AIMING AT A 1-CM ORBIT FOR LOW EARTH ORBITERS: REDUCED-DYNAMIC AND KINEMATIC PRECISE ORBIT DETERMINATION

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Abstract. The computation of high-accuracy orbits is a prerequisite for the success of Low Earth Orbiter (LEO) missions such as CHAMP, GRACE and GOCE. The mission objectives of these satellites cannot be reached without computing orbits with an accuracy at the few cm level. Such a level of accuracy might be achieved with the techniques of reduced-dynamic and kinematic precise orbit determination (POD) assuming continuous Satellite-to-Satellite Tracking (SST) by the Global Positioning System (GPS). Both techniques have reached a high level of maturity and have been successfully applied to missions in the past, for example to TOPEX/POSEIDON (T/P), leading to (sub-)decimeter orbit accuracy. New LEO gravity missions are (to be) equipped with advanced GPS receivers promising to provide very high quality SST observations thereby opening the possibility for computing cm-level accuracy orbits. The computation of orbits at this accuracy level does not only require high-quality GPS receivers, but also advanced and demanding observation preprocessing and correction algorithms. Moreover, sophisticated parameter estimation schemes need to be adapted and extended to allow the computation of such orbits. Finally, reliable methods need to be employed for assessing the orbit quality and providing feedback to the different processing steps in the orbit computation process.

Keywords: precise orbit determination, reduced-dynamic, kinematic, GPS, LEO

1. Introduction

The launch of CHAMP in July 2000 has triggered significant efforts by many scientific institutes in the field of precise orbit determination (POD). Without very high precision orbit determination, one of the most important mission objectives of CHAMP cannot be reached, namely a significant improvement in global Earth gravity field modeling (Reigber et al., 1999). High-precision orbit determination becomes even more of a challenge for the upcoming GRACE mission (launch in March 2002) and the future GOCE mission (expected launch in early 2006). These missions are much more demanding in terms of gravity field modeling performance than CHAMP and even more stringent orbit accuracy requirements are imposed. In order to get the most out of these missions, an orbit accuracy at the cm level is aimed at (NRC, 1997; ESA, 1999). All previously mentioned missions are Low Earth Orbiters (LEOs) flying at very low altitudes, in the 240–450 km height range

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above the Earth's surface. An orbit accuracy level of a few cm can only be achieved with high-quality, continuous tracking, such as achieved by high-quality space-borne receivers that acquire Satellite-to-Satellite Tracking (SST) observations to the Global Positioning System (GPS), appropriate data preprocessing and correction schemes, and orbit parameter estimation techniques. Two such techniques will be addressed below. They are referred to as reduced-dynamic and kinematic precise orbit determination.

POD is also in the spotlight due to the recent launches of Jason-1 (December 2001), equipped with a GPS receiver, and ENVISAT (March 2002), equipped with a DORIS receiver. For these missions, an orbit accuracy of about 1 cm is aimed at as well (particularly for the radial direction), but in these cases the satellites fly at higher altitudes, 1336 and 800 km, respectively, and a high orbit precision is required to support the interpretation of radar altimeter observations (Jason-1 and ENVISAT) and images taken by the Synthetic Aperture Radar (ENVISAT).

After introducing the principles of kinematic and reduced-dynamic POD, a few recent results will be discussed, including simulation studies to assess achievable orbit accuracies for GOCE and to identify critical items. After this, attention will be paid to activities related to the CHAMP mission, which is now in the center of LEO POD activities. Moreover, POD of CHAMP is the focus of an international initiative by the International GPS Service (IGS) to improve LEO POD. This initiative includes the application and tuning of reduced-dynamic and kinematic orbit determination schemes and upgrading of observation preprocessing and correction algorithms.

2. Precise Orbit Determination

In general, orbit determination is composed of the following steps: (1) collecting, preprocessing and correcting tracking observations, (2) defining standards and reference systems, (3) defining dynamic (optional) and satellite models, (4) estimating parameters and (5) assessing/verifying the orbit accuracy.

