Kinematic Precise Orbit Determination for Gravity Field Determination

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Abstract.
In this paper we first present approaches and results in precise orbit determination (POD) for satellites in Low Earth Orbit (LEO) based on one or two frequency GPS measurements and, secondly, we focus on the relations between kinematic POD and gravity field determination. Using GPS measurements of the CHAMP satellite we show that it is possible to estimate kinematic positions of a LEO satellite with the same level of accuracy ($\approx$ 1–3 cm w.r.t. SLR) as with the widely applied reduced-dynamic or dynamic approaches. Kinematic precise orbit determination (POD) as presented here is based on GPS phase measurements and is independent of satellite dynamics (e.g. gravity field, air-drag, etc.) and orbit characteristics (e.g. orbit height, eccentricity, etc.). We also looked at the LEO POD based on GPS measurements from only one frequency, where we make use of what we call the LP linear combination. We show that with this linear combination LEO POD can be performed with one frequency at the 10 cm level. In the second part of the paper the use of kinematic POD is discussed in the framework of the CHAMP, GRACE and GOCE gravity missions. With simulated GPS measurements we studied the impact of ambiguity resolution for the kinematic baseline between the two GRACE satellites. At the end of the paper we present an alternative approach in gravity field determination by measuring the gravitational frequency shift between (optical) atomic clocks in space. In this approach we require very accurate clocks positions, which may be obtained from kinematic POD.

Keywords. Kinematic orbit, LEO, POD, space clock

1 Introduction

With the pioneering satellite mission CHAMP, a new era in space geodesy and observing the planet Earth from space started. Today we are talking about gravity (CHAMP, GRACE, GOCE) and magnetic (CHAMP, ÖRSTED, SWARM) fields determined from space, atmosphere sounding from space (CHAMP, GRACE, COSMIC, SWARM), monitoring oceans (TOPEX/POSEIDON, JASON-1) and ice caps (ICESAT) from space, etc.

In all these missions, satellite orbit determination is used for geo-location of the satellite sensors on one hand and to measure the gravity field and its variations in time on the other hand, i.e., using the equation of motion to obtain information about dynamical processes in the Earth system, as e.g. Earth tides, mass distribution, ocean circulations, etc. (Balmino et al. (1999)).

In 1992, for the first time, high-precision LEO dynamic orbit determination was performed making use of GPS measurements from TOPEX/POSEIDON (Bertiger et al. (1994), Tapley et al. (1994), Yunck et al. (1994)). Since this time, GPS tracking has become an extremely successful method for POD and nowadays purely kinematic orbits can be determined with the same level of accuracy as orbits computed with the more common (reduced-)dynamic approach (Švehla & Rothacher (2002a)). Among all space geodetic techniques (SLR, DORIS, altimetry, etc.) only GPS allows purely kinematic precise orbit determination, where kinematic satellite positions can be estimated independently of orbit altitude and force modeling like, e.g., gravity field, air-drag, solar radiation, etc.

With highly accurate kinematic satellite positions available as pseudo-observations, interesting new methods are being developed nowadays to e.g. determine gravity field parameters, validate dynamical models or derive atmosphere density information.

2 Kinematic and reduced-dynamic POD

2.1 Description of methods

Using GPS measurements the orbit of a LEO satellite can be computed using kinematic as well as (reduced)-dynamic approaches.

The kinematic approach is a purely geometrical approach without using any information on satel-

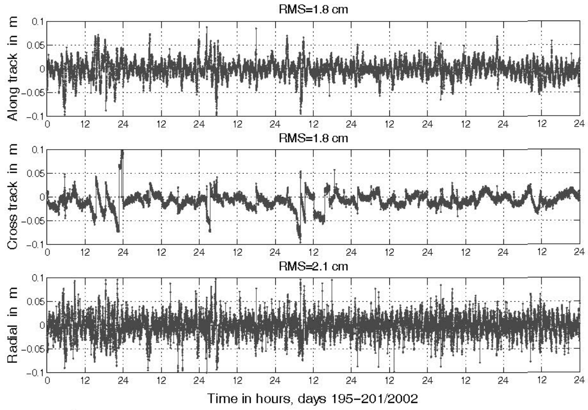

Fig. 1. Differences between CHAMP kinematic and reduced-dynamic orbit based on zero-differences, GPS week 1175/2002 (days 195-201/2002).

