CHAMP double-difference kinematic POD with ambiguity resolution

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Summary. Purely kinematic precise orbit determination (POD) was performed for the CHAMP satellite over 11 days in the framework of the CHAMP Orbit Comparison Campaign. For the same period, reduced-dynamic orbits were computed and both types of orbits were independently validated by SLR. The tests with SLR showed that the accuracy of CHAMP reduced-dynamic POD is at the level of 4-5 cm, whereas kinematic orbits have a quality of 5-6 cm. Neither in the kinematic nor in the dynamic orbits a significant SLR range bias could be detected. In addition, we will present results concerning the ambiguity resolution techniques used.

Key words: CHAMP, LEO, kinematic orbit, dynamic orbit, POD

1 Introduction

The CHAMP satellite with its very low altitude orbit opened a new era in precise orbit determination with GPS. Low altitude orbits pose high requirements on the orbit modeling due to the highly dynamic environment: on one side one has to cope with increased effects from the gravity field and on the other side there is a big influence of the non-conservative forces like air-drag and solar-radiation pressure. From that point of view, LEO orbits are very well-suited for various Earth sensing activities like, e.g., gravity field and magnetic field recovery and atmosphere sounding but as we come closer and closer to the Earth, the gravity field and non-conservative forces, especially air-drag, become more and more difficult to model or estimate. Kinematic orbit determination is therefore an interesting alternative to the reduced-dynamic approach, because it is fully independent of the forces acting on the satellite and our orbit modeling capabilities. The accuracy of kinematic positions only depends on the accuracy of the carrier-phase measurements and the number and constellation of the GPS satellites tracked. Instead of using the enormous amount of LEO GPS measurements, one might then use the kinematic positions, with corresponding variance/covariance information, as pseudo-observations to determine gravity field coefficients and other dynamical parameters.

In Sections 2 we will give an overview of our reduced-dynamic POD approach and then focus in Section 3 on purely kinematic CHAMP orbits. Results of ambiguity resolution over the period of 11 days will be presented in Section 3 and both types of orbits will be compared with SLR measurements and with the orbits of other POD centers.

2 Reduced-Dynamic POD

The concept of using dynamical models together with measurements stemming from the LEO spaceborne GPS receiver in precise orbit determination has been very well tested and documented in various papers. Some recent CHAMP results can be found, e.g., in (Rim et al. 2001), (König et al. 2001). By measuring the total effect of all non-conservative forces (e.g. air-drag and solar-radiation pressure) acting on the surface of the LEO with accelerometers, a separation of the gravitational force from the non-conservative forces is possible and gravity field recovery can be performed. That was for the first time demonstrated using the data of the CHAMP satellite and the new gravity model EIGEN1S was derived, see (Reigber et al. 2002).

Let us now have a closer look at our approach for reduced-dynamic POD. We use carrier-phase GPS measurements only and we may compute orbits on either the zero- or double-difference level. One of the advantages of using double-differences is, that we get rid of all epoch-wise GPS and LEO clock parameters. The drawback is, that measurements from the IGS ground network have to be included. The main advantage of the double-difference approach is, however, that ambiguity resolution can be done and in this paper we will consider only the double-difference approach. More information about the zero- and double-difference approach may be found in (Švehla and Rothacher, 2001). As mathematical model we use a normal least-squares adjustment with variational equations without making use of any filtering. The basic idea of our dynamic POD can be summarized in the following two step procedure: 1) using kinematic positions as pseudo-observations all dynamic parameters are solved for and an a priori dynamic orbit is computed. The partial derivatives of the satellite position with respect to all orbit parameters are computed in this step by a simultaneous integration of the equation of motion and the variational equations; 2) using the carrier-phase measurements the a priori orbit is improved by estimating orbital parameters and pseudo-stochastic pulses. Alternatively, the second step could be replaced by using highly accurate kinematic positions as pseudo-observations for the estimation of all dynamical parameters.

