Kinematic Orbit Determination of Low Earth Orbiter using Triple Differences

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ABSTRACT

Among numerous applications of GPS, the precise orbit determination of a low earth orbiter (LEO) has been one of the most actively developing fields in the past decade. The precise orbit determined from GPS is needed in many space science applications such as radar altimetry, satellite gravity/gradiometry, and atmospheric sounding. The LEO needs very precise mathematical model for the dynamic forces acting on it, because of its low altitude (below than 700 km). With errors induced by the imperfectness of the model, the orbit calculated by the dynamic approach degrade with the length of the arc. Thus, force model parameters need to be adjusted during the orbit determination (OD) procedure, adding more unknowns to the solution. Therefore, under the assumption of a complex dynamic behavior of LEO satellite, the kinematic strategy could potentially generate an orbit with the accuracy comparable to the dynamic approach with the force model estimated, provided good geometry (PDOP) is maintained. In addition, the procedures for the kinematic OD are much simpler and more efficient since neither dynamic nor physical models are necessary, and the number of unknowns is limited to the LEO position coordinates.

In this paper, a kinematic OD procedure for LEO using GPS triple-differenced observables is presented. Ion-free triple differenced phases are used as observables, and the coordinates at the initial epoch are held fixed, due to the fact that the triple difference method can only provide coordinate change from epoch to epoch. To achieve the computational efficiency, the precise orbits published by the International GPS Service (IGS), and well-distributed ground stations data/coordinates are utilized, leaving the satellite coordinates at each epoch as the only unknowns.

Currently, the 3D accuracy of the developed algorithm applied to the German CHAMP satellite (CHAllenging Minisatellite Payload, launched on July 15, 2000) shows better than 30 cm fit to the published rapid orbit solution (good to ~10 cm per coordinate) from GFZ (GeoForschungsZentrum Potsdam), and much better accuracy can be obtained for the portions of the trajectory with good satellite and ground station configuration.

Because the ultimate goal of this research is to provide rapid orbits (with 2-3 hour latency) to support GPS occultation data analysis, where the velocity information is required, the velocity is also derived from the orbit with a 3D accuracy of 1.2 mm/sec, which still needs to be improved, to meet the accuracy requirements in supporting the atmospheric sounding. Since the kinematic POD highly depends on the strength of GPS satellite and ground station geometry, the issue of optimal configuration of the ground stations is also discussed.

Keywords: kinematic POD (precision orbit determination), LEO (low earth orbiter), orbit accuracy analysis.

1. **INTRODUCTION**

For the past two decades, the Global Positioning System (GPS) has been continuously developed and applied to various scientific/engineering fields such as geodesy, aviation, geophysics, oceanography and atmospheric science, providing a superior capability of the continuous precise global 3-D positioning. In particular, GPS has significantly contributed to the various space missions, in which the precise orbit determination (OD) of satellites and/or space shuttle is crucial. With current fully operational configuration and technology, the orbit of LEO can be determined with accuracy better than 5 cm of RMS, as demonstrated in the satellite altimetry mission TOPEX/POSEIDON (Bertiger et al., 1994, Tapley et al., 1994).

Conventionally, there are three strategies to determine precise LEO orbits with GPS: dynamic, kinematic and reduced-dynamic or hybrid. The major difference between those strategies is the degree of incorporated dynamic modeling of the physical forces acting on the satellite such as gravity, solar radiation, atmospheric drag, etc. as well as the physical properties of the satellites like shape and dimensions.

While the dynamic strategy implements a full dynamic force models (usually improved in POD process), the kinematic strategy uses only the observations while the reduced dynamics applies proper weights between the observations and dynamic models in the OD procedure. Because of their low altitude (below than 700 km), LEOs need very precise mathematical models for their dynamics. However, the errors induced by the imperfectness of the model grow with the length of the arc, which could degrade the accuracy of the final orbit. Consequently, the force models become a part of the state vector during the orbit adjustment procedure. Therefore, under the assumption of a complex dynamic behavior of LEO satellite, the kinematic strategy could potentially generate more accurate orbit than the dynamic approach, provided good geometry (PDOP) is maintained.

