The Development of Automated Processing of Orbit Predictions for CHAMP

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Abstract. The German research satellite CHAMP, launched on July 15th, 2000, features two tracking systems: a GPS Black Jack flight receiver and a Laser Retro Reflector (LRR). For operating the ground station network of the International Laser Ranging Service (ILRS) orbit predictions are needed. In order to meet the accuracy requirements of the SLR technique orbit predictions for CHAMP are generated at 12-hours-intervals based on the on-board navigation solutions of the GPS flight receiver and on SLR data. For a continuous and timely updating of the orbit predictions 24 hours a day, i.e. also outside normal working hours and additionally during weekends, the processing of CHAMP orbit predictions has been automated.

Keywords. Orbit predictions, CHAMP, Satellite Laser Ranging (SLR)

Introduction

Although the GPS flight receiver is regarded as main tracking system, SLR data play an important role in operational and scientific aspects of the CHAMP mission. One major application is precise orbit determination (POD) where accurate SLR data – in addition to GPS – will support orbit restitution as well as gravity field recovery. During the commissioning phase of the CHAMP mission, SLR data are used in particular for the calibration/validation of the on-board microwave tracking system (GPS) as well as for the validation of gravity field solutions derived from GPS data. In both cases SLR data serve as independent tracking information at a measurement accuracy comparable to precise GPS data. Another important operational application is the generation of CHAMP orbit predictions where SLR data are routinely used in connection with the on-board navigation solutions of the GPS flight receiver. Finally, the design of the LRR allows two-color experiments.

Accurate orbit predictions for the pointing of SLR ground stations are required in contrast to the needs by the microwave tracking system on-board the CHAMP satellite. Internal investigations from GPS/MET data and simulations for CHAMP indicated that accurate orbit predictions could be derived from the so-called navigation solution which is continuously computed by the GPS flight receiver on-board. The accuracy of such states for GPS/MET turned out to be at the level of 60 meters. Simulations for CHAMP adopting this value had shown an agreeable accuracy of orbit predictions based on navigation solutions. Since the receiver on-board CHAMP got specifications much better than 60 meters, the usage of the navigation solution looked even more promising. In the orbit determination process such GPS deduced ephemeris are introduced as pseudo-observations, i.e. position and velocity vectors are treated as observations. Solved for parameters are the six initial elements (e.g. cartesian coordinates at epoch) and a global scaling factor for drag. The usage of the navigation solution offers several advantages. Firstly, provided the GPS flight receiver and data down links perform well, a continuous coverage of the CHAMP orbit at an agreeable accuracy is secured. Thus the prediction cycle becomes more stable than with the data outages as experienced during the GFZ-1 mission where SLR was the one and only tracking system. Secondly, the incorporation of navigation solutions is rather straight forward with only little preprocessing required. Precise SLR data is regarded as complementary data, improving the orbit predictions with respect to accuracy. Therefore orbit predictions for CHAMP are based on the navigation solutions of the GPS flight receiver and SLR data as available. It is evident that due to CHAMP's low altitude drag becomes the dominating - however difficult to predict – disturbing force. Therefore the Inter Range Vectors (IRVs) and coefficients of the so-called drag functions (DRAG) for CHAMP require sub-daily updating. Because CHAMP data dumps also occur outside normal daily working hours and on weekends and holidays, the processing had to be automated. This paper summarizes the development of the processing of orbit predictions from the initial orbit phase when the manual processing was based on separation information and radar tracking, up to the current operational automated processing based on SLR- and spaceborne GPS-data. Upcoming improvements are addressed at the end of the paper.

