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ORIGINAL ARTICLE

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Rapid orbit determination of LEO satellites using IGS clock and ephemeris products

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Abstract Different types of GPS clock and orbit data provided by the International GPS Service (IGS) have been used to assess the accuracy of rapid orbit determination for satellites in low Earth orbit (LEO) using spaceborne GPS measurements. To avoid the need for reference measurements from ground-based reference receivers, the analysis is based on an undifferenced processing of GPS code and carrier-phase measurements. Special attention is therefore given to the quality of GPS clock data that directly affects the resulting orbit determination accuracy. Interpolation of clock data from the available 15 min grid points is identified as a limiting factor in the use of IGS ultra-rapid ephemerides. Despite this restriction, a 10-cm orbit determination accuracy can be obtained with these products data as demonstrated for the GRACE-B spacecraft during selected data arcs between 2002 and 2004. This performance may be compared with a 5-cm orbit determination accuracy achievable with IGS rapid and final products using 5 min clock samples. For improved accuracy, high-rate (30 s) clock solutions are recommended that are presently only available from individual IGS centers. Likewise, a reduced latency and more frequent updates of IGS ultra-rapid ephemerides are desirable to meet the requirements of upcoming satellite missions for near real-time and precise orbit determination.

Keywords Orbit determination · GPS · LEO satellites · GRACE

Introduction

Aside from purely scientific applications, spaceborne GPS receivers have gradually evolved into a standard tracking system for low Earth orbiting (LEO) satellites. From a mission operations perspective it provides improved accuracy and coverage as well as reduced system cost in comparison to conventional ground-based radar tracking. Furthermore, the onboard availability of orbit information offers the prospect of increased spacecraft autonomy and a simplification of spacecraft operations.

Over the past decade, great efforts in GPS receiver technology and data processing have been made to improve the absolute orbit determination accuracy and a decimeter level is presently achieved in the post-facto processing of spaceborne dual-frequency measurements. Aside from high accuracy, increasing attention is now paid to a near real-time orbit determination to support the rapid delivery of end-user data products such as atmospheric profiles from occultation measurements or synthetic aperture images. Representative examples include the METOP mission of the Eumetsat Polar System (Eumetsat 2000; Martínez-Fadrique and Luengo 2001), the CHAMP mission (König et al. 2003) and the TerraSAR-X mission (DLR 2003), which demand a localization accuracy down to 10 cm and allow as little as 2 h 15 min between raw data reception and dissemination of processed user data.

The deactivation of Selective Availability (S/A) in May 2000 has resulted in a pronounced simplification of the GPS-based precise orbit determination process for LEO spacecraft. In the absence of S/A, GPS clock offsets can well be interpolated from 5-min grid points which are readily available from public sources along with precise orbits of the GPS constellation (Kouba 2002; Kouba and Heroux 2001). This allows a direct processing of undifferenced GPS observations and removes the need for supplementary ground-based GPS measurements (Montenbruck et al. 2004). Compared to traditional GPS-based orbit determination concepts based on double- or triple-differenced measurements (Kang et al. 2003; Van den Ijssel et al. 2003) or the independent computation of high-rate GPS clock data from a ground network (Bock et al. 2002) the computational effort and the operational complexity can thus be notably reduced. On the other hand, the orbit determination quality is not only dependent on the GPS orbit quality (Rim et al. 2002) but also on the accuracy of GPS clock solutions.

With the above background, the present report aims at the study of rapid orbit determination of low Earth orbiting satellites using pre-computed GPS ephemerides. Following an assessment of GPS clock and orbit solutions offered by the International GPS Service (IGS) and individual analysis centers, the report discusses the adopted processing scheme for LEO orbit determination and data screening. Subsequently, the orbit determination accuracy achievable with different types of GPS products is analyzed, using dual-frequency GPS measurements collected onboard one of the US-German GRACE (Gravity Recovery and Climate Experiment) spacecraft.

GPS ephemeris and clock products

Overview

The International GPS Service (IGS) began to provide precise GPS ephemeris information for geodetic users and surveyors as early as 1994 (Kouba 2002), when the Global Positioning System had almost reached its fully operational status. Within the IGS, various Analysis Centers derive their own, independent orbit and clock solutions. These are subsequently merged into combined IGS products applying proper weighting and quality control. Both the network of IGS ground stations and the quality of the resulting products have continuously increased over the past decade.