lite dynamics (e.g. gravity field, air-drag, etc.). In our case the LEO kinematic orbit is represented by three kinematic coordinates each epoch and estimated with a least-squares adjustment using phase measurements only. Code observations are only used in a pre-processing step to synchronize the LEO clock to GPS time. No constraints are applied to the kinematic positions in the adjustment.

Dynamic and reduced-dynamic POD on the other hand is based on the numerical integration of the equation of motion and the variational equations to obtain the orbit itself, as well as the partial derivatives with respect to the orbital parameters. In the reduced-dynamic case a large number of empirical (e.g. pseudo-stochastic pulses) or force field parameters are estimated in order to cope with the deficiencies in the dynamical models. In our case pseudo-stochastic pulses are set up as additional parameters in along-track, cross-track and radial direction every 6-15 min.

Kinematic or reduced-dynamic POD of a LEO may be carried out on the zero-, the double- or even the triple-difference level of GPS phase or code measurements. In this paper we will focus on zero- and double-difference procedures using phase measurements only.

In the zero-difference case, GPS satellite orbits and clocks are kept fixed and epoch-wise LEO GPS receiver clock parameters are estimated together with either epoch-wise kinematic positions in the kinematic case, or (reduced-)dynamic orbital parameters in the (reduced-)dynamic approach. Since phase GPS measurements are used, more than 400 zero-difference ambiguities are additional parameters for a 1-day orbit arc. POD based on zero-differences is a very fast and efficient approach, because only GPS measurements of the LEO are involved and therefore, the processing of a ground IGS network is only required in a preceding, independent step in order to obtain GPS satellite orbits and clocks.

In the double-difference approach, baselines between the LEO and GPS ground stations are formed and all clock parameters are eliminated. In our case baselines are formed between CHAMP and 40 IGS stations and all IGS products like CODE 3-day solutions for GPS orbits, ERPs, troposphere and weekly station coordinates are kept fixed. The main advantage of kinematic and reduced-dynamic POD based on double-differences is the possibility to resolve ambiguities to their integer values using ambiguity resolution strategies and thereby gain in accuracy. Our ambiguity resolution strategy is based on the Melbourne-Wübbena (MW) linear combination (Melbourne (1985)) to resolve wide-lane ambiguities in a first step and on a subsequent, iterative bootstrapping to resolve narrow-lane ambiguities. 10 narrow-lane ambiguities (out of $\approx$ 5000 ambiguities) are resolved in each iteration step, i.e. before the one-day normal equation matrix is re-inverted.

More details about our zero- and double-difference approaches, ambiguity resolution and the mathematical background of kinematic and reduced-dynamic POD can be found in Švehla & Rothacher (2002a), Švehla & Rothacher (2003b) and Švehla & Rothacher (2003c). Other approaches of kinematic POD can be found, e.g., in Colombo et al. (2002), Bock (2003) or Byun (2003).

2.2 CHAMP POD results

Two comparisons were performed to assess the consistency and accuracy of the CHAMP orbits computed: the comparison between kinematic and reduced-dynamic orbits and the comparison of CHAMP SLR measurements to the GPS-derived orbits.