Initial Orbit Phase

During the initial orbit phase, i.e. approximately the first 24 hours after separation and before the on-board GPS receiver was switch on, no precise GPS or SLR was available. Hence, orbit determination and generation of orbit predictions were based on less accurate radar tracking information of two different kinds. One observation type was the so-called angle-tracking of telemetry stations of the NASA polar station network and the two DLR facilities in Germany. Angle tracking data are azimuth and elevation angles of the telemetry antennae measured during the passes at the individual stations. Such data were treated similar to optical observations from star cameras within the GFZ orbit determination software EPOS. Another source of radar tracking consisted of two-line elements (TLE) for CHAMP computed at the German military-owned radar station FGAN located near Bonn/Germany. Such CHAMP-TLE were derived from each individual pass at the FGAN station. At GFZ the TLE were transformed into short arcs of a period of 8 minutes starting at the epoch of the TLE. This has been done to preserve the pass-wise observational character of the individual TLE sets. The 8 minutes time span represents the average duration of a single CHAMP pass over the FGAN station. Finally, the ephemeris of these TLE orbits were introduced as pseudo-observations into the orbit determination. Table 1 summarizes the orbital fit of the angle-tracking data, of the TLE ephemeris as well as of the ephemeris from the first GPS navigation solution (GPS-NAV) for arcs on July 15 and on July 16. Arc 20000715 was based on the angle-tracking data and on the TLE based 'passes' from FGAN. Arc 20000716 was based on angle-tracking data and on the first navigation solution of the GPS flight receiver. The orbital fit of angle-tracking data decreases by a factor of 3 towards approximately 60 " which reflects the order of the measurement accuracy of azimuth and elevation observations obtained by telemetry antennae. The initial values for the CHAMP state vector for arc 20000715 were derived from the post-processed orbital parameters of the COSMOS launch vehicle and the actual separation information at separation time. On the one hand the rather bad orbital fit of angle-tracking data in arc 20000715 is due to a degraded observation accuracy of azimuth and elevation angles when telemetry antennae were running in less accurate search mode. On the other hand the launch of CHAMP coincided with an extraordinary geomagnetic storm making orbit

Arc	Observation	RMS	N(obs)
20000715	TLE	730 m	93
	Declination	177 “	643
	Right Ascension	185 “	643
20000716	GPS-NAV	30 m	7997
	Declination	57 “	484
	Right Ascension	64 “	484

Table 1. Orbital fit of tracking data during the initial orbit phase. Azimuth and elevation angles have been converted to declination and right ascension. FGAN means ephemeris derived from FGAN-TLE. GPS-NAV are ephemeris from the navigation solution of the GPS flight receiver.

determination and orbit prediction difficult in that period (see Figure 2). Taking the RMS-values of table 1 as indicator for the orbit accuracy one can state that the accuracy of orbit recovery for orbit predictions increased from several hundreds of meters to tens of meters with the usage of the on-board GPS navigation solution. Based on the predicted orbit derived from arc 20000716 the SLR station 1884 at Riga observed the first SLR pass on July 17, 2000 at 00:11 UTC.

Automated Generation of CHAMP Orbit Predictions

The automated generation of CHAMP orbit predictions is based on the routinely acquisition of the navigation solutions of the GPS flight receiver. These data sets comprise quasi-continuous ephemeris for CHAMP given in the WGS reference frame and in the GPS time scale at 10 seconds intervals. The temporal and spatial coverage of the CHAMP orbit by the navigation solution sizes at about 98 %. The accuracy of these data turns out to be in the order of 30 to 40 meters with the first software version implemented in the GPS flight receiver. Together with SLR observations these state vectors are introduced as pseudo-observation data into the orbit determination process. The estimated parameters for CHAMP are the initial state vector at epoch and one global scaling factor for drag. Figure 3 shows the flow chart of the automated generation of CHAMP orbit predictions. The automated process is started shortly after the arrival of new navigation solution data via the DLR telemetry station in Neustrelitz/Germany, provided through the Information System and Data Center (ISDC) at GFZ Potsdam. The SLR data are collected on a hourly basis at the ILRS data centers CDDIS

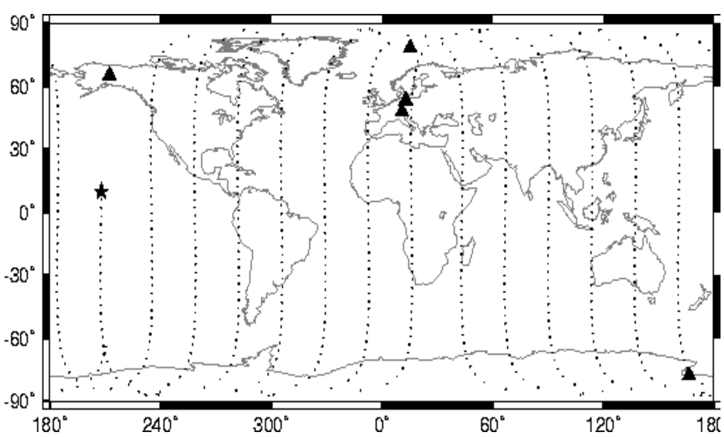

Figure 1. Geographical distribution of tracking stations during the initial orbit phase.

