01 cm when compared to IGS final orbits.

Keywords GPS orbits · Modelling improvements

2.1 Reference Processing

To demonstrate the impact of the modelling improvements we started from the GPS orbits generated using modelling standards close to that used in the Release 04 (or RL04) of the GFZ GRACE gravity field modelling (Flechtner et al. 2010). These orbits were generated using EPOS-OC (Earth Parameter and Orbit System—Orbit

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Computation module) software package (Zhu et al. 2004) and the applied background models include:

- Earth gravity potential model: EIGEN-6C (Shako et al. 2013),
- Lunar gravity field model: Ferrari (1977),
- Sun, Moon and planets ephemeris: JPL DE421,
- Earth Tide model: Wahr (1981),
- Nutation and precession models: IERS Conventions 2003 (McCarthy and Petit 2004),
- Earth Orientation Parameters (EOP): EOP04C05,
- Ocean Tide model: EOT11 (Savcenko and Bosch 2012),
- Ocean pole tide model: Desai (2002),
- Atmospheric Tide model: Biancale and Bode (2006),
- Relative station antenna phase centre offsets and variations: igs_01.pcv,
- Solar radiation pressure: GPS model ROCK 4 (Fliegel et al. 1992),
- Tropospheric delay estimated with the Vienna Mapping Function 1,
- Empirical periodic accelerations (1/rev), unconstrained cosine and sine in transversal and normal direction,
- Post-Newtonian relativistic corrections, Lense-Thirring and deSitter effect,
- Elevation cut-off angle: 20°, no elevation dependent weighting,
- Arc length: 26 h (1d $\pm$ 1h),
- GPS data: undifferenced ionosphere-free L3 code and phase combinations
- A-priori standard deviation for GPS code = 250 cm, phase = 2.5 cm,
- Ambiguity fixing: double difference integer wide-lane/narrow-lane ambiguity fixing, constraining combinations of 4 undifferenced L3 ambiguities (Blewitt 1989; Ge et al. 2005) and
- Station coordinates: a-priori coordinates from IGS08 solution with 10-cm constraints.

Parameters which are estimated are the following:

- Satellite initial state vectors,
- Ground station coordinates,
- Global scaling factor and Y-bias of the solar radiation pressure model for each satellite,
- 10 tropospheric scaling factors for each station (every 2.6 h),
- Empirical periodic accelerations, unconstrained cosine and sine in transversal and normal direction, once per revolution,
- Floating L3 ambiguities and
- Satellite and ground station clock offsets.

One month of GPS data collected by a network of ~80 globally uniformly distributed ground stations (June 2008) was selected as a test period, and orbits for all GPS satellites were generated using the modelling standards given above. The orbits were compared next with the International GNSS Service (IGS) final orbits. The daily 3D RMS values, both before and after applying of the ambiguity fixing, are shown in

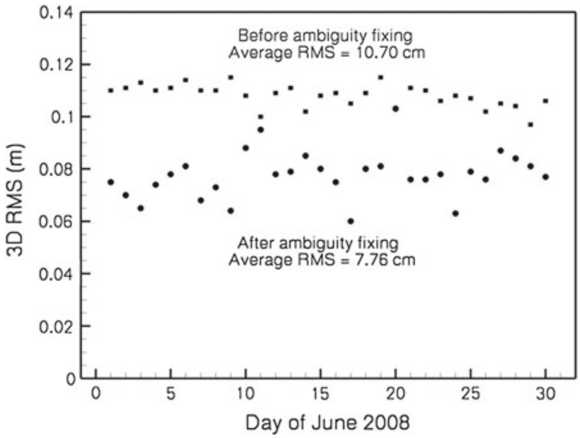

Fig. 2.1 Comparison of the initial RL04 orbits with IGS final orbits. The daily 3D RMS values before applying ambiguity fixing are plotted as *squares*; those after applying ambiguity fixing are plotted as *circles*

Fig. 2.1. The mean values are 10.70–7.76 cm, before and after applying of the ambiguity fixing, respectively. These modelling standards and orbits (denoted hereafter as RL04) are used as a reference for subsequent tests.

2.2 Improvements of the Processing

The modelling standards given in the previous sections for RL04 orbits were next sequentially changed by updating/adding new models. The resulting orbits were again compared with the IGS final orbits. From this comparison the daily RMS values of the 3D position differences ("3D RMS") were obtained, both without and with ambiguity fixing. A table summarizing the results of the modeling improvements will be given in the Sect. 2.2.7.