Fig. 1 shows the difference between CHAMP kinematic and reduced-dynamic orbits based on zero-difference phase measurements for GPS week 1175/2002. The consistency between these two orbits is on the level of about 2 cm over the entire week. The differences between CHAMP kinematic and reduced-dynamic orbits computed using double-differences are displayed in Fig. 2 for day 199/2002. A more detailed look at Fig. 2 reveals that CHAMP kinematic positions sometimes exhibit large spikes, due to the small number of GPS satellites tracked and the resulting poor satellite geometry. These points can easily be recognized when looking at the variance-covariance information. Due to the nature

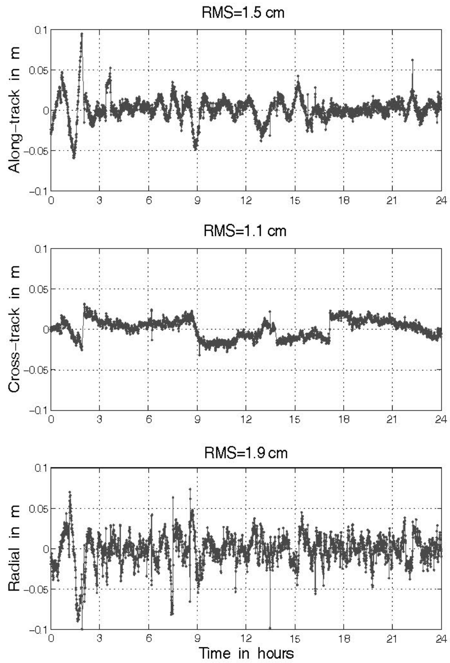

Fig. 2. Difference between CHAMP kinematic and reduced-dynamic orbits based on double-differences, day 199/2002.

of the GPS phase observable, kinematic positions are very smooth from epoch to epoch and as a consequence high-frequency gravity signals may be extracted from these positions. Keep in mind that in our kinematic approach no constraining is applied. Systematic deviations can be recognized in the along-track and radial component pointing, apart from obvious problems with satellite geometry, at deficiencies in the gravity field and air-drag modeling of the reduced-dynamic approach. That we are not just talking about consistency but also accuracy, can be seen in Fig. 3, where SLR residuals are shown for the same kinematic and reduced-dynamic CHAMP orbit as those displayed in Fig. 1. Tropospheric delays for SLR measurements were modeled using the Marini-Murray model and standard corrections like ocean loading (GOT00.2), Shapiro relativistic effect and station velocities were applied. The analysis was performed using ITRF 2000 station coordinates, velocities and eccentricities published by ILRS at http://ilrs.gsfc.nasa.gov/. All SLR stations and SLR measurements were used in this validation (elevation cut-off 10°). Both orbit types exhibit the same quality of about 2.5 cm. It is interesting to note that the SLR residuals show a similar behaviour for kinematic and reduced-dynamic orbits and that no significant bias can be identified in the SLR residuals.

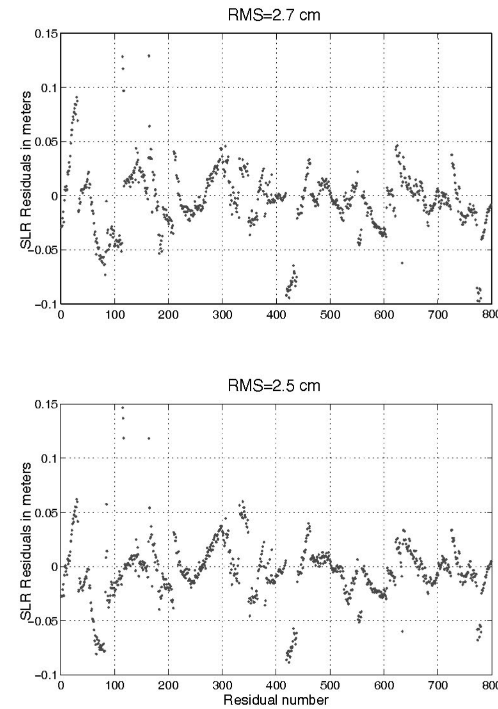

Fig. 3. SLR residuals for CHAMP kinematic (top) and reduced-dynamic orbits (bottom) for GPS week 1175/2002 (days 195-201/2002). All SLR residuals were used in the analysis, elevation cut-off 10°.

Table 1 summarizes the daily RMS of the SLR residuals for our CHAMP orbits based on four different POD approaches, namely kinematic and reduced-dynamic orbits based on zero- and double-differences. One can see that CHAMP orbits are of similar quality for a purely kinematic and reduced-dynamic approach. This also stands for CHAMP orbits computed using either zero- or double-difference phase measurements. Slightly better orbit quality (2.56 cm) is obtained when using kinematic POD and double-differences.