Although the reduced dynamics was proven to be the best method in TOPEX/POSIDON mission, the procedure for the reduced dynamics is much more complex than that of the kinematic case, since it also implements all the dynamic models. Therefore, with its much simpler and efficient procedures, the kinematic strategy can generate the orbit much faster as compared to the other strategies. This becomes very important in some of the applications like, for example, weather forecasting using atmospheric sounding data. This application is not fully operational yet, but it is feasible to except that with more LEO missions providing atmospheric sounding, these data might be eventually incorporated to the weather prediction process.

Kinematic approach has already been applied to the TOPEX/POSEIDON mission (circular orbit, 1336 km nominal altitude). Using double differenced phase observables, the accuracy of better than 5 cm in radial direction and 16 cm in 3D has been achieved (Byun and Schutz, 2001). Considering the receiver on TOPEX/POSEIDON has only 6 channels, better results may be expected with a receiver having more channels under the assumption of good quality of data. However, the much lower altitude of a satellite like CHAMP introduces another challenge: the satellite moves very fast, and it is moving in the mid-layer of the fast changing ionosphere (especially currently, where the ionosphere is still very active), which makes the data screening process much more difficult.

In this paper, a kinematic LEO positioning algorithm using the triple differenced GPS phase data with the results applied to CHAMP satellite is presented. The main goal of this study includes the fast generation of the orbit with a full analysis of CHAMP data, related to the geometric strength and data quality. The results of this study can be used as a basis for further refined OD process, such as reduced dynamic strategy.

The processing of triple differenced phases is a very efficient procedure in kinematic OD, because many nuisance parameters, including the ambiguity, are cancelled out through the differencing. In fact, the triple difference technique presented here is the extended version of the GPS POD software GODIVA developed at the Ohio State University (Grejner-Brzezinska, 1995; Goad et al., 1996; Kwon, 1997). After removing all dynamic elements used in GODIVA, the processing has been changed to a sequential batch filter for kinematic LEO POD.

Currently, the precise GPS orbits published by IGS and well-distributed ground stations data and coordinates are utilized in our procedure. The ionospheric effect is removed by performing the ion-free combinations, and the modeled tropospheric effect is used to minimize the number of unknowns. Therefore, the only parameters in the procedure are the positions of LEO at each epoch. With the kinematic OD procedure presented here, and the developed earlier GODIVA providing GPS orbits, we are able to obtain fast and independent LEO POD, as long as the ground station data are provided.

1. DATA PROCESSING

The kinematic POD method developed in this study consists primarily of three main procedures, namely preprocessing of GPS data, main estimation of LEO POD, and post processing of the estimated orbit (Figure 1).