2.2.1 Phase Wind-Up and the GPS Attitude Model

The corrections due to GPS phase wind-up (Wu et al. 1993) and the GPS attitude model (Bar-Sever 1996; Kouba 2009) were implemented into EPOS-OC and were applied for the RL04 orbits. Additional details of the implementation can be found also in (Michalak and König 2010). The mean 3D RMS value for solution without ambiguity fixing reduced by 0.14 cm from 10.7 cm (Fig. 2.1) to 10.56 cm. For the ambiguity-fixed solution it dropped significantly by 2.03 cm from 7.76 cm (Fig. 2.1) to 5.73 cm.

2.2.2 Improved Ambiguity Fixing

For the original RL04 orbits and orbits from the Sect. 2.1 the ambiguity fixing was done by means of an old external procedure. Since many deficiencies of this procedure were found, a new one was written and applied. The new procedure is essentially based on an approach described in Blewitt (1989) and Ge et al. (2005) but is made more flexible. The ambiguity fixing is performed using the well-known double differenced wide-lane/narrow-lane approach and applying constraints to the combinations of four L3 floating undifferenced ambiguities. The fixing decision for the double differenced ambiguities is based on the fixing probability, in contrast to the old procedure which mainly used simply the difference to the nearest integer. After application of the new ambiguity fixing to orbits from Sect. 2.1 the mean 3D RMS value improved by another 1.5 cm to just 4.24 cm. In all following tests only the new ambiguity fixing procedure was applied.

2.2.3 Absolute Antenna Phase Centre Offset/Variation

The EPOS-OC software was updated to enable application of absolute antenna phase centre offsets and variations for GPS measurements. The relative antenna phase centres were replaced by the absolute ones used by the IGS analysis centres (IGS08.atx file). The 3D RMS for the solution without ambiguity fixing was significantly reduced by 2.65 cm (from 10.56 to 7.91 cm), for ambiguity-fixed solution by 0.4 cm (from 4.24 to 3.84 cm).

2.2.4 No-Net Translation/Rotation/Scale Conditions

In the previous orbits 10-cm constraints are imposed on all a-priori station coordinates (RL04 standards). This constraining scheme originates from operational GPS orbit determination to prevent bad measurements taken at a ground station with reliable station coordinates to destroy the whole solution. By applying individual constraints on the coordinates of each station, however, makes the whole solution overly constrained, as there are maximally seven datum defects possible (three translations, one global scale, three rotations) that should be removed. To make the solution as free as possible on the one hand, and to tighten the solution to the underlying terrestrial reference frame, only No-Net Translation/Scale/Rotation conditions with an a priori sigma of 0.1 mm are imposed over the whole ground station network. This allows each single station moving free but keeping the ground network fixed as a whole. The application of these conditions, in addition to all previous changes improved the ambiguity-free solution by 0.09 cm (from 7.91 to 7.82 cm), the ambiguity-fixed solution improved by 0.17 cm (from 3.84 to 3.67 cm).

2.2.5 Change of the Observations Weight, Frame Transformations and Applications of Higher Order Ionospheric Corrections

In the next step the a priori standard deviations for code and phase observations were changed, respectively, from 250 to 2.5 cm (RL04 standards) to 100–1 cm as adopted in the new release 05 (RL05) orbits (Dahle et al. 2012). In addition the frame transformations according to IERS Conventions 2010 (Petit and Luzum 2010) as well as higher order ionospheric corrections (Bassiri and Hajj 1993) were implemented and used. For the ambiguity float solution the daily 3D RMS improved by 0.33 cm (from 7.82 to 7.49 cm); the ambiguity-fixed orbits improved by 0.2 cm (from 3.67 to 3.47 cm). The modelling standards at this point are the same as used for generating the latest RL05 GRACE gravity field models (see Dahle et al. this book).

2.2.6 Solar Radiation Pressure Model Reparameterization

It was also found, that the GPS orbit accuracy is significantly sensitive to modelling the solar radiation pressure. In the current version of EPOS-OC only the ROCK-4 model is implemented with the possibility of estimating global scaling factors as well as biases and periodic accelerations in all 3 directions X, Y, and Z of the satellite body fixed system. Up to this point only the global scaling factor and the Y-bias has been estimated. After a series of tests it was found that improvement of the RL05 orbits can be achieved, if the estimation of a bias in Z (radial) direction is added. The average 3D RMS of the ambiguity-free orbits decreased noticeable from 7.49 to 6.89 cm; the ambiguity-fixed solution reduces the RMS from 3.47 to 3.01 cm, i.e. by 0.46 cm. The daily RMS values for these orbits are given in Fig. 2.2.