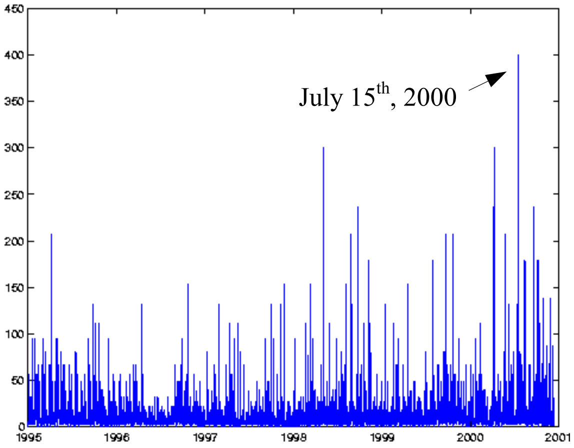

Figure 2. Geomagnetic ap indices 1995 - 2000

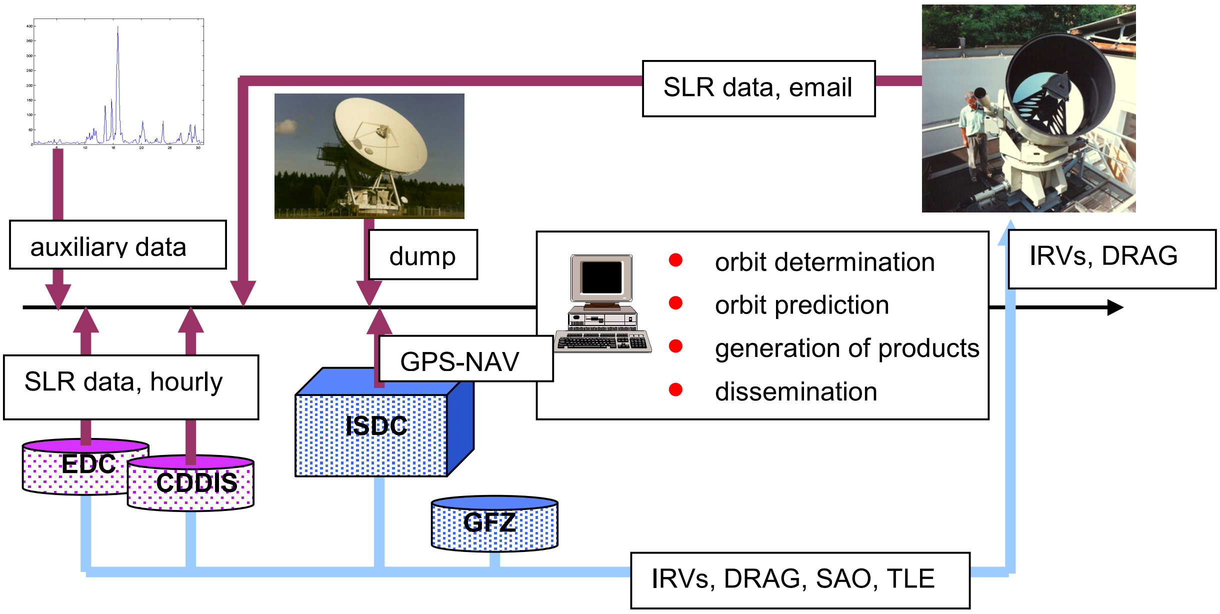

Figure 3. Flow chart of the automated generation of CHAMP orbit predictions

and EDC. In addition, some stations transfer their NPs directly to GFZ via email. This procedure has been initiated for immediate transfer of NPs being regarded vital during the initial orbit phase. Additional auxiliary data sets like solar flux, geomagnetic activity, polar motion, etc. are also frequently acquired from various sources. The first step of the processing is the collection of all relevant data sets, i.e. observations (navigation solution, SLR), auxiliary data (solar flux, geomagnetic indices, polar motion) and an initial state vector at epoch. The next step is the estimation of an improved set of orbit parameters, i.e. an improved initial state vector and a global scaling factor for drag. The force modeling comprises the gravitational force of the Earth, ocean-tides, Earth tides, gravitational accelerations due to the masses of Moon and Sun, non-conservative forces like drag, solar radiation and Earth albedo. For the evaluation of the surface forces a detailed 3-dimensional macro-model of the CHAMP satellite is used. Based on the estimated parameters and the models used in the second step the CHAMP orbit is extrapolated into the future. The length of these orbit predictions is 3 days. Then, the predicted orbit is transferred into standard ILRS orbit prediction products, i.e. IRVs and coefficients of the so-called drag functions. Additionally, TLEs and SAO-elements are generated. Finally, all generated products are disseminated to the ILRS data centers, to the ISDC and to an additional ftp-server at GFZ for back-up purposes. IRVs and DRAG are by request sent directly to SLR station via email, also.

Data Availability and Latency

Due to the location of the DLR telemetry station at Neustrelitz/Germany at a latitude of 53 degrees the number of contacts per day for CHAMP data dumps varies from 3 to 5. As can be seen from Figure 4 for the first 100 days of the mission there are two dump windows per day of two to three consecutive contacts (i.e. consecutive revolutions) separated by gaps of about 12 hours. Because of the precession of the orbital plane the contact epochs are slowly shifting through the day. The gray shaded area indicates normal working hours of an operator despite of weekends. In order to provide timely updates of the SLR orbit predictions close to the actual CHAMP data dumps, the processing had to be automated, also in view of weekends and holidays. At the time being, the processing of a new orbit prediction is initiated after the