Day	Zero difference red.-dyn.	Zero difference kinematic	Double difference red.-dyn.	**Double difference kinematic**
195	4.02	4.17	3.22	2.66
196	2.90	2.93	3.19	3.03
197	3.40	3.11	3.29	2.90
198	2.07	2.07	1.99	1.34
199	1.94	1.66	1.91	1.70
200	1.43	1.45	1.69	1.83
201	3.59	4.65	4.32	5.00
202	2.03	2.08	1.93	2.05
Mean	2.67	2.77	2.69	**2.56**

Table 1. Daily RMS of SLR residuals in cm for CHAMP kinematic and reduced-dynamic ("red.-dyn.") orbits based on zero- and double-differences (days 195-202/2002).

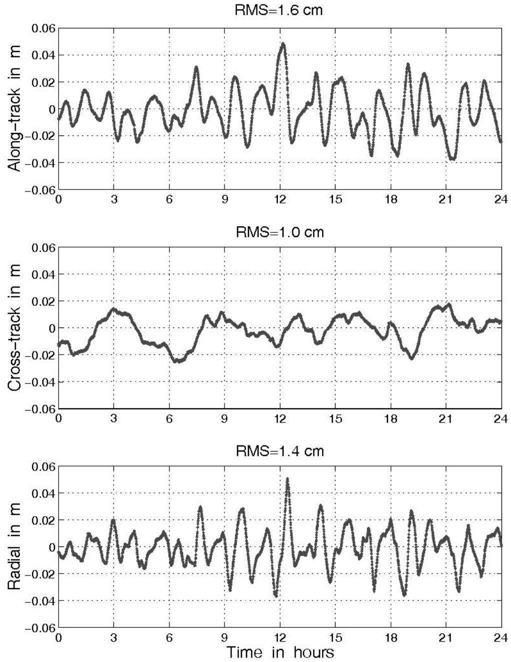

Fig. 4. Impact of ambiguity resolution: difference between reduced-dynamic orbits with float and fixed ambiguities, day 200/2002.

To try to further improve the orbit quality, ambiguity resolution was performed in the double-difference case for GPS week 1175/2002. Using the MW linear combination, about 50% of the wide-lane ambiguities could easily be resolved. These wide-lane ambiguities were introduced in the next step to resolve the narrow-lane ambiguities. Epoch-wise coordinates were pre-eliminated from the normal equation system in kinematic and orbital parameters in reduced-dynamic POD, leaving ambiguities only for bootstrapping. With CHAMP data 20.8% of all ambiguities were resolved in kinematic and 20.4% in reduced-dynamic bootstrapping. Due to the huge number of ambiguity parameters (5000 per day) bootstrapping is very time-consuming and requires about 100 inversions of the 1-day normal equation matrix for both POD approaches. Fig. 4 shows the impact of ambiguity resolution on reduced-dynamic orbits based on double-differences. One can see that ambiguity resolution changes the orbit by 1-2 cm. Unfortunately, the difference between the ambiguity-fixed and ambiguity-free reduced-dynamic orbits is not large enough to give a significantly different results when compared to SLR data.

3 LP linear combination

In this Section the high accuracy of the CHAMP code measurements (used for ambiguity resolution) is assessed by estimating CHAMP orbits using GPS measurements from only one frequency. Following Švehla & Rothacher (2003c), a simplified version of the observation equation for the phase $L^s_{LEO,i}$ and code $P^s_{LEO,i}$ observations (frequency i, between LEO and GPS satellite s) is given as

$$L^s_{LEO,i} = \rho^s_{LEO} + \lambda_i N^s_{LEO,i} - \delta\rho^s_{ion,i} + \\ + c\,\delta t_{LEO} - c\,\delta t^s + \epsilon(L_i) \qquad (1)$$
$$P^s_{LEO,i} = \rho^s_{LEO} + \delta\rho^s_{ion,i} + c\,\delta t_{LEO} - c\,\delta t^s + \epsilon(P_i)$$