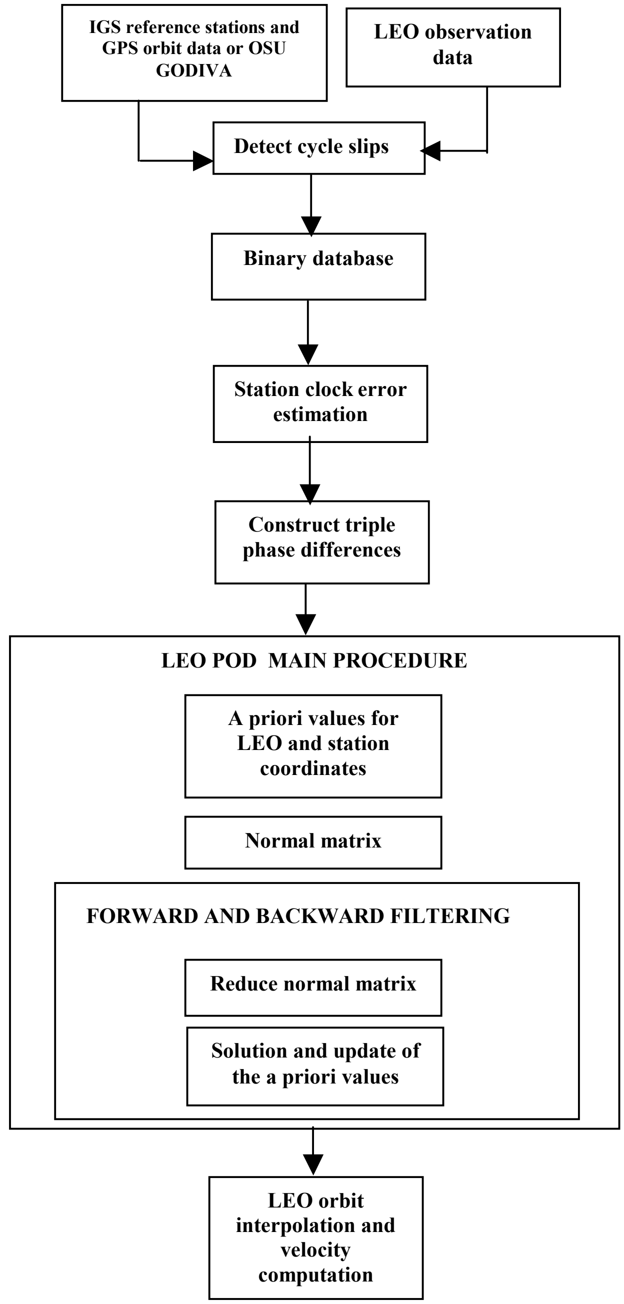

Figure 1. Schematic diagram of the kinematic LEO POD.

1.1 Preprocessing step

In the preprocessing module the following steps are executed: construction of the data base using IGS reference stations and LEO observation data, cycle slip detection, stations' clock correction, and forming the triple difference database. For more efficient processing, the databases of the raw and triple differenced phases are stored in binary files.

The most important procedure in this step is the cycle slip detection. Since kinematic approach completely relies on the measurements, the data containing cycle slips significantly degrade the accuracy of the orbits. If a good a priori orbit is available, the cycle slips can be detected and removed during the orbit estimation procedure. In other words, in the procedure of normal matrix accumulation, the difference between the observables and the calculated values (residuals) using a priori values can be computed. If the residuals were big compared to the accuracy of the a priori values (and the measurement), the observation would most probably suffer from a cycle slip. If a good a priori value is not available, the cycle slip should be detected at the raw data level by investigating ion-residuals, comparing pseudoranges and phases, etc. In our approach, four standard cycle slip detection algorithms are implemented, which use the test quantities of ionospheric residual, double differenced ion-residual, ion free range-phase combinations, and double differenced (DD) phase data.

To analyze the results of cycle slip detection from the tested methods, the rapid science orbit (RSO) from GFZ were used to generate a benchmark solution. Using RSO, it is possible to detect cycle slips and bad observations by comparing the observables with the computed values. Unfortunately, it turned out that none of the traditional methods for the cycle slip is fully reliable for cleaning the CHAMP data because of the low signal to noise ratio (at low elevation angle), variable ionosphere and high speed of the vehicle, as mentioned earlier. As a result, the traditional methods tend to report false cycle slips and discard more data, as compared to the procedure using RSO as reference. According to the cycle slip detection using RSO, the data from CHAMP contain 5.5 % of cycle slip (8.5% using traditional methods), while the ground stations have only 0.2 %. For details on the data screening and the processing accuracy analysis, see Bae et al. (2002, in this volume).

Figure 2 shows the distribution of the 65 ground stations selected from the International GPS Service (IGS) centers for this study. The important condition on selecting the ground stations is the uniform distribution covering whole globe to maintain the consistent good geometry at any time. At his point, however, the station configuration is not optimized yet. While many stations are densely located in North America and Europe, not many stations are available in Africa, central Asia and the Polar Regions. The optimization procedure will require many tests with varying baseline length and the distribution of the ground stations.