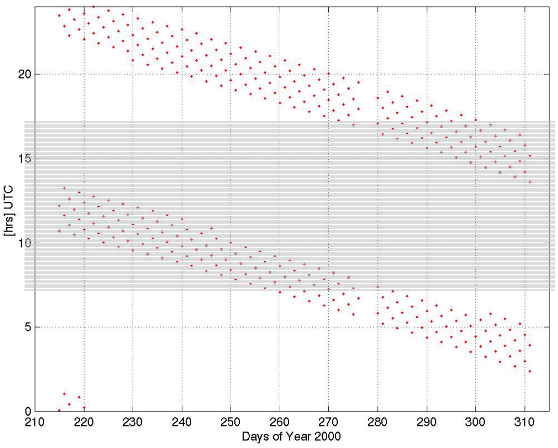

Figure 4. Contacts at Neustrelitz

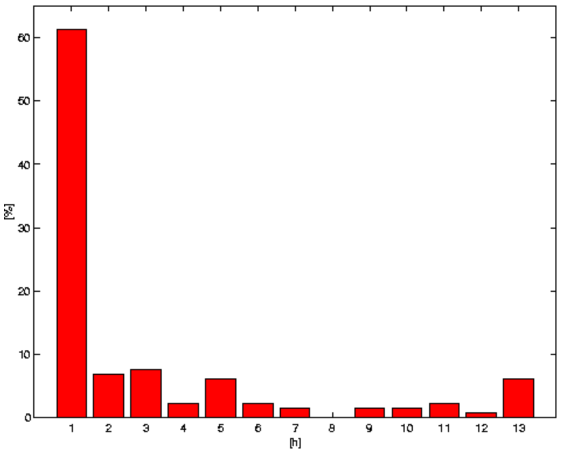

Figure 5. Latency of the navigation solution

last dump of the consecutive passes of the corresponding dump window. Thus the nominal update rate of CHAMP orbit predictions is approximately 12 hours. Since the quality of orbit predictions depends on the 'freshness' of actual observations, the delay of observational data for both, navigation solution as well as for SLR data has been investigated. The latency of the navigation solution, i.e. the difference between dump time and the epoch of the last state vector (i.e. the last observation) included in the corresponding data dump has been evaluated for 132 dump files from mid of October 2000 until the end of December 2000. The results are displayed in Figure 5. The horizontal axis labels the offsets in hours between dump time and the epoch of the last state. The actual offset values have been classified at 1-hour intervals, ranging from offsets less equal 1 hour to offsets greater than 12 hours. All offsets larger than 12 hours are merged in label '13'. The vertical axis shows the percentage of the corresponding class. As can be seen almost 60 percent of the dumps indicate an agreeable small latency of less than 1 hour. Approximately 87 percent of the dumps show offsets smaller than 8 hours. Larger offsets than 9 hours occur at about 13 percent of the investigated data files. Such large latencies depend on the filling of the mass memory unit on-board the CHAMP satellite and at the possibilities of downloading the data. In general, the availability of the navigation solution is sufficient. Figure 7 depicts the situation for SLR data. A bulk of the data arrives 2 hours after observation. It must be emphasized that the availability of SLR data has significantly improved by the establishment of hourly update within the ILRS in view of the CHAMP launch. Figure 8 depicts the number of passes per station for the period July to October 2000. Table 2 lists some global statistics for the same period.