The final IGS ephemerides (identified by the letters "igs") are released some 13 days after the end of a GPS week and have a reported position and clock accuracy of better than 5 cm (IGSCB 2004). The "igr" rapid products, in contrast, are available within 17 h past the end of each day and, meanwhile, achieve an almost identical accuracy. In response to the increasing need for near real-time GPS data processing, the IGS has, furthermore, implemented an ultra-rapid ("igu") ephemeris service (Fang et al. 2001; Kouba 2002) on a routine basis in 2001. Since April 2004 this service provides updated GPS clock and orbit information four times a day with a latency of 3 h past the last observations. Each ultra-rapid ephemeris file combines an "observed" part based on 24 h of past GPS measurements with a 24 h prediction of the satellite orbits and clocks. The predicted orbit information is presently accurate to roughly one decimeter, whereas irregularities of the clock drift cause prediction errors of the order of one meter (IGSCB 2004). As a result, the use of predicted ultra-rapid ephemerides is only meaningful for differential positioning and the present analysis is therefore restricted to the observed orbit and clock information in the igu data sets.

All types of IGS ephemeris products (final, rapid, and ultra-rapid) provide GPS orbit and clock offset data in the standard SP3 format (Remondi 1991) on a regular 15 min grid. This allows accurate polynomial interpolation of the GPS satellite position at the time of a measurement, whereas the accuracy of linearly interpolated clock values is rather limited. Supplementary to the SP3 ephemeris products, clock offset data at 5 min intervals are therefore made available as part of separate (final and rapid) clock products.

Aside from their official IGS contributions, various IGS Analysis Centers provide special GPS orbit and clock products to the community or specific users. In the context of the present study, high-rate (30 s) clock solutions (AIUB 2004) released by the Center for Orbit Determination in Europe (CODE) and the Jet Propulsion Laboratory (JPL) 'Real-Time GIPSY (RTG)' ephemerides (Muellerschoen et al. 2001) offered by the Jet Propulsion Laboratory have been analyzed and compared to routine IGS products. JPL also offers 30 s clock solutions for their 'Final' GPS product, but it was not analyzed here. While CODE's and JPL's high-rate products are freely available to world wide users at this time (November 2004), the same is no longer true for JPL's real-time generated ephemerides, and since May of 2004 access to this product must be specifically requested from JPL (see JPLRTG 2004).

An overview of the key characteristics of the various GPS orbit and clock data considered in this study is provided in Table 1. Here, the latency specifies the interval between the last observation incorporated into a data set and the time of its release. Peak waiting times

Table 1 GPS orbit and clock products

Identifier	Description (file names)	Step size orbit/clock	Availability and latency (Nov. 2004)
igu (15 m)	IGS ultra-rapid ephemerides	15 min	4× per day (3 h, 9 h, 15 h, 21 h UTC); 3 h latency ftp://igscb.jpl.nasa.gov/pub/products/wwww/iguwwwwd_hh.sp3
igr (15 m)	IGS rapid ephemerides	15 min	1× per day (17 h UTC); 17 h latency ftp://igscb.jpl.nasa.gov/pub/products/wwww/igrwwwwd.sp3
igr (5 m)	IGS rapid ephemeris and clock products	15 min/5 min	1× per day (17 h UTC); 17 h latency ftp://igscb.jpl.nasa.gov/pub/products/wwww/igrwwwwd.sp3 ftp://igscb.jpl.nasa.gov/pub/products/wwww/igrwwwwd.clk
igs (15 m)	IGS final ephemerides	15 min	1× per week (Friday); 13 days latency ftp://igscb.jpl.nasa.gov/pub/products/wwww/igrwwwwd.sp3
igs (5 m)	IGS final ephemeris and clock products	15 min/5 min	1× per week (Friday); 13 days latency ftp://igscb.jpl.nasa.gov/pub/products/wwww/igswwwwd.sp3 ftp://igscb.jpl.nasa.gov/pub/products/wwww/igswwwwd.clk
rtg (5 m)	JPL real-time generated ephemerides	5 min	96× per day (every 15 min) for use in this study (presently available at rates of 1 min and latency of 2 min). No longer freely available; see ftp://sideshow.jpl.nasa.gov/pub/15 min/
cod (30 s)	CODE rapid ephemeris and high-rate clock solutions	15 min/30 s	1× per day (10 h UTC); 10 h latency ftp://ftp.unibe.ch/aiub/CODE/yyyy/CODwwwwd.EPH ftp://ftp.unibe.ch/aiub/misc/products/HRRAPCLK/HR_yyddd.clk

encountered by the user of a specific product are determined by the sum of the latency and the update interval (e.g., 17 h + 24 h = 41 h for IGS rapid ephemerides). This is of primary concern for ultra-rapid ephemerides, where the 6 h update cycle (12 h before April 2004) results in peak delays of 9 h, much larger than suggested by the 3 h latency. So far, JPL's real-time ephemerides are therefore the only source of orbit and clock data suitable for near real-time processing of undifferenced GPS measurements.