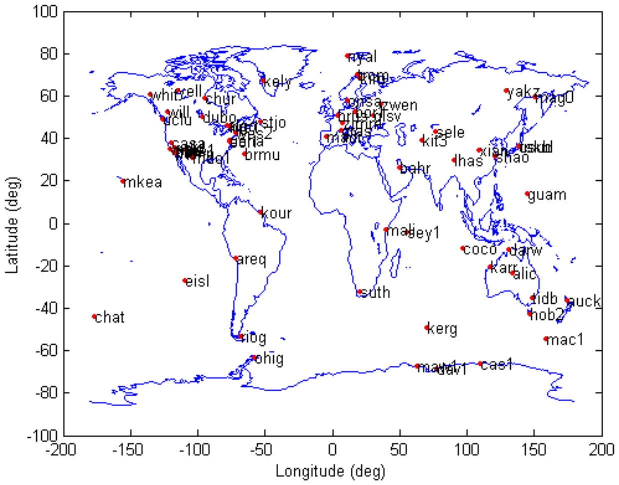

Figure 2. Distribution of selected ground stations for kinematic LEO POD.

Once the ground stations are selected, the data for all station are screened for cycle slips and the station containing too many cycle slips (> 2 %) are removed and replaced by another neighboring station with good quality data. Overall, the selected ground stations contain less than 1 % of the cycle slips in 24 hr data span.

1.2 Main estimation procedure

The main estimation step consists of a calculation of the a priori orbit from double differenced pseudoranges, construction and reduction of the normal matrix, and the estimation of the final orbit. As already explained, the main observable in this study is the ion-free triple differenced phase. Using the dependency of the ionospheric effect on the frequency, an ionosphere-free measurement can be obtained by combining the phase observations as follows:

$$\Phi_{1,2} = \alpha_1 \Phi_1 + \alpha_2 \Phi_2 \quad , \tag{1}$$

where α_1, α_2 are arbitrary constants, which should meet the following condition:

$$\alpha_1 \cdot \Delta_{ion,1} + \alpha_2 \cdot \Delta_{ion,2} = 0 \quad , \tag{2}$$

where

$\Delta_{ion,1}$ and $\Delta_{ion,2}$ are the ionospheric terms on L1 and L2 frequency, respectively. For example, a popular ion-free combination is obtained using the constants as follows:

$$\alpha_1 = \frac{f_1^2}{f_1^2 - f_2^2}, \qquad \alpha_2 = -\frac{f_2^2}{f_1^2 - f_2^2}. \tag{3}$$

Then, the observation equation of an ionosphere-free triple-differenced measurement between two receivers *i* and *j*, two satellites *k* and *l*, and over a time interval *dt* between epoch *t1* and *t2*, can be written as:

$$\Phi^{kl}_{ij,iono-free,dt} = \rho^{kl}_{ij,dt} + T^{kl}_{ij,dt} + \alpha_1 \varepsilon^{kl}_{ij,1,dt} + \alpha_2 \varepsilon^{kl}_{ij,2,dt}\,, \tag{4}$$

where $\Phi^{kl}_{ij,iono-free,dt}$ is the ion-free triple-differenced phase; $\rho^{kl}_{ij,dt}$ is the triple-differenced geometric ranges; $T^{kl}_{ij,dt}$ is the triple-differenced tropospheric effect; $\varepsilon^{kl}_{ij,1,dt}, \varepsilon^{kl}_{ij,2,dt}$ are triple-differenced phase errors in L1 and L2 frequencies, respectively.

Compared to the undifferenced observables, triple differenced phases have some advantages such as reduced number of unknowns (no ambiguity terms), and reduced computer memory use and processing time. On the other hand, the complicated structure of the covariance matrix is a potential disadvantage of triple differencing. The consecutive triple differenced observations are correlated via differencing. The covariance matrix is, therefore, neither diagonal nor block-diagonal. It is a banded matrix where the profile depends on the manner in which the triple differences are built.

Since the procedure designed for the OD is the kinematic batch, not the epoch-by-epoch filter, the total number of observations in a batch could be very large, depending on the number of epochs forming the batch. In such a case, a conventional inverse routine might not be enough to handle the complex large matrix in terms of the efficiency as well as the numerical accuracy. In this study, a convenient and efficient decorrelation scheme using Cholesky factorization is applied to the covariance matrix. The decorrelation replaces the inversion procedure with simple forward substitution for the solution of the system of the linear equations. For details on decorrelation scheme, see Grejner-Brzezinska (1995) and Yang (1995).