The focus in the remainder of this paper will be on the 4*th* step, namely two parameter estimation techniques referred to as reduced-dynamic and kinematic orbit determination. In dynamic orbit determination, the orbit is obtained by determining those state vector values, e.g., initial position and velocity at the start of an orbital period, atmospheric and solar radiation scaling parameters, etc., in such a way that the resulting orbit represents all observations best in a least squares sense. The orbit is completely determined by the dynamic model implemented in the equations of motion.

Reduced-dynamic orbit determination might be defined as a dynamic orbit determination augmented with an additional set of dynamic parameters, e.g., empirical accelerations. In general, at least two important parameters can be optimized (or *manipulated*) with respect to these accelerations: the correlation length or time interval τ and the a priori standard deviation σ_{acc} (see also (Wu et al., 1990)). These parameters should reflect the quality of the a priori dynamic models (Visser and van den IJssel, 2000). Another important parameter is the weight of the tracking observations, which in fact has to be optimized simultaneously with the empirical acceleration parameters. Reduced-dynamic orbit determination may be seen as a trade-off between using a priori knowledge in the form of dynamic models and geometric information content of tracking observations. In the case of an optimal trade-off, reduced-dynamic orbit determination should give the best orbit solution possible using a certain data set of tracking observations. Different implementations of reduced-dynamic orbit determination techniques exist, which can be divided into sequential and batch parameter estimation methods, for example Kalman filtering and batch least squares estimation with constraint equations. Dynamic orbit determination can be considered to be a limit of reduced-dynamic orbit determination and is effectively obtained by specifying $\tau = \infty$ and $\sigma_{acc} = 0$.

Kinematic orbit determination is based on the idea that no a priori dynamic models are required in deriving the orbit positions of the LEO satellite. In a way, it can be regarded as the other limit of reduced-dynamic orbit determination, where the weight of the a priori dynamic model approaches the value zero by specifying $\tau = 0$ and $\sigma_{acc} = \infty$. Kinematic orbit determination can be categorized in point positioning methods, where the position of the LEO satellite is obtained for each epoch by geometric relations between the GPS observations and the GPS and LEO positions (Bock et al., 2001; Svehla and Rothacher, 2001), and sequential estimation methods, where use can be made of, e.g., a Kalman filter (Byun and Schutz, 2001).

In the case of kinematic POD, the point positioning method can only result in cm level orbits when using phase observations and fixing (a significant percentage of) the ambiguities. The sequential estimation method is more flexible with respect to the form in which the observations are used and the character and amount of unknowns (Bisnath and Langley, 2001).

The reduced-dynamic orbit determination technique allows the inclusion of dynamic models. This technique also allows the estimation of certain dynamic parameters, including the initial position and velocity of LEO and GPS satellites and empirical accelerations. An important issue that needs to be addressed concerns the computation of the orbits of the GPS satellites: it has to be assessed whether the best LEO orbit is obtained by estimating this orbit simultaneously with the LEO orbit or not.

3. Results

The capability of computing sub-decimeter accuracy orbits has been demonstrated for a few satellite missions in the past. Further improvements in terms of orbit accuracy, down to the cm level, are expected to be realized for currently flying satellites. The following two sections will address results obtained with a few typical satellites that are equipped with a space-borne GPS receiver.

3.1. Past Missions and Feasibility Studies

Decimeter level accuracy orbits were for the first time demonstrated for the T/P satellite, which was not only equipped with a GPS receiver, but also with a DORIS receiver and an array of SLR retro-reflectors allowing an independent assessment of the achieved orbit quality (Smith et al., 1994). The accuracy in the radial direction is estimated to be around 3 cm (Tapley et al., 1994). Although the GPS receiver allowed tracking of at most six GPS satellites simultaneously, the concepts of reduced-dynamic and kinematic POD could be tested successfully for this satellite.

The reduced-dynamic POD technique should be relatively insensitive to dynamic model errors provided that a proper accuracy assessment of the dynamic models is made and in conjunction the empirical acceleration unknowns are properly tuned. Reduced-dynamic and dynamic T/P orbits computed with the JGM2 gravity field model display similar differences as dynamic orbits computed with the JGM2 and JGM3 gravity field models (Figure 1), where the JGM3 gravity field model is a significant improvement over JGM2 (Tapley et al., 1994). In other words, the reduced-dynamic POD technique in combination with a relatively inaccurate gravity field model provides an orbit with about the same accuracy as a dynamic orbit using a more accurate gravity field model, thereby proving the feasibility of this technique.