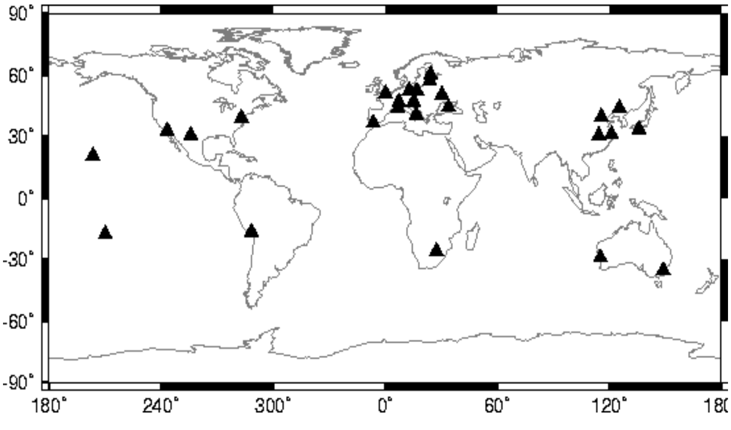

Figure 6. Network of SLR stations tracking CHAMP

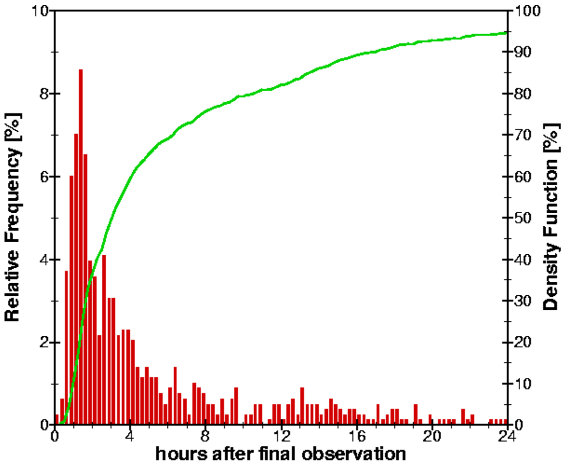

Figure 7. Latency of SLR data

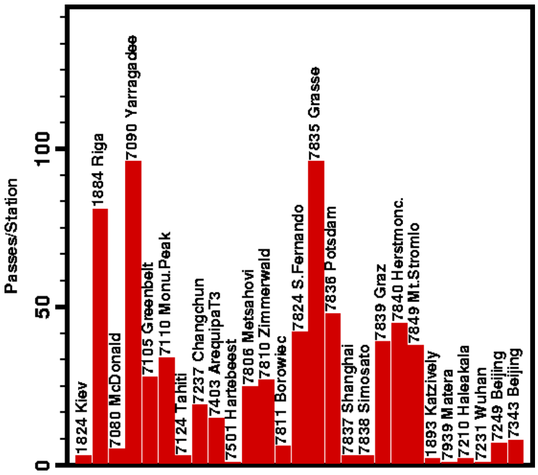

Figure 8. SLR passes per station. Jul – Oct 2000

SLR Tracking Jul – Oct 2000

- 678 passes at 27 ILRS stations
- 16977 NPs
- ~ 25 NPs/pass
- ~ 6 passes/day

Table 2. Statistics of SLR tracking Jul-Oct 2000

The overall situation can be regarded as good in knowledge of the problems encountered with low altitude targets. A more detailed look however shows the inhomogenuous distribution of the observed passes in the space and the time domain. Thus CHAMP SLR tracking reflects the capabilities of the ILRS network for tracking LEO targets. In November and December 2000 the tracking record decreased to an average of about 3 passes per day, which can typically be attributed to the weather conditions in winter on the Northern hemisphere.

Accuracy of CHAMP Orbit Predictions

Due to its low orbit (initial altitude appr. 450 km) CHAMP's large relative velocity with respect to a SLR ground stations makes targeting difficult. Therefore accurate orbit predictions are