Since the observations are non-linear with respect to the unknowns, the equation (4) should be linearlized to construct the observation model in the usual form of

$$Y = A\xi + e, \qquad e \sim N(0, \Sigma)\,, \tag{5}$$

where Y is the measurement, A is the design matrix, ξ is the unknown parameter and e is the measurement error with assumed normal distribution of zero mean and variance of Σ.

Then, a least square estimation can be performed to estimate the unknowns, namely the positions of LEO. Among various methods of estimating the positions such as epoch-by-epoch filtering, multi-epoch batch and sequential adjustment, a multi-epochs batch process are selected in this study, as mentioned earlier. Naturally, triple difference as a relative method, provides only the change in coordinates from epoch to epoch, not the coordinates themselves. To overcome this problem, two methods are possible. One is to provide stochastic a priori information for all unknowns, and estimate those unknowns using the so-called adjustment with stochastic constraints (however too loose constraints might result in a biased solution). The other approach is to provide a fixed reference at the starting epoch and estimate all other unknowns in the batch. In this study, the second approach was selected to estimate the LEO orbit by fixing the positions of the first epoch in every batch. Therefore, the number of unknowns for the batch of k-epochs is $3 \times k-1$.

It should be mentioned, however, that if the initial position is not known with a high accuracy, fixing this initial position will introduce errors to the subsequent epoch solutions. Since the initial values are connected to the positions at all other epochs through the variance-covariance matrix, the first portion of the estimates is considerably effected by the initial bias. In our test, it has been shown that first about 120 estimates in 500 epochs batch appear to suffer from the wrong initial values of 5 meters. Only beyond 120 epochs, the convergence has been achieved. Therefore, using the results from the forward batch filter, backward filtering should be conducted to eliminate the bias effect of the wrong initial values. In that case, the position of the last epoch in a batch is fixed and the order of the data is reversed in the backward filtering. Obviously, the forward and backward filtering should be iterated until the solution fully converges.

1.3 Post-processing

One of the drawbacks of the kinematic approach is the fact that the estimated orbits may suffer from the singularities when the data were lost due to cycle slips or signal outages, and bad quality estimates may happen due to poor geometry (they appear as spikes in the estimated orbits). Therefore, a spike removal and interpolation routines should be applied to the estimated orbits to get smoothed and continuous orbits. In the test with 500 epochs data, no singularity has occurred but a few spikes can be observed. Using a cubic spline spike remover and a 5-th order B-spline interpolator, the spikes are removed and gaps are interpolated generating continuous orbits.

Once the continuous orbits are calculated, they are numerically differentiated to obtain the velocities. Of course a smoothing has to be applied to reduce the noise introduced by the numerical differentiation. A numerical differentiator of B-spline with 2 seconds of smoothing was applied to get the velocities. Currently, a 24-hour orbit can be calculated in 2 hrs on 1.8 GHz Pentium processor.

2. RESULTS AND ANALYSIS

2.1 A priori orbits

A two-step procedure is applied to obtain the a priori orbit, namely using one-way range data in absolute kinematic positioning and subsequently double differenced ranges in relative kinematic positioning. The absolute kinematic positioning with four unknowns (positions and receiver clock errors) is performed using pseudoranges to obtain the initial coarse orbits, and then those are used as the initial values in double differenced relative positioning, which in turn is used as an approximation in the final OD based on phase triple differences. In the double differenced estimation, the GPS coordinates are fixed to the precise orbits from IGS and the coordinates of the sixty-five ground stations selected from IGS are held fixed.

The 250-minute orbital arc from the absolute kinematic positioning using pseudorange and double differenced pseudorange data are shown in Figure 3. Although the accuracy of this orbit is not good enough to be used in any scientific applications, it is good enough to be used as initial values in further estimation procedure, namely triple differenced phase procedure. Furthermore, this initial result provides the information about the raw configuration of satellites and quality of the LEO clock. For example, one can immediately notice that some peaks around epochs 1500 and 1630 have disappeared at the DD estimates indicating that the clock of LEO was particularly unstable for these epochs. In addition, the big peak around epoch 1750 appearing in both absolute and DD estimates indicates that the geometry for those epochs is relatively poor.