where ρ^s_{LEO} denotes the distance between LEO and GPS satellite s, $N^s_{LEO,i}$ the zero-difference ambiguity of wavelength λ_i, $\rho^s_{ion,i}$ the ionospheric correction, $c\,\delta t_{LEO}$ and $c\,\delta t^s$ the LEO and GPS satellite clock values and $\epsilon(L_i)$ and $\epsilon(P_i)$ the phase and code noise. The LP linear combination of phase and code measurements on frequency i is then defined as

$$LP^s_{LEO,i} := \frac{1}{2}(L^s_{LEO,i} + P^s_{LEO,i}). \qquad (2)$$

See also Bertiger et al. (1996), where this linear combination is called "graphic data". The ionosphere effects in $L^s_{LEO,i}$ and $P^s_{LEO,i}$ cancel and we obtain

$$LP^s_{LEO,i} = \rho^s_{LEO} + \frac{1}{2}\lambda_i N^s_{LEO,i} + \\ + c\,\delta t_{LEO} - c\,\delta t^s + \epsilon(LP_i). \qquad (3)$$

We note that the wavelength of the LP linear combination is half the size of the original wavelength λ_i and that the noise $\epsilon(LP_i)$ is a factor of 2 smaller than the code noise

$$\epsilon(LP_i) \approx \frac{1}{2}\epsilon(P_i) \approx 5 - 8\,cm. \qquad (4)$$

Since the accuracy of the CHAMP ionosphere-free P-code measurements is about 48 cm (derived from kinematic POD results), we expect the accuracy of the P_1-code measurements to be about 10–16 cm, resulting in a noise level of about 5–8 cm for the CHAMP LP_1 observable. Fig. 5 shows the CHAMP reduced-dynamic orbit we obtain for day 200/2002 using the LP_1 linear combination on the zero-difference level compared to our best reduced-dynamic orbit (double-difference, ionosphere-free phase data). This indicates that in principal LEO orbits with 10 cm accuracy can be obtained using one frequency data only.

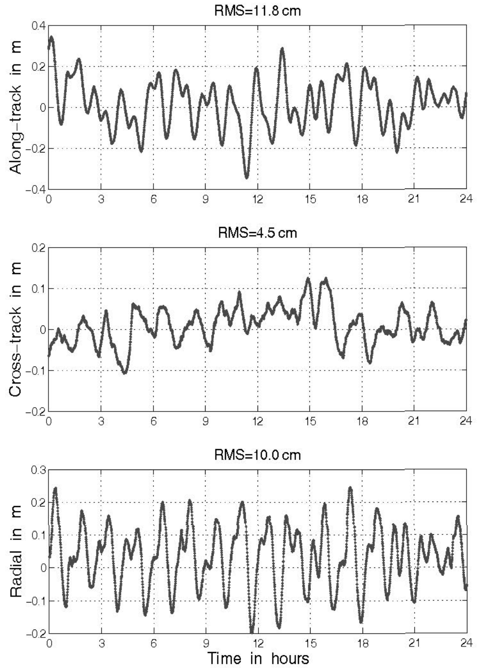

Fig. 5. CHAMP reduced-dynamic orbit estimated using the LP linear combination of the L_1 and P_1 measurements, day 200/2002, showing that LEO orbits can be determined with an accuracy of 10 cm based on single-frequency data only.

The disadvantage of the using LP linear combination and one frequency only is that pre-processing has to be performed with single-frequency data, which might be more difficult. In our analysis pre-processing was done based on dual-frequency data.