needed. The requirement for such a LEO spacecraft can be specified as an accuracy of 10 milliseconds in along-track direction. Because of the low altitude again, the motion of CHAMP in that direction is strongly dominated by drag. State-of-the-art models used for predicting acceleration due to drag – in particular at such altitudes – will increasingly deviate from the truth over longer periods. Hence, timely updating of orbit predictions is essential. Pre-flight simulations have shown that an update frequency at least at 12-hours intervals is needed to keep the required accuracy. For validating this procedure, the accuracy of actual orbit predictions for CHAMP is investigated for a set of seven orbit predictions in the period July 30 to August 6, 2000. The predicted orbits were compared to precise CHAMP orbits.

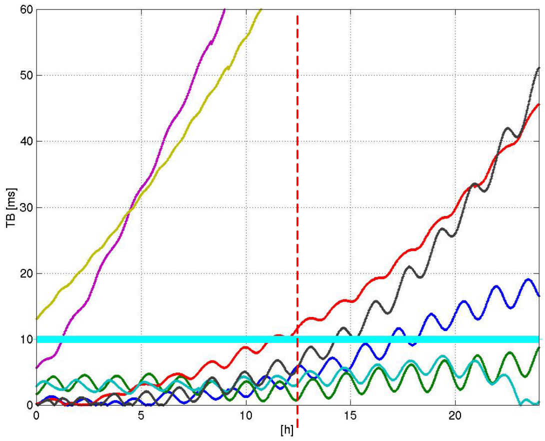

Figure 9. Development of time bias of CHAMP orbit predictions during first 24 hours

Time Bias [ms]	12 [h]	24 [h]	36 [h]
1	4.6	16.5	36.5
2	2.5	7.3	24.8
3	9.9	46.2	110.5
4	10.1	11.5	70.3
5	81.4	175.0	268.7
6	59.2	160.2	333.1
7	3.2	52.6	152.7

Table 3. Time bias after 12, 24, and 36 hours for each orbit prediction.