It should be noted that the overall accuracy of the estimated orbits from the absolute and DD pseudorange are much poorer than expected. This is considered to be the effect of low signal to noise ratio of the signals from low altitude satellites and weaker geometry on some portions of the trajectory. In general, the low number of the observations and baselines involved results in lower quality estimates in DD pseudorange algorithm (see Figure 3 and Figure 4).

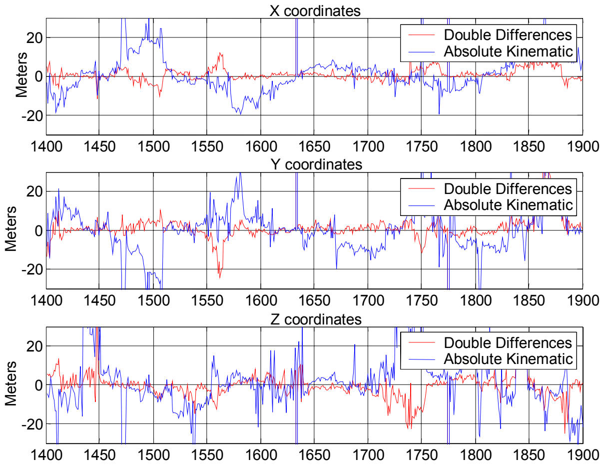

Figure 3. The difference between RSO and the a priori orbits from absolute kinematic and DD pseudorange algorithm.

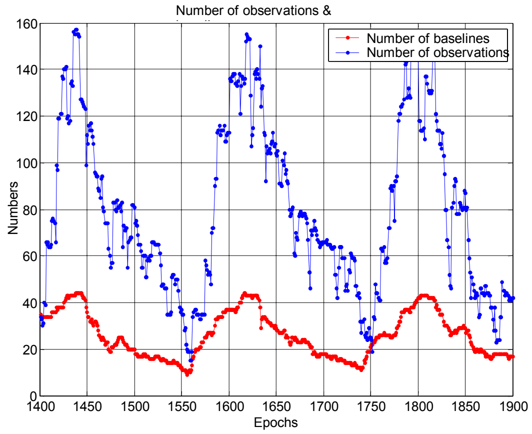

Figure 4. The number of baselines and observations for DD orbit estimates.

2.2 Final orbits based on phase triple difference

As mentioned before, the orbits from DD pseudorange are being used as an approximation in the triple differenced phase algorithm for precise orbit calculation. (this was said many times before) Theoretically, if the a priori orbit had a sufficient accuracy, then the cycle slips as well as the outliers could be easily detected by investigating the differences between the observations and calculated ranges in the process of final orbit determination. Since the accuracy of the a priori orbits based on DD pseudorange is no better than 5 meters RMS, those orbits cannot be used in the detection of the cycle slips and the outliers during the normal matrix construction. In other words, because of the big errors in the a priori orbits, one cannot distinguish between the cycle slips or outliers and the effect of erroneous a priori orbits or relatively big differential ionospheric effect. Therefore, a separate procedure for the data prescreening, as indicated in Section 2.1, must be applied.

It should be indicated here that the data screening procedure is still under development, with the major objective of making the screening independent of the RSO orbit, which has a latency of several days. However, the results presented here are based on data cleaned for cycle slip and outlier detection using CHAMP RSO. The rationale for this approach is that it allows analyzing the feasibility of the kinematic approach under the assumption of reliable data screening.

Figure 5 illustrates the difference between the RSO and the estimated orbits from the forward adjustment for an arc of 500 epochs (epoch separation is 30 s). As mentioned before, the coordinates of CHAMP at the first epoch are held fixed while the coordinate differences from epoch to epoch are estimated by the triple differences. In the example shown here, the fixed initial position contains the biases with respect to the true orbit, since we assumed that only the approximated coordinates are known. In this case, the biases at the first epoch affect the orbit estimates for up to ~120 epochs, as shown in Figure 5.