4 Gravity field determination based on kinematic orbits

The use of kinematic positions together with their variance-covariance information as an interface to gravity field determination avoids the simultaneous adjustment of gravity field coefficient together with a huge amount of global GPS parameters, like GPS satellite orbits/clocks, zero- or double-difference ambiguities, station coordinates, troposphere parameters, Earth rotation parameters, etc. Comparison with reduced-dynamic orbits and external validation with SLR show that, due to the nature of the phase observable, kinematic positions are very smooth from epoch to epoch (see Fig. 2 and Fig. 3) as long as there are no phase breaks. As a consequence, high-frequency gravity signals may be extracted from these positions. An elegant way to derive gravity field coefficients from kinematic positions is the use of the energy conservation law which may be written in an inertial frame as

$$V = \frac{1}{2}(\frac{d\vec{x}}{dt})^2 - \int_{\vec{x}} \vec{a}_t d\vec{x} - \int_{\vec{x}} \vec{a}_{non} d\vec{x} - C. \quad (5)$$

with the gravitational potential V, the accelerations $\vec{a}_t$ and $\vec{a}_{non}$ due to the time-varying part of the gravity field (e.g. tides) and the non-gravitational forces, respectively, and the total energy constant C. A similar formulation in the earth-fixed frame can be found in Gerlach et al. (2003). An advantage of the gravity field determination based on the energy integral is that we can directly work with the gravity potential as a scalar field instead of having to integrate the equation of motion and all variational equations.

Whereas $\vec{a}_t$ can be obtained from models, the non-gravitational accelerations $\vec{a}_{non}$ are measured by accelerometers. The kinematic energy of the satellite can be computed using velocities derived from kinematic positions by numerical differentiation procedures. At the moment we are providing CHAMP kinematic positions with a sampling of 30 s, which means that the spatial resolution of the estimated gravity field is limited to about 230 km and that much care has to be taken when deriving kinematic velocities. Going to a higher sampling rate, numerical differentiation will become more accurate and a higher spatial resolution will become possible. Making use of the energy integral and kinematic positions from one year of CHAMP data, several gravity field models have recently been computed at the TU Munich, among them the models TUM-1S and TUM-2S (see Gerlach et al. (2003), Földváry et al. (2003)).

In order to get an indication of the quality of these models, CHAMP, JASON-1 and LAGEOS-1 orbits were determined based on GPS (CHAMP, JASON-1) and SLR measurements (LAGEOS-1) using the TUM-1S gravity model. For CHAMP and JASON-1 Table 2 shows the mean RMS of the SLR validation (days 196-202/2002), whereas for LAGEOS-1 the a posteriori RMS of the SLR observations when

Model	JASON-1	CHAMP	LAGEOS-1
EIGEN-1S	4.89	2.24	1.61
EIGEN2	4.69	2.26	1.59
TUM-1S	**4.73**	**2.46**	**1.79**
JGM3	4.28	3.26	1.62
GRIM5-C1	4.96	3.35	1.60
GRIM5-S1	5.03	4.87	1.61

Table 2. Second and third column: Mean RMS of SLR residuals (days 196-202/2002) in cm for CHAMP and JASON-1 GPS-derived orbits based on different gravity models. Last column: A posteriori RMS for LAGEOS-1 dynamic orbits, 8-day arc (days 010-017/1999).

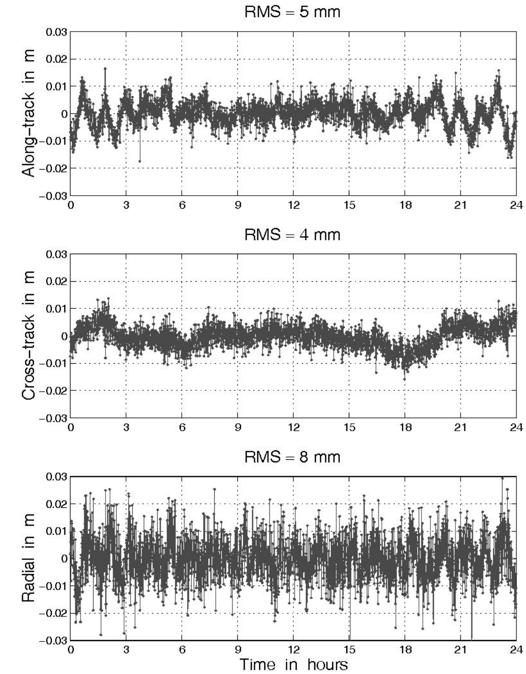

Fig. 6. Kinematic positions of GRACE-A w.r.t. GRACE-B from simulated data with float ambiguities compared to true baseline. Notice colored noise, reflecting correlations between positions and ambiguities.