The reduced-dynamic T/P orbit accuracy clearly depends on the correlation times and a priori and steady-state standard deviations (denoted by σ_p and σ_0). Different settings of these parameters may lead to orbit differences of the order of 10 cm 3-dimensionally for this relatively high-flying satellite (Figure 2).

Figure 3 displays the orbit differences between a T/P orbit obtained by a sequential filter kinematic technique and a high-precision reduced-dynamic orbit solution. The tracking data consisted of undifferenced single-frequency pseudo-range and phase observations. This experiment suggest that a 3-dimensional orbit accuracy of about 30 cm is possible for T/P using a kinematic POD approach. Other experiments have indicated that this can be improved to better than 15 cm, *cf.* (Byun and Schutz, 2001).

Probably the most challenging planned satellite from the viewpoint of POD will be the GOCE satellite, which will fly at an extremely low altitude around 240–250 km. A detailed orbit accuracy assessment has been conducted by full-scale reduced-dynamic and kinematic POD simulations. It was found that the eventually achievable orbit accuracy depends on the success of carrier phase ambiguity fixing (especially for the kinematic approaches) and thus on the quality of the GPS receiver (especially the quality of the pseudo-range observations). When ambiguity fixing cannot be done, the accuracy of the reduced-dynamic orbits depends to some

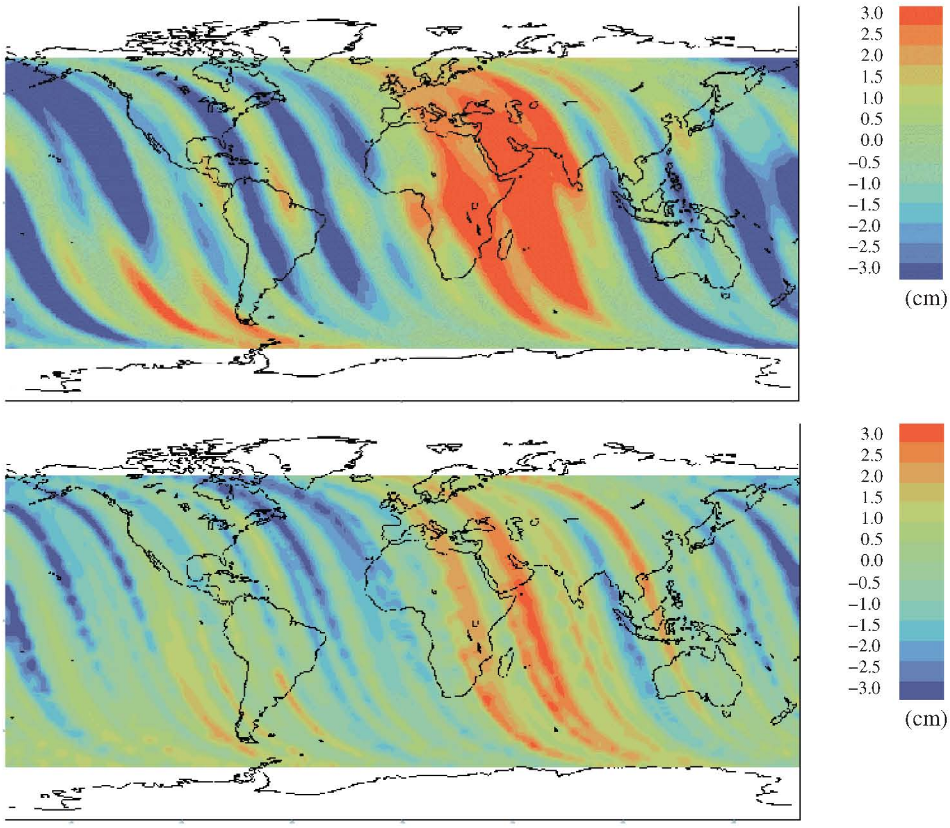
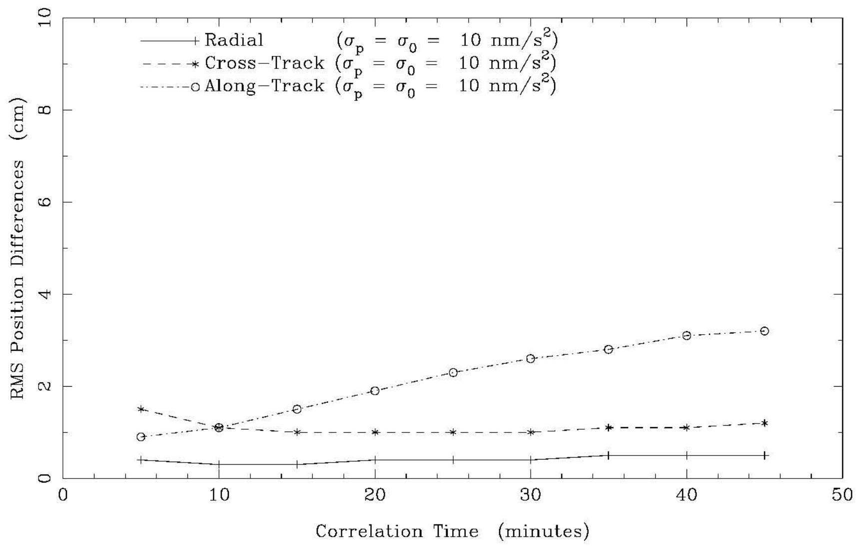