Signal-in-space range error of IGS products

The analysis of GPS error budgets commonly distinguishes between the User Equipment Range Error, which comprises receiver related noise and multipath errors, and the Signal-In-Space Range Error (SISRE), which covers error sources external to the receiver (e.g., GPS ephemeris uncertainties as well as tropospheric and ionospheric path delays). Both GPS position and clock errors contribute to the SISRE through errors in the modelled pseudoranges when processing undifferenced measurements. Atmospheric contributions, in contrast, can be neglected to first order, when working with ionosphere-free dual-frequency measurements collected by a spaceborne GPS receiver.

Following Warren and Raquet (2003) a suitable approximation of the SISRE may be obtained from the standard deviation (σ) of the clock offset error ($\Delta c\delta t$) and the position errors (Δr_{R}, Δr_{T}, Δr_{N}) in radial, transverse and normal direction using the relation

$$\mathrm{SISRE} = \sqrt{\sigma^2(\Delta r_{\mathrm{R}} - \Delta c\delta t) + \frac{1}{7^2}(\sigma^2(\Delta r_{\mathrm{T}}) - \sigma^2(\Delta r_{\mathrm{N}}))}. \quad (1)$$

Here, the weighting factor $1/7 \approx \sin(8°)$ for the transverse and normal component accounts for the average angle between the line-of-sight and the radial direction for observers on the surface of the Earth and its immediate vicinity. With the above definition, the SISRE properly accounts for the dominating impact of radial orbit errors as well as the possible correlation of clock and orbit errors in GPS ephemeris products. It is therefore more suitable for error analyses than the independent orbit and clock errors quoted e.g., in (IGSCB 2004). For completeness, we also provide the "orbit-only" value

$$\mathrm{SISRE}_{\mathrm{orb}} = \sqrt{\sigma^2(\Delta r_{\mathrm{R}}) + \frac{1}{7^2}(\sigma^2(\Delta r_{\mathrm{T}}) - \sigma^2(\Delta r_{\mathrm{N}}))} \quad (2)$$

to study the accuracy of the GPS ephemeris products irrespective of the clock quality.

When comparing GPS clock solutions from different sources, a de-trending is, furthermore, required to remove a bias and drift in the average clock solutions that is common to all GPS satellites. These parameters represent different implicit realizations of GPS system time and change the user clock solution but do not affect the positioning accuracy. In most cases the average bias of IGS rapid and ultra-rapid clock solutions with respect to the final values amounts to less than a few meters and the mean drift rarely exceeds a meter per day.

Using the above concepts, the quality of IGS rapid ephemerides and the observed part of IGS ultra-rapid ephemerides has been assessed in a day-by-day comparison with IGS final products for the May 2000 to November 2004 time frame. From an initial value of about 8 cm at the time of S/A deactivation, the combined orbit and clock error of the IGS rapid products has decreased to roughly 3 cm within these 5 years (Fig. 1). Likewise, the orbit-only SISRE improved by roughly a factor of 2–3 and presently amounts to 1 cm on average. The results demonstrate a high level of consistency between rapid and final IGS ephemeris products despite the widely different latency of both data sets.

The quality of ultra-rapid orbits as indicated by the value of $SISRE_{orb}$ improved from roughly 4 cm in early 2000 to 2 cm in 2004 and is thus only marginally worse than that of IGS rapid products (Fig. 2). However, a notably degraded performance may be observed, if clock errors are taken into account as well. Signal-In-Space Range Errors of typically 25 cm were encountered in the early years of the ultra-rapid ephemeris service but have now decreased to 8 cm on average. It may further be noted that the SISRE values exhibit a sudden degradation from April 2004 onwards, but have gradually recovered their earlier quality since then. The discontinuity coincides with the transition from 12 h update intervals to a 6 h update scheme and is probably related to operational changes in the combination of individual solutions from different Analysis Centers.

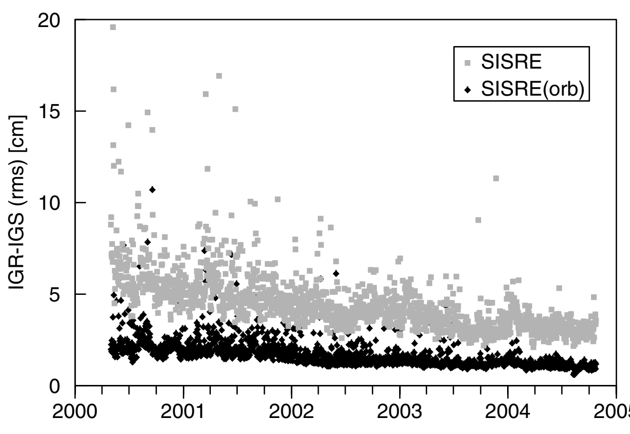

Fig. 1 Signal-In-Space Range Error (SISRE) for IGS rapid products. *Grey squares* indicate the SISRE including both orbit and clock errors, *black diamonds* indicate the contribution of orbit errors, only