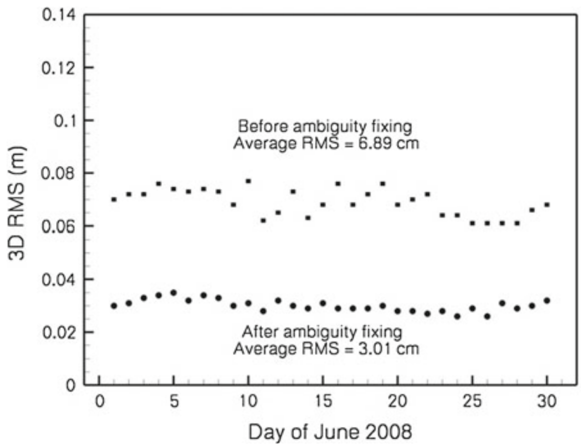

Fig. 2.2 Comparison of the GPS orbits after application of all modelling improvements to IGS final orbits. The daily 3D RMS values before applying ambiguity fixing are plotted as *squares*, those after applying ambiguity fixing are plotted as *circles*

Table 2.1 Cumulative effects of modelling improvements

Modelling characteristics	Without ambiguity fixing	With ambiguity fixing	
	3D RMS before/after Helmert transf. (cm)	3D RMS before/after Helmert transf. (cm)	Code /Phase RMS (cm)
Reference orbits (modelling standards similar to RL04)	10.70/10.47	**7.76** /7.14	60.66/0.689
+ Wind-up + GPS attitude model	10.56/10.27	**5.73** /5.34	60.50/0.666
+ New ambiguity fixing	10.56/10.27	**4.24**/3.96	60.48/0.643
+ Absolute phase center offsets/variations	7.91/7.61	**3.84**/3.62	57.80/0.559
+ No-Net translation/Rotation/Scale conditions	7.82/7.63	**3.67**/3.57	57.81/0.559
+ Weights/frame of RL05, higher-order ionospheric corrections	7.49/7.30	**3.47**/3.38	50.20/0.372
+ Reparameterization of GPS solar radiation pressure model	6.89/6.69	**3.01**/2.91	50.11/0.369

2.2.7 Summary of the Modelling Improvements

The cumulative effect of the modelling improvements applied sequentially as described in previous sections is summarized in Table 2.1.

In this table the 3D RMS values come from the comparison to the IGS final orbits for the solution without and with ambiguity fixing, before and after applying a Helmert transformation. The resulting post-fit code and phase RMS values are also presented there. From analysis of the 3D RMS values for ambiguity-fixed solutions before Helmert transformation (highlighted using bold-type) it can be seen, that the largest impacts come from the application of phase wind-up and the GPS attitude model, the new procedure for ambiguity fixing, absolute phase centre offsets/variations, reparameterization of the solar radiation pressure model, and No-Net Translation /Rotation/Scale conditions.

2.3 Influence of Single Modelling Components on RL05 Orbits

In the previous section the cumulative impact of the modelling components or groups of components on the GPS orbits was presented. In this section more detailed analysis of the influence of a single modelling component on the RL05 orbits is done. For this purpose the RL05 modelling standards (as in Sect. 2.2.5) were taken as a reference and series of test runs were carried out with changing/deactivating only

Table 2.2 Sensitivity of the RL05 orbit accuracy to different modeling components

Changes in modelling	Without ambiguity fixing	With ambiguity fixing		
	3D RMS before/after Helmert tr. (cm)	3D RMS before/after Helmert tr. (cm)	Difference to RL05 orbits (cm)	Code /Phase RMS (cm)
Ref. RL05	7.49/7.30	**3.47**/3.38	–	50.20/0.372
1	7.85/7.60	**6.35**/5.86	+2.88	50.10/0.372
2	10.90/10.68	**4.15**/4.01	+0.68	53.00/0.416
3	7.49/7.20	**4.13**/4.00	+0.66	50.21/0.374
4	6.89/6.69	**3.01**/2.91	−0.46	50.11/0.369
5	7.83/7.34	**3.73**/3.42	+0.26	50.18/0.372
6	7.80/7.62	**3.64**/3.54	+0.17	57.81/0.559
7	7.50/7.31	**3.49**/3.40	+0.02	50.19/0.372
8	7.74/7.46	**3.47**/3.36	0.00	50.24/0.372
9	7.50/7.29	**3.47**/3.39	0.00	50.20/0.372
10	7.49/7.30	**3.47**/3.38	0.00	50.20/0.372
11	7.48/7.29	**3.47**/3.38	0.00	50.19/0.372