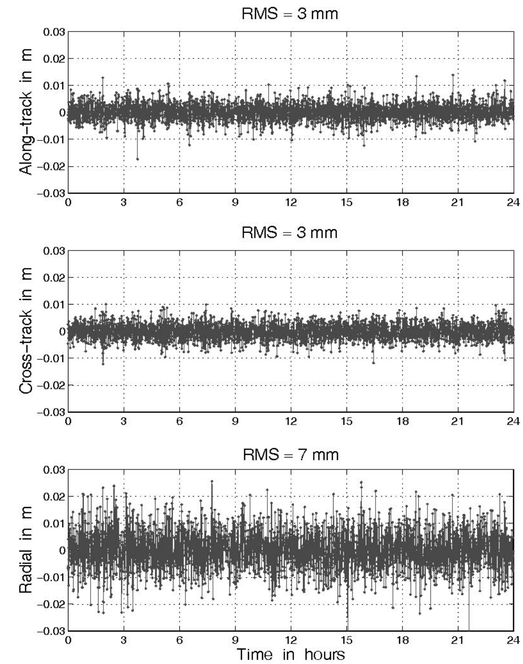

Fig. 7. Kinematic positions of GRACE-A w.r.t. GRACE-B from simulated data with resolved ambiguities compared to true baseline. Notice white noise in the kinematic positions and reduction of the a posteriori RMS from 5 to 3 mm.

determining a dynamic orbit over 8 days (days 010-017/1999) is given. The numbers in Table 2 confirm that kinematic orbits can be used for gravity field determination giving results comparable to the CHAMP models EIGEN-1S and EIGEN2, see Reigber et al. (2003). TUM-1S is the first gravity model derived from purely kinematic orbits and the energy integral.

The quality of the CHAMP GPS data is much better than that of JASON-1 (many data gaps per day, L2-ramps, etc.). This is the reason why CHAMP orbits in Table 2 seem more accurate than JASON-1 orbits. In addition, we should keep in mind that the EIGEN2 and the TUM-1S models were derived from CHAMP SST data only and we may therefore expect a better performance for CHAMP. Such a tuning effect (ICESAT satellite) seems to be less pronounced for the new GRACE gravity model, see Rim et al. (2003).

4.1 GRACE kinematic baseline in space with ambiguity resolution

Let us now see what accuracy might be achievable for the inter-satellite baseline between the two GRACE satellites using a kinematic approach. In order to do this, phase zero-difference measurements were simulated for both GRACE satellites, assuming the noise level and the number of GPS satellite tracked to be similar to CHAMP (only a noise of 1.1 mm was considered with multipath included in this noise level). A typical noise value for the a posteriori RMS of the phase zero-differences in CHAMP kinematic POD is about 1.5–2.0 mm or 1.2–1.4 mm when using double-differences. Whereas zero-differences are mainly affected by the GPS satellite orbit/clock errors, double-differences primarily reflect ground station specific errors like troposphere, multipath, etc. Therefore, the noise level of 1.1 mm adopted for the GRACE simulation might be considered rather pessimistic, keeping in mind that for the short GRACE baseline (220 km), the effect of GPS orbit errors should be only about 0.2 mm, tropospheric refraction is nonexistent and multipath is expected to be very small.

Fig. 6 shows GRACE kinematic baseline results with float, Fig. 7 those with fixed ambiguities. In both cases, GRACE-B was kept fixed to the a priori orbit and GRACE-A positions were estimated kinematically. Comparing these two figures, one can clearly notice that ambiguity resolution de-correlates kinematic coordinates and ambiguities and changes the colored noise present in the kinematic positions of the float solution into white noise. A decrease of the a posteriori RMS from 5 to 3 mm for the along-track component can also be noticed. Ambiguity resolution was performed as explained in Section 2.1 (Melbourne-Wübbena wide-laning, narrow-lane bootstrapping) and all ambiguities were correctly resolved. Similar results are to be expected with real GRACE data. GRACE GPS data will be a very nice playground to study, for the first time, an inter-satellite baseline with the unique possibility to validate the results with the much more accurate measurements of the K-band link.