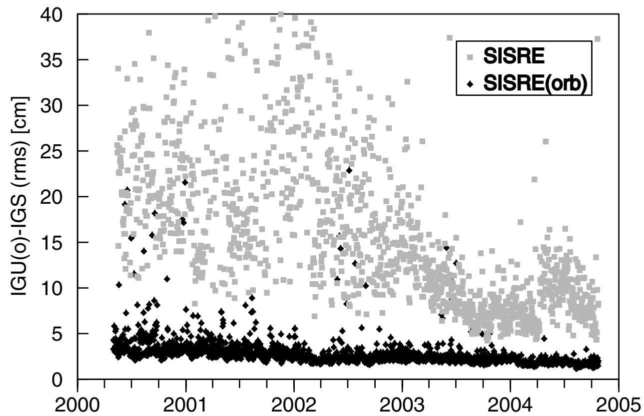

Fig. 2 Signal-In-Space Range Error (SISRE) for the observed part of IGS ultra-rapid products. Note the different scales in Figs. 1 and 2

Despite the remarkable overall accuracy of IGS ultra-rapid ephemerides achieved during the past 2 years, a notable number of erroneous values (exceeding the plot range of Fig. 2) is still present. Pronounced jumps in the ‘‘igu’’ clock solutions for individual GPS satellites are encountered on 2–4% of all days in 2003–2004. These discontinuities (e.g., 80 m on 18 August 2004) are clearly inconsistent with the physical clock behavior and must be attributed to the way, in which individual clock solutions form the contributing Analysis Centers are combined into a common IGS product. With proper outlier detection strategies, the erroneous clock values can readily be removed in precise point positioning or orbit determination applications. In particular, gross errors can be recognized by monitoring the deviation of individual clock solutions from a linear polynomial over 1 day. Nevertheless, a careful review of IGS combination strategies may be advisable to further improve the robustness of the igu products and facilitate their use in near real-time positioning.

Clock interpolation

When processing GPS measurements at epochs that do not coincide with grid points of the IGS ephemeris products, the position and clock offset of the observed GPS satellite have to be obtained by interpolation. In contrast to orbital data, high-order polynomial interpolation is not suitable for clock parameters due to the underlying random noise processes and linear interpolation is therefore advisable (J. Kouba, private communication). The errors resulting from the interpolation of clock data depend on the interval size and the Allan variance of the respective clock (cf. Kouba 2000; Zumberge and Gendt 2001). On the other hand, the interpolation error does not depend on the quality of the clock data set itself and can thus be incorporated into the Signal-in-Space Range Error as an independent and uncorrelated noise source.

To assess the error associated with the interpolation of 5 min and 15 min clock data sets, we made use of high-rate (30 s) clock solutions provided by the Center for Orbit Determination in Europe (AIUB 2004). The test data sets were first reduced to 5 min and 15 min intervals, then interpolated to 30 s steps and finally compared with the original data. To explore the dependence on the employed clock type, we distinguished between Block II/IIa satellites operating cesium clocks, Block II/IIa satellites working with rubidium clocks and Block IIR satellites that use rubidium clocks exclusively. Comparisons conducted at different epochs in the 2000–2004 time frame did not indicate a general trend in the clock noise characteristics. It is therefore appropriate to work with time-averaged values for the clock interpolation error that are summarized in Fig. 3 for the individual clock types.

The biggest errors are clearly encountered for Block II/IIa cesium clocks, which exhibit an r.m.s. interpolation error of almost 10 cm at 15 min intervals. This notably exceeds the accuracy of IGS final and rapid clock solutions and underlines the need for 5 min or even higher-rate clock products for undifferenced GPS data processing. Among the rubidium clocks, the best interpolation results are obtained for Block II/IIa satellites. For 5 min intervals the interpolation error decreases to a few centimeters for all clock types, even though the relative gain for rubidium clocks is less pronounced than for the Block II/IIa cesium clocks.