Figure 1. Comparison between reduced-dynamic and dynamic T/P orbits using different gravity field models (orbits by *F. Nouel (CNES, France)*, Kalman filter). In this particular case the orbits were based on DORIS tracking data, which is also near-continuous in time. Similar results were obtained with GPS data (Smith et al., 1994). The top figure displays the radial orbit differences between dynamic orbits obtained using JGM2 and JGM3. The bottom figure displays radial orbit differences between a dynamic orbit and a reduced dynamic orbit obtained using JGM2.

extent on the quality of the a priori dynamic models and the risk arises of "biting one's own tail", because the primary mission objective of GOCE is to obtain a very accurate and high-resolution gravity field model. The GOCE simulations indicate that the achievable 3-dimensional orbit accuracy is about 3 cm when the ambiguities can be fixed (reduced-dynamic and kinematic), but this accuracy can deteriorate significantly when the ambiguities cannot be fixed (see Tables 4 and 5 in (Visser and van den IJssel, 2000)). The results were inconclusive concerning the issue of simultaneously estimating the LEO and GPS orbits or fixing the orbits of the latter, e.g., to the solution provided by the IGS. Similar GOCE orbit accuracies were obtained with both concepts. The simulations included the incorporation of accelerometer observations in the POD. It was assumed, however, that these observations must meet the requirements of the mission ("specs") and the issue of



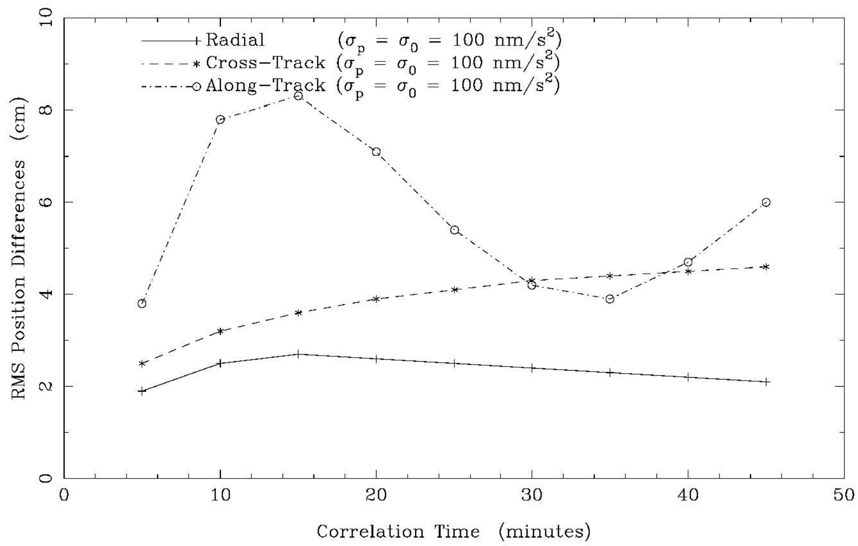


Figure 2. Differences with respect to "best" T/P reduced-dynamic orbit caused by different values for the correlation time and acceleration standard deviation (Gauss-Markov, Kalman filter). Results were obtained with JPL GIPSY/OASIS software using the JGM1 gravity field model.