After the least-squares adjustment the orbits are defined by 6 initial conditions (Keplerian elements), 9 solar radiation pressure parameters, 1 scaling factor for the air-drag and pseudo-stochastic pulses in along-track, cross-track

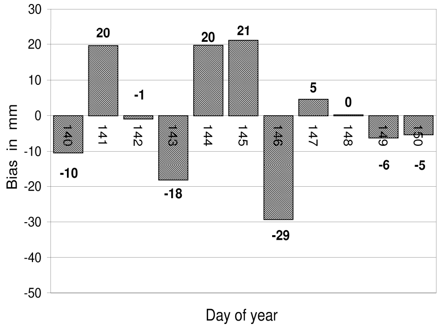


Fig. 1. Daily SLR range bias for dynamic orbit, mean SLR bias= -1.1 mm ± 44 mm over all SLR residuals.

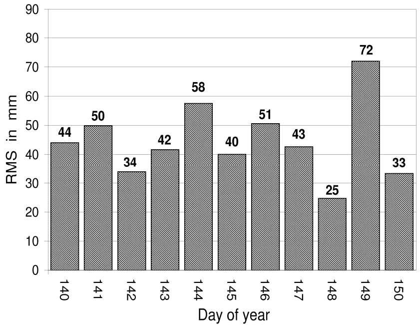


Fig. 2. Daily RMS of SLR residuals for dynamic orbit, RMS=44.3 mm over all SLR residuals.

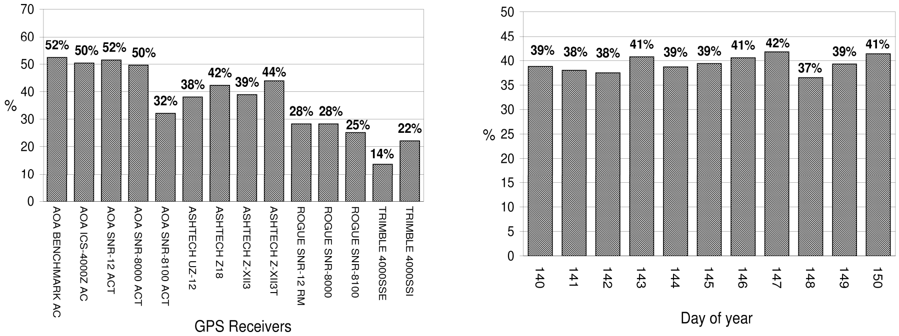
and radial component. The pseudo-stochastic pulses are small changes in velocity which allow a better fit of the orbit to the measurements and are set up every 9 minutes in our case. The nice feature of these pseudo-stochastic pulses is, that partials can be computed as a linear combination of the partials with respect to the osculating elements. More frequent setting up of stochastic pulses may be considered equivalent to modeling the air-drag with more parameters. Air-drag densities are modeled using MSISE-90, see (Hedin 1991).

The dynamic orbits determined in arcs of 24 hours were validated by SLR measurements over the period of 11 days and the RMS of the SLR residuals is presented in Fig. 2. The SLR residuals were computed as the difference between the SLR measurements (corrected for the tropospheric delay with the Marini-Murray model) minus the distance between the SLR station and the GPS-derived orbit position. Altogether 2007 SLR residuals were obtained in this way using 69 daily station files from 17 SLR stations.

The mean RMS of the reduced-dynamic orbit over 11 days is 44.5 mm and Figure 1 clearly shows that there is no significant SLR range bias in the dynamic orbit. Station-dependent SLR biases were not estimated in this analysis, although some SLR stations might have significant range biases.

3 Kinematic POD

Kinematic POD procedures were developed for the zero- and double-difference processing of carrier-phase measurements. There was no improvement in orbit accuracy by including code measurements. Since ambiguity resolution can only be done with double-differences we prefer the double-difference POD approach. An alternative zero-difference approach based on forming differences



(a) w.r.t. types of GPS receivers (b) w.r.t. days 140-150 of 2001.