Over the past 5 years, a notable number of Block II/IIa satellites has been replaced by the follow-on IIR model. Also, numerous II/IIa satellites no longer operate their cesium clocks but have been switched to one of their backup rubidium clocks. The fraction of GPS satellites operating cesium clocks has thus decreased from 2/3 in early 2000 to about 1/3 in late 2004 (Fig. 4). This change has resulted in a continuous reduction of the average clock interpolation error for the entire GPS constellation from about 8 cm to 6 cm for 15 min interpolation and from 4 cm to 3 cm for 5 min interpolation. The results presented here are in good consistency with an analysis of GPS clock data performed by (Zumberge and Gendt 2001) right after the deactivation of Selective Availability. Based on a 2 weeks data set in May 2000, these authors determined an average interpolation error of 3.5 cm for 5 min interpolation that decreases linearly to 4 mm at 30 s sampling.

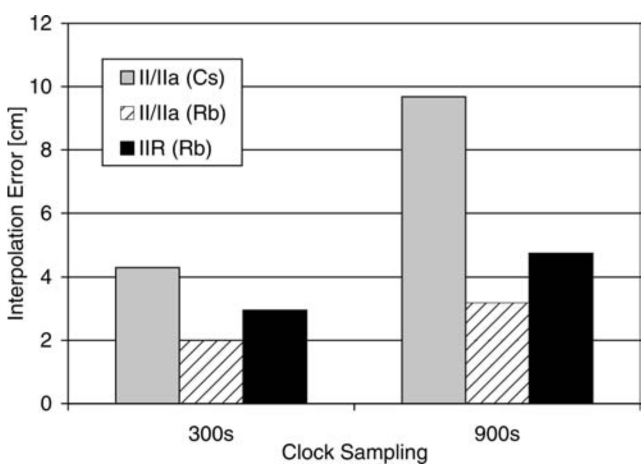

Fig. 3 Root-mean square error of GPS clock interpolation for 5 min and 15 min clock products

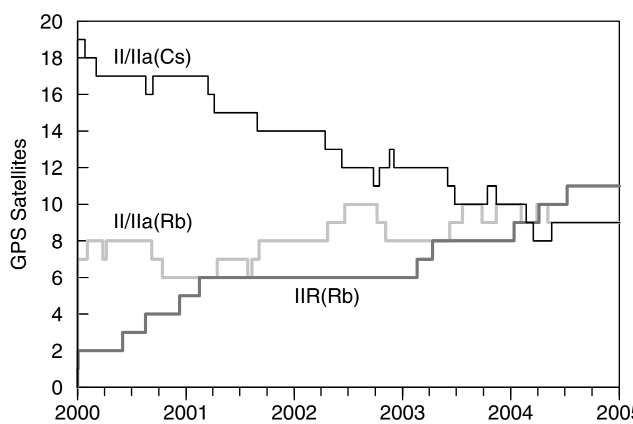

Fig. 4 Number of GPS satellites operating cesium and rubidium clocks

Precise orbit determination using GPS

Processing concept and software

Following its successful demonstration in a series of geodetic space missions (e.g., TOPEX, CHAMP, JASON), reduced dynamic orbit determination (cf. Yunck 1996) is now widely accepted as a standard technique for the GPS-based positioning of LEO satellites. Here, the deterministic model of the spacecraft dynamics is complemented by empirical accelerations that are adjusted along with other parameters in the orbit determination process. In this way, the high accuracy and kinematic strength of GPS measurements may be favorably combined with the robustness of purely dynamic orbit determination techniques.

For the present study of rapid orbit determination using IGS ephemeris products, a batch least-squares approach has been adopted. Compared to an extended Kalman filter, the batch estimation technique has earlier been shown to offer a better overall accuracy along with a lower sensitivity to measurement outages (Montenbruck et al. 2004). Even though the Kalman filter exhibits a notably reduced software complexity and improved run-time performance, high accuracy and reliability were considered of primary importance for the delivery of rapid orbit determination products. Using a least-squares estimation scheme, total computing times of about 2 min have been obtained on a standard desktop computer (3 GHz Pentium IV processor) for a 12 h data arc with 30 s observation interval. This is less than the time required for data downlink and pre-processing in representative missions and thus renders the batch estimator fully suitable for near real-time orbit determination.

All computations described, hereafter, have been performed using DLR's GPS High precision Orbit determination Software Tools (GHOST, van Helleputte 2004). The employed dynamical model comprises the gravitational acceleration of the Earth [using a 100×100 subset of the GGM01S model, (UT/CSR 2003), and supplementary terms for solid Earth, pole and ocean tides] as well the third-body perturbations caused by luni-solar gravity. Non-gravitational forces include the atmospheric drag (using a Jacchia-71 density model) and solar radiation pressure forces that are both described by a simple canon-ball model. Residual deficiencies of the deterministic force model are compensated by empirical accelerations in radial, transverse and normal direction which are adjusted in the orbit determination along with other parameters. One set of acceleration parameters is estimated per 10 min interval, which offers a good compromise between computational efficiency and time resolution.