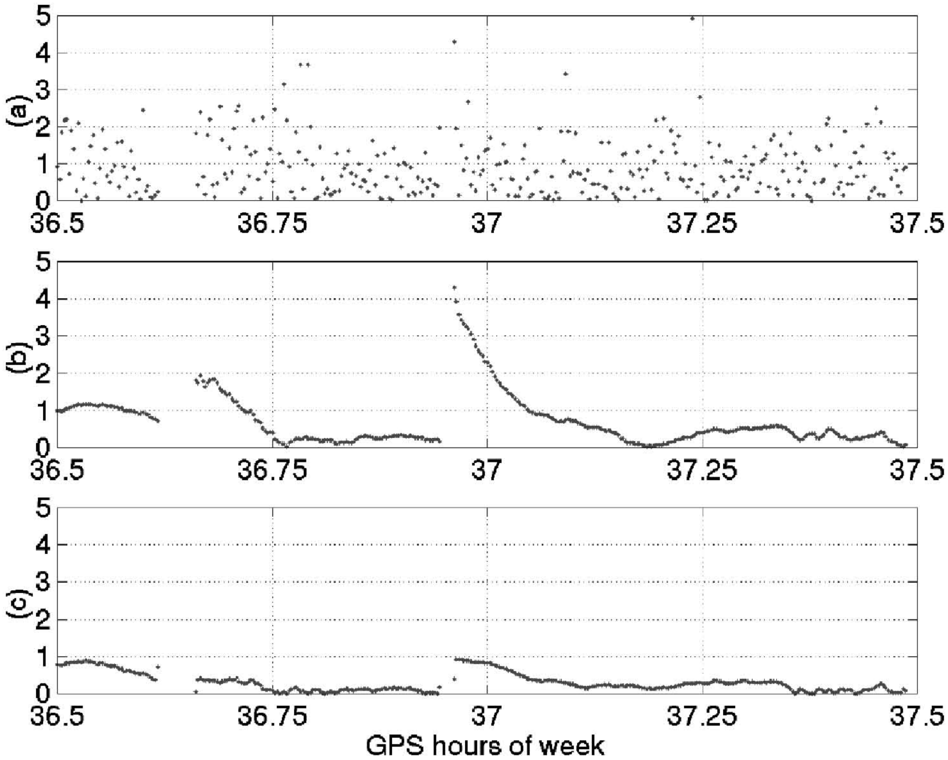


Figure 3. Comparison of T/P orbit obtained by a sequential filter kinematic technique and high-precision JPL POE for 13 November 2000. The rms of 3-dimensional orbit errors is equal to 154 cm when using pseudo-range observations (top), 43 cm in the forward filter step using phase observations (middle) and 33 cm after backward smoothing (bottom). Results were provided by *S. Bisnath, New Brunswick* (values along vertical axis in m).

accelerometer biases and scale factors was not addressed. Recent experiences with the CHAMP accelerometer data show that this issue needs further attention. More details of the GOCE simulations can be found in (Visser and van den IJssel, 2000).

3.2. Current Missions

High-precision orbit determination is now the focus of activities related to, e.g., the Jason-1 satellite (GPS, DORIS, SLR), ENVISAT (DORIS, SLR) and CHAMP (GPS, SLR, accelerometer). CHAMP obviously poses the biggest challenge, because it flies at very low altitudes, 450 km and below. It has to be noted that precise orbit determination is also a challenge for ENVISAT despite the fact that it flies at a much higher altitude of 800 km. This is because the modeling of non-gravitational forces is very complicated due to its massive dimensions. The focus of this section is on CHAMP POD activities, because kinematic POD for ENVISAT