The modelling changes applied to the Ref. RL05 orbits are following: (1) No phase wind-up. (2) Relative instead of absolute antenna phase centres. (3) Old procedure for ambiguity fixing (3 days failed). (4) Reparameterization of the solar radiation pressure model. (5) Disabling of No-Net Translation/Rotation/Scale conditions. (6) A-priori Std. Dev. 250/2.5 cm for Code /Phase (RL04). (7) Frame transformations of RL04 instead of RL05. (8) No GPS attitude model. (9) No higher order ionospheric corrections. (10) Gravity potential max. degree 12×12 changed to 24×24. (11) No de-aliasing models

one modelling component. Resulting orbits were compared with IGS final orbits and the average 3D RMS values were computed. The results are summarized in Table 2.2 where we provide the information on modelling changes, 3D RMS values for the cases without and with ambiguity fixing applied (both before and after applying the Helmert transformation), the difference to the reference RL05 RMS values and the post fit code/phase RMS values. The RMS differences to the RL05 orbits were computed using values for the cases with ambiguity fixing and before the Helmert transformation (bold-type in Table 2.2). The results presented in Table 2.2 are sorted with decreasing absolute value of the difference, e.g. the modelling components having largest impact are given in the top of the table. Analysis of the results allows drawing the following conclusions:

- The largest impact on the accuracy of the GPS orbits has the application of phase wind-up corrections, while the influence of the GPS attitude model turned out to be negligible. Also large impact has the application of absolute phase centre offsets/variations to the GPS sender and receiver antennas, the improved procedure of ambiguity fixing, the reparameterization of the ROCK-4 solar radiation pressure model and the application of No-Net Translation/Scale/Rotation constraints.
- Noticeable total impact of the three following components: changing the a-priori weights of code and phase observations, frame transformations according to the

IERS Conventions 2010 and applying higher-order ionospheric corrections (see Table 2.1) comes mainly from the first of these components. The RL04 weights resulted in 50 % increase in the phase RMS value (from 0.372 to 0.559 cm) but did not translate into comparable large degradation of the orbit accuracy (only 0.17 cm, i.e. about 5 %). The impact of the application of higher-order ionospheric corrections turned out to be negligible. The maximum orbit difference was found to be on the level of 1.5 mm what is in contrast to 1.6 cm reported in Fritsche et al. (2005) using the Bernese software. This issue requires further investigation.

- No impact was found when increasing the degree and order of the background gravity potential expansion or taking into account the short term atmospheric and oceanic mass variations (GRACE de-aliasing products, Flechtner 2007). This is due to large distance of the GPS satellites from the Earth surface.

2.4 Summary

During the last years GFZ has achieved remarkable improvement in the quality of its GPS orbits used for a variety of applications (e.g. Earth gravity field modelling, processing of LEO radio occultation data, precise LEO baseline determination, integrated approach for estimating terrestrial reference system parameters) by implementing a number of new models and standards. It was found that the modelling improvements (see Table 2.1) reduced the average 3D RMS of the differences to IGS final orbits by 60 %, from 7.76 to 3.01 cm. The largest impact has the application of phase wind-up corrections (improvement by 2 cm), the new procedure for ambiguity fixing (1.5 cm), the absolute antenna phase centre offsets/variations (0.4 cm), the No-Net Translation/Scale/Rotation conditions (0.2 cm), the change of observation weighting (0.2 cm), and improved modelling of the solar radiation pressure (0.5 cm). No influence was found when increasing the resolution of the gravity field, using GRACE de-aliasing models, the GPS attitude model and higher-order ionospheric corrections. The lack of the influence of the last component needs future investigations.