Fig. 3. Percentage of resolved Melbourne-Wübbena ambiguities over 11 days.

between phase observations of consecutive epochs and avoiding ambiguity parameters can be found in (Bock et al. 2001). Our kinematic POD approach is also based on a least-squares adjustment without making use of filtering. The use of Kalman filtering in long-distance kinematic GPS is discussed in (Colombo et al. 1998), (Colombo et al. 2000) and (Bisnaith and Langley 2001). By forming double-differences between the IGS ground stations and the CHAMP satellite, epoch-wise GPS and LEO clocks are eliminated and CHAMP kinematic positions and ambiguities are the remaining parameters. In order to avoid an impact of the ionosphere on ambiguity resolution, wide lane ambiguities were estimated by making use of the Melbourne-Wübbena linear combination of code and phase observations. Figure 3(a) shows the percentage of resolved wide-lane ambiguities over 11 days and Figure 3(b) the percentage of resolved wide-lane ambiguities for each receiver type. One can immediately see that some of the IGS receivers are better performing than others. This is due the fact that not all of them provide P-code measurements on both, the L1 and L2 frequency. According to (Ray 2002) there are three main classes of GPS receivers within the IGS network, namely: 1) cross-correlators that observe C1 and P2'=C1 + (P2-P1) (ROGUE SNR-x, AOA ICS-4000Z, TRIMBLE 4000, and TRIMBLE 4700); 2) Y-codeless, non-cross-correlators that observe P1 and P2 (ASHTECH Z-XII3, AOA SNR-12 ACT, and AOA BENCHMARK ACT); 3) C1, Y-codeless, non-cross-correlators that apparently function like other modern Y-codeless receivers but report C1 (instead of P1) and P2 (TRIMBLE 5700, LEICA CRS1000, and LEICA SR9600). For those receivers that do not provide P-code measurements on both frequency the use of differential code biases (P1-C1) for the GPS satellites, available from (Schaer 2002), considerably improves wide-lane ambiguity resolution.

Subsequently, by using the ionosphere-free linear combination of the carrier-phase measurements and the resolved wide-lane ambiguities, an iterative resolution of the narrow-lane ambiguities (bootstrapping) can be performed. Two main methods were developed to perform this narrow-lane ambiguity resolution. In the kinematic bootstrapping epoch-wise coordinates are pre-eliminated in order to reduce the size of the normal-equation matrix. The first solution is a float solution where the ambiguities are real numbers. Then the best estimated ambiguities are set to integer numbers, the normal equation system is updated and re-inverted and the whole procedure is repeated. More about this type of bootstrapping and the criteria applied for ambiguity fixing can be found in (Švehla and Rothacher, 2001). The same procedure can also be used when estimating dynamic orbit parameters and we then speak of dynamical bootstrapping. Baseline-wise ambiguity resolution could in principle be applied for kinematic as well as for dynamic orbits, but highly accurate a priori orbits have to be available in that case. The orbits are then fixed in the baseline by baseline ambiguity resolution. The drawback of this method is, that the criteria to fix the ambiguities have to be very restrictive in order to assure that ambiguities are correctly resolved. In principle, baseline-wise ambiguity resolution can be performed iteratively: after the first baseline-wise ambiguity resolution step a new orbit is computed making use of the fixed ambiguities and a new iteration of the baseline-wise ambiguity resolution is performed with the updated orbits. Our experience with baseline-wise ambiguity resolution showed that highly accurate dynamical orbit models are a prerequisite for this method. More details about Melbourne-Wübbena wide-laning with narrow-lane bootstrapping may be found in (Švehla and Rothacher, 2001). Figure 4 shows the percentage of resolved narrow-lane ambiguities and Figure 5 the accuracy of the kinematic orbits with fixed ambiguities over 11 days (days 140-150 in 2001) obtained from SLR validation. The RMS of all SLR residuals for the kinematic orbits with fixed ambiguities over 11 days is 56.4 mm, a considerable improvement compared to the RMS of 117 mm for kinematic orbits with float ambiguities.