Within GHOST, the GPS code and carrier measurements are treated as undifferenced observations. In this way the processing does not require supplementary ground station measurements but depends on the quality of the employed GPS clock solutions. All reference system transformations are modelled in accordance with IERS conventions (McCarthy 1996) and the resulting LEO trajectory is expressed in an Earth-fixed reference frame. The alignment of this frame is implied by the reference system of the employed GPS orbit products and is essentially independent of Earth orientation parameters used for intermediate transformations between terrestrial and inertial coordinate systems. Antenna positions relative to the center-of-mass are modelled using predetermined offsets in the spacecraft body systems and inertial spacecraft orientations derived from star sensor measurements. Further details of the GHOST dynamic, measurement and estimation models are given by (Montenbruck et al. 2004).

Considering the fact that solar-flux values and geomagnetic indices for modelling the atmospheric density in the Jacchia-71 model might not be available in (near) real-time applications, constant values of $F_{10.7} = \overline{F}10.7 = 160$ and $K_P = 3$ have been employed in this study when working with rapid and ultra-rapid GPS ephemeris products. True space weather indices (provided by the NOAA Space Environment Center) were only used in combination with high-latency, final IGS products. Any drag modelling errors caused by the use of constant flux values and geomagnetic indices were found to be well compensated by the estimation of empirical accelerations and no adverse impact on the resulting orbit determination accuracy could be detected.

For accurate orbit determination results, a thorough screening of bad GPS code and carrier phase measurements is crucial. A three-step processing scheme has therefore been adopted which is illustrated in Fig. 5. Following the reception of the LEO GPS observations and the auxiliary GPS ephemeris products, single-point position solutions are first obtained from the available pseudo-range measurements within the SPPLEO program. An adequate number (typically 5 or more) of tracked satellites is required to compute epoch-wise position and clock solutions and to perform a coarse consistency check. To fill any gaps and to obtain a continuous trajectory approximation for the entire data

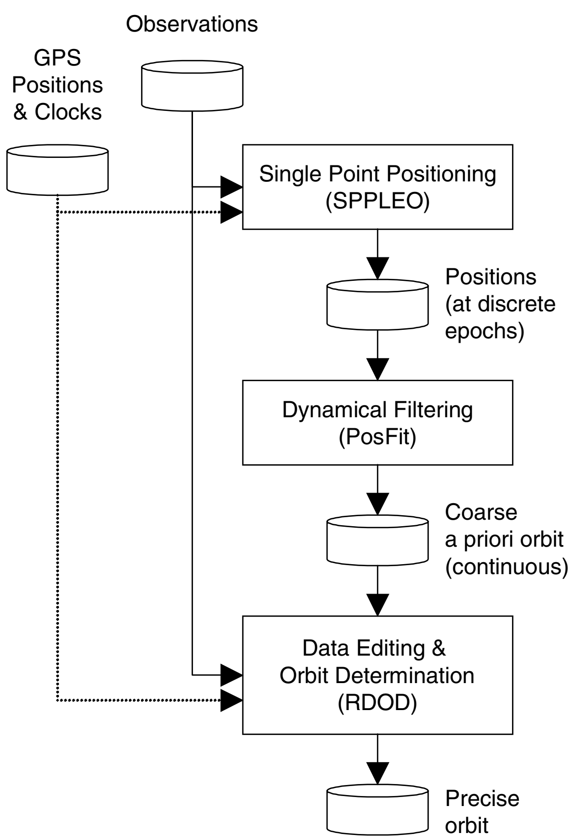

Fig. 5 Processing scheme for GPS-based precise orbit determination of LEO satellites

arc, the single-point positions are subsequently smoothed in the PosFit program which performs a preliminary dynamical trajectory adjustment. When working with dual-frequency observations, an accuracy of better than half a meter is obtained at this stage, which meets the requirements for the detection of outliers, cycle slips and bad measurements in the code and carrier observations The actual screening is performed inside the Reduced Dynamic Orbit Determination (RDOD) program, which employs the preliminary trajectory as a reference for various types of data consistency tests. The overall validity of this approach has been demonstrated in a series of tests and was found to provide robust results even in the presence of unstable GPS tracking, major outages and severe solar storms.

Data sets

The subsequent assessment of rapid orbit determination results is based on GPS measurements collected onboard the GRACE-B satellite. Level 1B science data from the GRACE mission (Case et al. 2002) are publicly available at the Physical Oceanography Distributed Active Archive Center (PODAAC 2004) and presently cover a time frame from end July 2002 to early August 2004. Aside from the GPS measurements themselves, the Level 1B data sets provide spacecraft attitude data derived from the GRACE star cameras and concise reference trajectories generated by the Jet Propulsion Laboratory.