4.2 Gravity field determination based on kinematic orbits and clocks in space

As a direct consequence of Einstein's general theory of relativity, a source of radiation in a gravitational potential V_B appears shifted in frequency to an observer in a different gravitational potential V_A by an amount $\Delta f/f = -\Delta V/c^2$, where $\Delta V = V_B - V_A$ is the gravitational potential difference between the source B and the observer A positions.

If we approximate the gravitational potential by the central term GM/r (radial geocentric distance r, gravity constant GM, and speed of light in vacuum c), we get

$$\frac{\Delta f}{f} = \frac{\Delta V}{c^2} \approx \frac{GM}{c^2 r^2}\Delta r. \tag{6}$$

If we now assume that two extremely performing clocks in space are stable at the level of 10^{-18} over 15 s (corresponding to $\approx$ 100 km in the orbit of the clocks) and that the gravitational frequency shift between these two clocks can be measured with a similar accuracy, we will be able to directly measure differences in the gravity potential that correspond to a change Δr in the equipotential surface of $\approx$ 1 cm over 100 km. Since kinematic positions can already be determined with an accuracy of 1-3 cm and the relative accuracy between successive epochs is even better, the positions (geometry) of the pair of clocks is well-enough known to support such measurements of the gravity potential difference.

Ultra-stable clocks, matter-wave interferometers and atom lasers based on Bose-Einstein condensation are developing rapidly and it is now conceivable to fly such a clock aboard the International Space Station (ACES mission), see Salomon et al. (2001). Space offers weightlessness and atoms can be cooled to such low temperatures that the Earth gravity field represents a major perturbation to their motion. Micro-gravity conditions aboard the Space Station allow to keep these atoms in the observation volume for several seconds (Salomon et al. (2001)), much longer than on the ground, which leads to the increased stability and accuracy. Although a frequency stability of 10^{-16}–10^{-17} over one day still does not meet the above requirements for the gravity field determination, the latest developments in high-precision optical spectroscopy outperform today's state-of-the-art caesium clocks, especially over short periods (Udem et al. (2001)).

5 Conclusions

Using CHAMP GPS measurements we showed that it is possible to estimate the orbit of a Low Earth Orbiting (LEO) satellite purely kinematically with the same level of accuracy ($\approx$ 1-3 cm, w.r.t. SLR) as by the widely employed (reduced-)dynamic approaches.

Kinematic precise orbit determination (POD) is a purely geometrical approach and therefore independent of satellite dynamics (e.g. gravity field, air-drag, etc.) and orbit characteristics (e.g. orbit height, eccentricity, etc.).

Kinematic and reduced-dynamic POD for CHAMP was carried out for GPS week 1175 using zero- and double-differences with ambiguity resolution. It has been shown that all developed kinematic and reduced-dynamic approaches allow for a similar accuracy of 1–3 cm (w.r.t. SLR) and that ambiguity resolution changes the orbit by $\approx$ 1–2 cm.

With a new type of linear combination, called LP (based on phase and P-code GPS measurements from only one frequency) we showed that reduced-dynamic LEO POD can be performed with an accuracy of $\approx$ 10 cm.

With simulated data, the baseline between the two GRACE satellites was estimated kinematically and a clear increase in accuracy could be demonstrated by performing ambiguity resolution.

Finally, kinematic POD in combination with space (optical) atomic clocks for gravity field determination was discussed. Space offers weightlessness and atoms can be cooled to such low temperatures that the Earth gravity field represents a major perturbation to their motion. It is to be expected in the near future that the idea of measuring gravitational frequency shift and thus gravitational potential differences between space clocks, together with geometry known from kinematic POD, will become reality.

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