The SLR residuals for kinematic orbits were computed in the same way as for reduced-dynamic orbits, the only difference was, that the kinematic orbits are given with a sampling of 30s and, thus, an interpolation procedure is required in order to obtain positions at the epochs of the SLR normal points. A first order polynomial was used to interpolate kinematic positions within the sampling interval along an a priori dynamic orbit. We noticed that the validation of kinematic orbits with SLR is more difficult and the necessary interpolation may easily increase the RMS by 1-2 cm.

The impact of ambiguity resolution on the kinematic orbits can be seen in Figure 6 (day 148/2001). Figure 10(a) shows the comparison of our kinematic orbits with the dynamic orbits computed at GeoForschungsZentrum (GFZ) Potsdam and Figure 10(b) the comparison with the dynamic orbits computed at Center for Space Research (CSR), Texas (day 148/2001). The differences

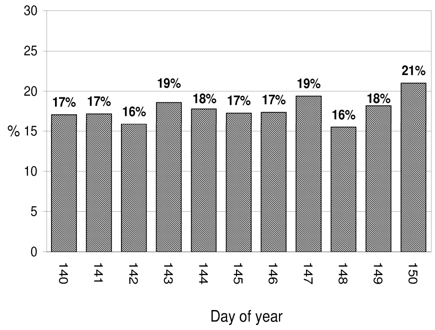


Fig. 4. Percentage of resolved narrow-lane ambiguities over 11 days.

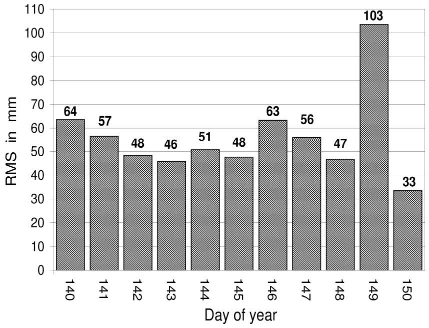


Fig. 5. RMS of SLR residuals for kinematic orbit with fixed ambiguities (using dynamic bootstrapping), RMS=56.4. mm over all SLR residuals.

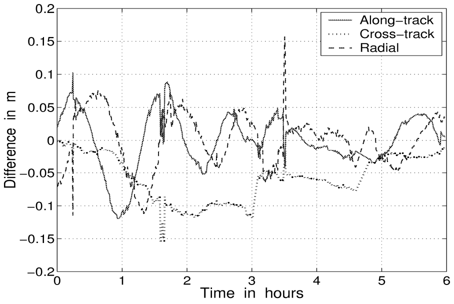


Fig. 6. Differences between kinematic orbit with float and fixed ambiguities (148/2001).

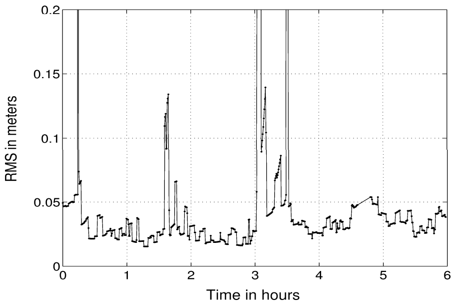


Fig. 7. Formal RMS of kinematic positions, day 148/2001.

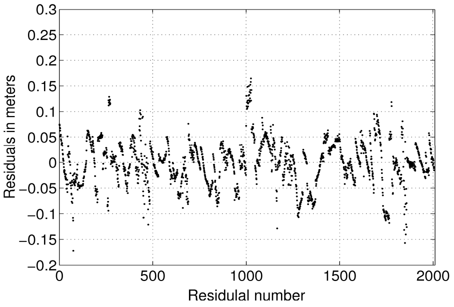


Fig. 8. SLR residuals for dynamic orbit (RMS=44.3 mm).