Three independent data arcs in Nov. 2002, Oct./Nov. 2003 and July/Aug. 2004 have been selected for the comparison, each of which covers between 1 week and 2 weeks. Individual days with obvious tracking problems, large data gaps or periods of exceptional solar activity have been excluded from the analysis to avoid undue biases in the results. IGS final, rapid and ultra-rapid GPS orbit and clock products for all relevant dates were obtained from the archives of the IGS Central Bureau as indicated in Table 1. Likewise, CODE orbits and 30 s clock solutions were retrieved from the Astronomical Institute of Berne (AIUB 2004). Finally, JPL real-time generated orbits were provided by the Jet Propulsion Laboratory.

While the absolute accuracy of JPL's GRACE reference trajectories is not known with final confidence, we may note that precise orbit determination results obtained by different institutions (JPL, UT/CSR, TUM, DLR) exhibit representative differences of 5 cm (Kang et al. 2003; Montenbruck et al. 2004). Residuals of Satellite Laser Ranging measurements with respect to the GPS based orbits amount to roughly 2 cm (Dunn et al. 2003). Both values may serve as an indication of the presently achieved GRACE orbit determination performance.

Results and discussion

Orbit determination results obtained with different types of GPS ephemeris products are summarized in Table 2 for each of the three selected data arcs. The quoted accuracies represent the average root-mean square error of daily orbit determinations in comparison with JPL's reference orbits for the GRACE-B spacecraft. For each day, measurements at 30 s intervals covering a 12 h arc from noon to midnight have been processed.

A clear benefit of dense GPS clock data is obvious irrespective of the latency of the employed GPS ephemeris products. When working with 15 min IGS products an almost identical accuracy of roughly 10 cm is obtained with ultra-rapid, rapid and final ephemerides. A factor of two improvement is obtained both with rapid and final IGS products when combining the 15 min orbit data with separate 5 min clock information. Despite their small latency and large SISRE, the JPL ephemerides with 5 min sampling perform better than the IGS ultra-rapid ephemerides that are only available at 15 min steps. The best overall agreement with the available GRACE reference trajectories amounts to roughly 4 cm and was achieved when using CODE high-rate (30 s) clock solutions for the GPS constellation.

Almost identical pseudo-range residuals of about 35 cm are obtained in all cases, which suggests that the existing GPS clock and ephemeris errors are small enough to be masked by the code tracking noise even for geodetic-grade receivers. Pseudo-range residuals in excess of the measurement noise have only been encountered with JPL's real-time generated ephemerides that exhibit a SISRE of roughly 40 cm in November 2002.

Carrier-phase residuals, on the other hand, show a clear correlation with the noise contributed by the clock interpolation. Due to the adjustment of empirical accelerations and pass-by-pass biases for carrier-phase measurements, only short term GPS clock errors show up in the post-fit measurement residuals. These depend mainly on the interpolation interval but are essentially independent of the GPS ephemeris quality as shown by the near equal values obtained with IGS ultra-rapid, rapid and final products. Typically, carrier-phase residuals of 6 cm are obtained with clock data sampled at 15 min, and a factor-of-two reduction is achieved through the use of 5 min clock products. No interpolation at all is required with CODE's high-rate clock data that coincide with the 30 s measurement epochs. Here, carrier phase residuals of less than 1 cm are obtained. This additional improvement is only reflected in a moderate gain of the achieved orbit determination accuracy but facilitates a thorough measurement screening and cycle slip detection based on data residuals and consistency tests.

Table 2 GRACE-B orbit determination accuracy and measurement residuals (pseudorange and carrier phase) using different types of GPS ephemeris products (12 h data arcs)