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References

Bar-Sever YE (1996) A new model for GPS yaw-attitude. JoG 70:714–723

Bassiri S, Hajj G (1993) Higher-order ionospheric effects on the global positioning system observables and means of modeling them. Manuscr Geod 18:280–289

Biancale R, Bode A (2006) Mean annual and seasonal atmospheric tide models based on 3-hourly and 6-hourly ECMWF surface pressure data. Scientific Technical Report. STR 06/01, GeoForschungsZentrum, 33

Blewitt G (1989) Carrier phase ambiguity resolution for the global positioning system applied to geodetic baselines up to 2000 km. J Geophys Res 94/B8:10187–10203

Dahle Ch, Flechtner F, Gruber C, König D, König R, Michalak G, Neumayer KH (2012) GFZ GRACE level-2 processing standards document for level-2 product release 0005, (Scientific Technical Report - Data, 12/02), Revised Edition, January 2013), Potsdam, 21 p. doi:10.2312/GFZ.b103-1202-25

Desai S (2002) Observing the pole tide with satellite altimetry. J Geophys Res 107(C11):3186. doi:10.1029/2001JC001224

Ferrari AJ (1977) Lunar gravity: a harmonic analysis. J Geophys Res 82(20):3065–3084. doi:10.1029/JB082i020p03065

Flechtner F (2007) AOD1B product description document for product releases 01 to 04 (Rev. 3.1). GRACE project document 327–750. http://isdc.gfz-potsdam.de/

Flechtner F, Dahle Ch, Neumayer KH, König R, Förste Ch (2010) The release 04 CHAMP and GRACE EIGEN gravity model. In: Flechtner et al (ed) System earth via geodetic-geophysical space techniques, Adv. technologies in earth sciences, Springer, Berlin. doi:10.1007/978-3-642-10228-8_4

Fliegel HF, Gallini TE, Swift ER (1992) Global positioning system radiation force model for geodetic applications. Geophys Res Let 97(B1):559–568

Fritsche M, Dietrich R, Knoefel C, Ruelke A, Vey S, Rothacher M, Steigenberger P (2005) Impact of higher-order ionospheric terms on GPS estimates. Geophys Res Lett 32(L23311). doi:10.1029/2005GL024342

Ge M, Gendt G, Dick G, Zhang FP (2005) Improving carrier-phase ambiguity resolution in global GPS network solutions. JoG 79(1–3):103–110. doi:10.1007/s00190-005-0447-0

Kouba J (2009) A simplified yaw-attitude model for eclipsing GPS satellites. GPS Solut 13:1–12

McCarthy DD, Petit G (eds.) (2004) IERS Conventions (2003). IERS Technical Note 32, Frankfurt am Main: Verlag des Bundesamts für Kartographie und Geodäsie. ISBN 3-89888-884-3, http://www.iers.org/TN32. Accessed 20 March 2012

Michalak G, König R (2010) Improvements for the CHAMP and GRACE observation model. In: Flechtner F, Gruber T, Güntner A, Mandea M, Rothacher M, Schöne T, Wickert J (eds) System earth via geodetic-geophysical space techniques. Springer, pp 29–39. doi:10.1007/978-3-642-10228-8_3

Petit G, Luzum B (eds) (2010) IERS Conventions 2010. IERS Technical Note 36; Frankfurt am Main: Verlag des Bundesamts für Kartographie und Geodäsie. ISBN 3-89888-989-6. http://www.iers.org/TN36. Accessed 20 March 2012

Savcenko R, Bosch W (2012): EOT11a - empirical ocean tide model from multi-mission satellite altimetry. Report No. 89, Deutsches Geodätisches Forschungsinstitut, München

Shako R, Förste Ch, Abrikosov O, Bruinsma S, Marty JC, Lemoine JM, Flechtner F, Neumayer KH, Dahle Ch (2013) EIGEN-6C: A high-resolution global gravity combination model including GOCE data. In: Flechtner F et al. (eds.) Observation of the system earth from space - CHAMP, GRACE, GOCE and future missions, advanced technologies in earth sciences, Springer, Berlin

Wahr J (1981) Body tides on an elliptical, rotating, elastic and oceanless earth. Geoph J Inter 64(3). doi:10.1111/j.1365-246X.1981.tb02690.x

Wu JT, Wu SC, Hajj GA, Bertiger WI, Lichten SM (1993) Effect of antenna orientation on GPS carrier phase. Manusc Geod 18:91–98

Zhu S, Reigber Ch, König R (2004) Integrated adjustment of CHAMP. GRACE and GPS Data JoG 78(1–2):103–108

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