TABLE I

DEOS CHAMP GPS-based reduced-dynamic orbit determination

6-hour overlaps (cm)					SLR rms (cm)	
DOY 2001	Radial	Along-track	Cross-track	Norm	DOY 2001	SLR rms
140–141	1.46	2.03	2.03	3.22	140	5.26
141–142	2.04	3.32	1.88	4.33	141	5.01
142–143	1.74	3.00	2.52	4.29	142	4.88
143–144	1.25	2.39	1.49	3.08	143	3.17
144–145	1.85	2.89	1.69	3.83	144	6.33
145–146	0.99	1.68	2.16	2.91	145	3.61
146–147	1.56	2.65	2.90	4.23	146	2.52
147–148	1.75	1.41	1.61	2.77	147	4.96
148–149	0.91	1.76	1.38	2.42	148	5.55
149–150	1.16	1.85	1.66	2.74	149	3.49

Comparison with external orbits				
Institute	Radial	Along-track	Cross track	Norm
TUM	8.81	9.53	8.71	15.63
UT/CSR	2.67	6.01	4.21	7.81

is impossible, since it is not equipped with a GPS receiver. These activities were carried out predominantly in the framework of the IGS/LEO POD Pilot Project (IGSLEO PP) (*http://nng.esoc.esa.de/gps/igsleo.html*, accessed May 2002).

Reduced-dynamic orbits have been computed by several institutes, including the Delft Institute for Earth-Oriented Space Research (DEOS). The DEOS reduced-dynamic POD approach is based on ionospheric-free triple-difference GPS observations with a ground network of 50 GPS stations and the estimation of radial, along-track and cross-track accelerations in 30-min intervals, *cf.* (Rim et al., 2001). The a priori dynamic model included the TEG-4 gravity field model (Tapley et al., 2001). The rms of fit of the observations is about 0.3 mm/s (30 second time interval). The IGSLEO Pilot Project test period covers DOY 140–150, 2001. The orbit arc length was selected to be equal to 30 hours resulting in 6-hour overlaps between consecutive orbit solutions. The rms of 3-dimensional overlap orbit differences (status 8 March 2002) was found to be at the 3 cm level and the comparison of the GPS-derived CHAMP orbits with SLR observations (which were not used in the POD) results in rms of fit values of around 5 cm, including all laser stations which tracked CHAMP in the relevant time frame (Table I).

Comparisons were made between reduced-dynamic orbits computed by the Technical University of Munich (TUM) and the Center for Space Research of the

University of Texas (UT/CSR). These orbits were all computed or provided in the same time frame (January 2001 – March 2002) and are of good quality enabling a “fair” comparison (CHAMP orbit accuracy improved rapidly in the first months of 2002). The 3-dimensional orbit differences are at the 15 cm (TUM) and 8 cm level (CSR) indicating that it is fair to assume that orbit solutions are converging to within the decimeter level. Moreover, TUM is currently (March 2002) computing kinematic orbit solutions for CHAMP that are in close agreement with its reduced-dynamic POD solutions (M. Rothacher and D. Svehla, personal communication). One of the questions that needs to be addressed is whether orbit accuracy and consistency can be improved by including the CHAMP accelerometer observations in the POD. This issue currently attracts much attention, but is yet unresolved. Issues like accelerometer bias and scale factor estimation are under review and algorithms are updated continuously.

4. Conclusions and Outlook

Reduced-dynamic and kinematic precise orbit determination of LEO satellites have evolved into mature techniques. The feasibility and capability of these techniques have been clearly demonstrated by missions in the past and by the existing CHAMP satellite. GPS-based LEO orbit accuracies are rapidly approaching the cm level.

In order to further improve orbit accuracy, clear challenges can be identified in the field of carrier phase ambiguity resolution. Moreover, more attention needs to be paid to optimal parameter estimation schemes (such as keeping GPS orbits fixed or estimating them simultaneously with the LEO orbit). Other issues that deserve more attention are the inclusion of attitude and accelerometer observations in the POD. In addition, a satellite like GOCE will be equipped with a Drag Free Control (DFC) system. DFC information might also be included and help improving orbit accuracy. Concerning GRACE, it is interesting to assess the possible impact of using low-low SST in the POD and to apply space-borne GPS differencing schemes.

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