Ephemeris	Position rms (m)	PR resid rms (m)	CP resid rms (m)	SISRE (orb) rms (m)	SISRE rms (m)	Interpolation rms (m)
Nov. 2002						
igu (15 m)	0.110	0.35	0.053	0.030	0.155	0.068
igr (15 m)	0.107	0.35	0.052	0.015	0.041	0.068
igs (15 m)	0.107	0.35	0.052	–	–	0.068
rtg (5 m)	0.089	0.42	0.033	0.183	0.376	0.032
igr (5 m)	0.049	0.34	0.030	0.015	0.041	0.032
igs (5 m)	0.049	0.34	0.030	–	–	0.032
cod (30 s)	0.043	0.34	0.009	0.019	0.087	–
Oct./Nov. 2003						
igu (15 m)	0.109	0.36	0.050	0.026	0.080	0.062
igr (15 m)	0.103	0.36	0.051	0.014	0.035	0.062
igs (15 m)	0.099	0.36	0.050	–	–	0.062
rtg (5 m)	0.068	0.36	0.030	0.104	0.213	0.031
igr (5 m)	0.057	0.34	0.030	0.014	0.035	0.031
igs (5 m)	0.056	0.34	0.030	–	–	0.031
cod (30 s)	0.043	0.34	0.009	0.021	0.045	–
July/Aug. 2004						
igu (15 m)	0.086	0.35	0.045	0.018	0.096	0.059
igr (15 m)	0.087	0.35	0.045	0.012	0.033	0.059
igs (15 m)	0.087	0.36	0.044	–	–	0.059
rtg (5 m)	0.070	0.36	0.029	0.088	0.164	0.029
igr (5 m)	0.052	0.34	0.030	0.012	0.033	0.029
igs (5 m)	0.051	0.34	0.030	–	–	0.029
cod (30 s)	0.043	0.34	0.009	0.019	0.046	–

The specified position error has been determined relative to JPL reference trajectories for the GRACE-B spacecraft. For comparison the Signal-In-Space Range Error of the employed GPS ephemerides (referred to IGS products at 15 min steps) and the associated interpolation error for 30 s measurement intervals is given

Complementary to the half-daily data arcs considered so far, the case of 2 h batches covering the final (observed) part of the employed GPS orbit and clock products has been considered. It reflects the rapid processing of GPS measurements collected between consecutive ground station contacts of a user spacecraft. Here, border effects are expected to be more pronounced, which may degrade the achievable orbit determination accuracy. Results collated in Table 3 for the July/Aug. 2004 period do in fact exhibit a slightly lower performance even though the achievable accuracy with ultra-rapid and real-time generated GPS ephemeris products is still highly satisfactory. As for the longer orbit determination arcs, the benefit of 5 min clock samples is again clearly evident.

Summary and conclusions

A comparison of GPS ephemerides and their use for GPS-based precise orbit determination of LEO satellites has been conducted. To avoid the need for supplementary ground station data, an undifferenced processing has been assumed which requires both accurate GPS orbit and clock information.

Among the publicly available IGS data sets an almost identical performance is achieved with rapid and final products. Given a latency of 17 h and the 1 day update interval of IGS rapid ephemerides, high precision (5 cm) orbit determination results can thus be generated within 41 h after the measurement epoch. A slightly smaller processing delay of 34 h and an even better orbit determination accuracy is achieved with CODE rapid orbit and high-rate clock products, even though the associated guarantee of service remains to be assessed.

A notably faster turnover time (less than 9 h) is offered by the use of IGS ultra-rapid products that are presently generated four times per day with a 3 h latency. They provide observed GPS orbit data with a Signal-In-Space Range Error of only 2 cm (compared to IGS final orbits) but exhibit a notably lower clock data accuracy than the rapid products. More important, however, is the fact that IGS ultra-rapid clocks are only available at 15 min samples, which introduces a major interpolation error and limits the achievable orbit determination accuracy to 10 cm.

So far, only JPL's real-time generated GPS orbit and clock products can be used for rapid orbit determination of LEO satellites with total processing delays of presently 1–2 min (Bar-Sever, private communication) after

Table 3 GRACE-B orbit determination accuracy and measurement residuals for 2 h data arcs. Other data as in Table 2

Ephemeris	Position rms (m)	PR resid rms (m)	CP resid rms (m)
July/Aug. 2004			
igu (15 m)	0.116	0.37	0.043
igr (15 m)	0.115	0.36	0.041
igs (15 m)	0.115	0.36	0.041
rtg (5 m)	0.073	0.36	0.027
igr (5 m)	0.063	0.35	0.027
igs (5 m)	0.061	0.35	0.027
cod (30 s)	0.048	0.34	0.007

the measurement epoch. In addition to its small latency this service now offers 1 min clock solutions and thus enables more accurate orbit determination results than the use of IGS ultra-rapid ephemerides. However, these products must be specifically requested from JPL.

To support the increasing interest in rapid and precise orbit determination of LEO satellites, the IGS is encouraged to further enhance its ultra-rapid ephemeris service. Desired improvements include an increased update interval and reduced latency to better meet the timelines requirements of upcoming space missions. A notable benefit is expected from an increased clock sampling rate (5 min or better) for ultra-rapid products, which would help to improve the achievable near real-time orbit determination accuracy to a level of 5–7 cm. Finally, a careful review of the clock combination process is suggested to reduce the existing risk of anomalous clock data and to further enhance the quality and robustness of the IGS ultra-rapid ephemerides.

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