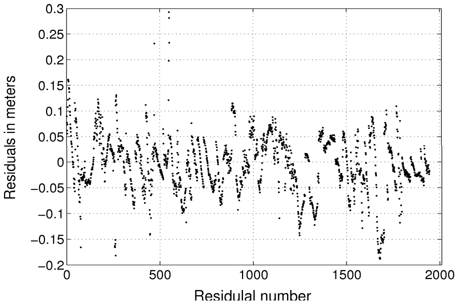
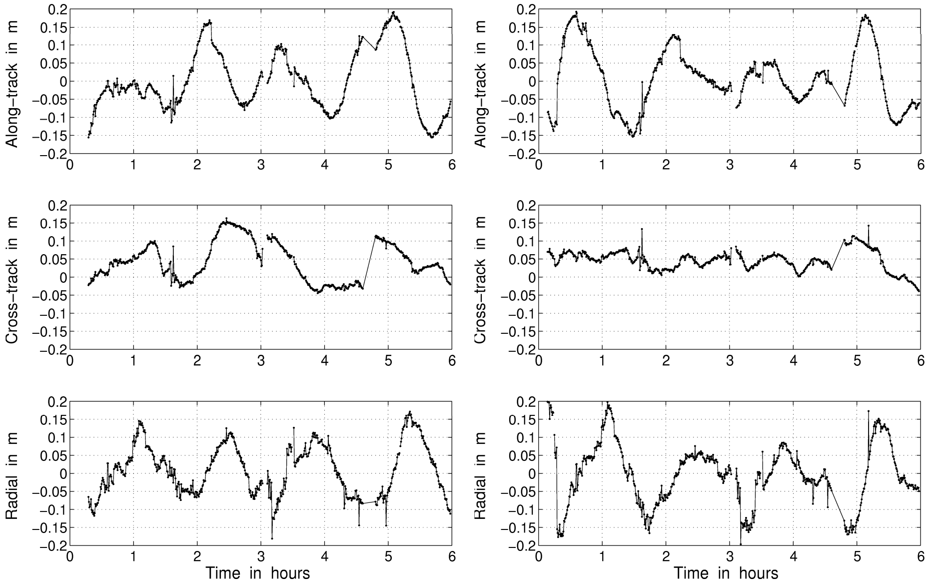


Fig. 9. SLR residuals for kinematic orbit (RMS=56.4 mm).



(a) Comparison with dynamic GFZ orbit (b) Comparison with dynamic CSR orbit

Fig. 10. Comparison of our kinematic orbits with GFZ and CSR dynamic orbits (days 148/2001).

clearly show interesting once per revolution terms, especially in the radial and along-track directions. One has to keep in mind that kinematic orbits do not depend on any force model or gravity field. Kinematic orbits can therefore be used as a validation tool for dynamic orbit modeling. Looking at Figure 7 with the formal a posteriori RMS of the kinematic positions we may conclude that each kinematic position has a different level of accuracy and that kinematic orbit positions should always be used together with the corresponding variance-covariance information.

4 Conclusion

Purely kinematic precise orbit determination (POD) for the CHAMP satellite was performed over 11 days in the framework of the CHAMP Orbit Comparison Campaign. In order to avoid the effects of ionosphere, ambiguity resolution was performed using Melbourne-Wübbena wide-laning with narrow-lane bootstrapping. For the same period (days 140-150 in 2001), reduced-dynamic orbits were computed and both types of orbits were validated with SLR. The accuracy of the dynamic orbits is at a level of 4-5 cm (44.3 mm), whereas the kinematic ambiguity-fixed orbits have a quality of about 5-6 cm (56.4 mm).

Kinematic orbits of such a quality are extremely valuable to assess dynamical orbit models and parameterizations. No significant SLR bias could be detected in the two orbit types. It is important to note that kinematic orbit positions should always be used together with the corresponding variance-covariance information.

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