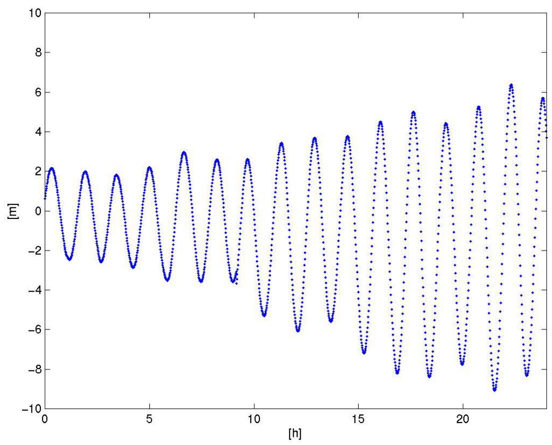

Figure 10. Differences in radial direction of prediction set no. 1

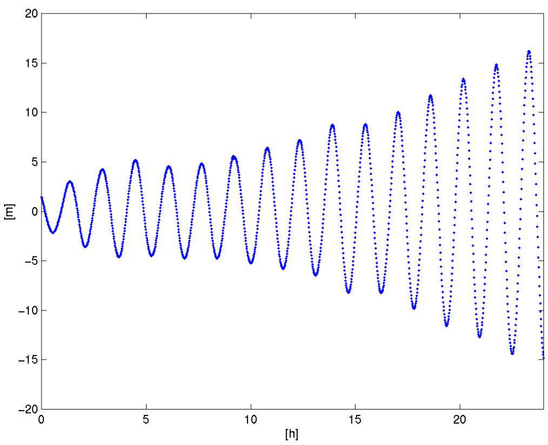

Figure 11. Differences in cross-track direction of prediction set no. 1

The reference orbits are based on GPS pseudo-ranges and carrier-phases, a refined modeling and parametrization and final values for the auxiliary data. The differences in radial, cross-track, and along-track direction for the first 48 hours of each individual orbit prediction are computed. Figure 9 depicts the absolute values of the development of the time bias during the first 24 hours. The horizontal line at 10 milliseconds indicates the required accuracy. The dashed vertical line marks the 12 hours update interval. Table 3 lists the time biases of each orbit prediction after 12, 24, and 36 hours, respectively. The 1/rev oscillations visible in Figure 9 have been removed by fitting the individual time bias data to quadratic or cubic functions in a least squares adjustment combined with a check of significance of the estimated polynomial parameters. It can be seen that five of the seven investigated predictions agree well with the 10 millisecond requirement, whereas prediction sets no. 5 and no. 6 violate it by a factor of 6 or 8, respectively. Figures 10 and 11 depict typical values for the differences of the orbit predictions in radial and cross-track direction for orbit prediction set no. 1 as an example. The corresponding graphs for the other investigated prediction sets show similiar behaviour and similar order of magnitudes. Typically, the differences are dominated by revolution dependent oscillations with an increasing amplitude of the oscillations. In the radial direction a linear trend is visible which however stays small with respect to the magnitude of the amplitude. For the differences in the cross-track direction no linear trends show up. The differences in radial and cross-track direction of the investigated prediction sets are of the order of a few meters before and at the 12 hours interval. From this it can be concluded that the chosen update procedure is in general sufficient to meet the accuracy requirement. It is also clear that the along-track direction is the most critical component due to drag.

Upcoming improvements

As stated in the previous section the quality of the CHAMP orbit prediction can be considered to be sufficient, but improvements are still favorable. The following procedurale changes will enhance the quality of CHAMP orbit predictions. First, the accuracy of the navigation solution will increase to 10 m and better due to a planned software upgrade of the on-board GPS receiver in January 2001. Second, the establishment of an additional dump station on Spitzbergen/Norway will increase the number of data dumps per day to almost the orbital frequency. Hence, it may be expected to further reduce the latency and improve the availability of the navigation solution. The update rate of CHAMP orbit predictions can be increased accordingly. Finally, an advanced modeling with respect to a refined gravity field derived from CHAMP observations should help advance the accuracy of orbit predictions, too.

Conclusions

During the initial orbit phase the CHAMP orbit determination and generation of orbit predictions have been operated manually. Two kinds of radar tracking data (angle-tracking, two-line elements) have been successfully adopted in CHAMP orbit determination. The accuracy of orbit determination and prediction is limited by the poor precision of this type of tracking data. Additionally, due to an extra-ordinary geomagnetic storm at launch orbit recovery was degraded in that period. The first SLR tracking succeeded after the switch-on of the GPS flight-receiver.

For standard operations for the generation of CHAMP orbit predictions an automated process based on the navigation solution of the GPS flight receiver on-board CHAMP and on additional SLR data has been developed. SLR and space-borne GPS data are complementary input data with respect to accuracy and coverage. The investigation of a set of actual orbit predictions verifies the requirement of sub-daily updating of CHAMP orbit predictions. The chosen update rate at 12-hours intervals is in general sufficient to provide accurate orbit predictions. Upcoming improvements with respect to accuracy and availability of the navigation solution and a refined modeling are expected to further increase the quality of CHAMP orbit predictions.