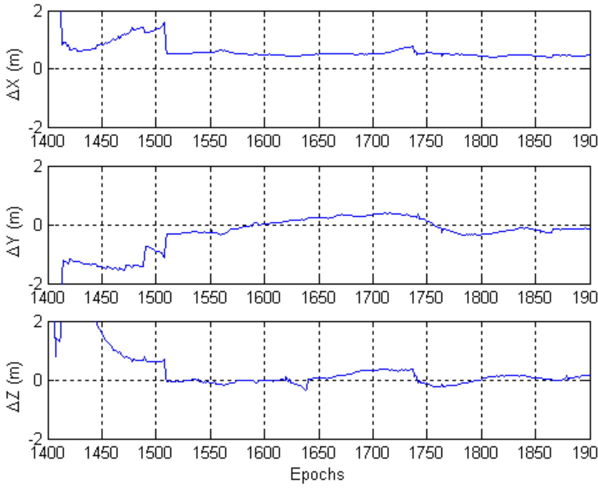

Figure 5. The difference between RSO and the estimated orbits from the forward filtering.

To reduce the effect of the biased initial position, the same filter can be applied backward. That is, fixing the last epoch's position with the values estimated at the forward filtering, the estimation is again performed in backward direction to mitigate the bias effect from the forward filter. The effect of the backward filtering can be observed in Figure 6 and Table 1, which display a significant decrease of the RMS of fit of the final orbit the reference RSO orbit. According to Zhao (1998), the orbit error of 30 cm is required to estimate the temperature profile in GPS sounding to better than 1 degree K up to the altitude of 40 km. So, theoretically, the triple difference method is capable of meeting these requirements. However, to support operational forecasting, a reliable cycle slip detection routine, independent of RSO must be developed, to assure fast availability of the final kinematic orbit.

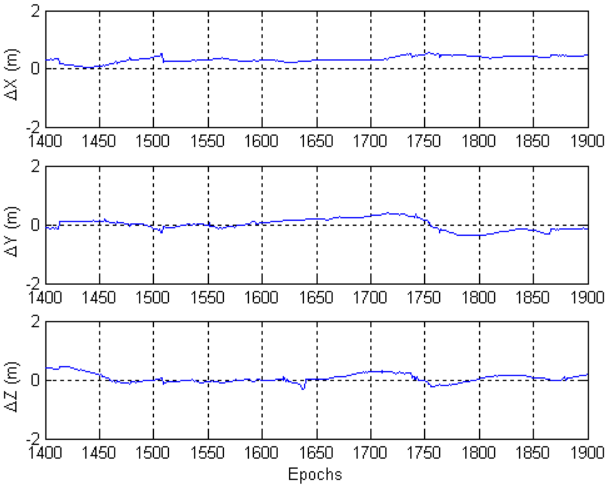

Figure 6. The difference between RSO and the estimated orbits from the forward & backward filtering.

Table 1. RMS of fit of the kinematic solution to the CHAMP RSO after forward & backward filtering.

	RMS_x (m)	RMS_y (m)	RMS_z (m)	RMS_{3D} (m)
Forward	1.15	2.22	0.79	2.62
Backward	0.11	0.20	0.15	0.27

2.3 Derived velocity

Because the velocity is not directly estimated in the kinematic OD procedure, it can be obtained by applying a numerical differentiator to the estimated orbits. Figure 7 shows the comparison of the velocity between the published RSO and that derived from the kinematic orbits through the numerical differentiation. A 5th order B-spline differentiator with a smoothing window of 2 epochs was applied to obtain the velocity. As shown in Table 2, the 3D accuracy (RMS) of 1.2mm/s can be achieved, as compared to the published RSO.

Obviously, this method of velocity calculation has certain disadvantages. Firstly, there is no estimated velocity variance since it is not directly estimated in the adjustment procedure. Secondly, the result of the numerical differentiation depends on many factors such as the order of the polynomial and the smoothing window. Therefore, to obtain a consistent results of the velocity, many tests has to be carried out by comparing it to reference velocity of high accuracy, for example the velocity from the dynamic approach.

Table 2. RMS of fit of the estimated velocity to RSO.

RMS_{Vx} (mm/s)	RMS_{Vy} (mm/s)	RMS_{Vz} (mm/s)	RMS_{V3D} (mm/s)
0.5	0.6	0.9	1.2

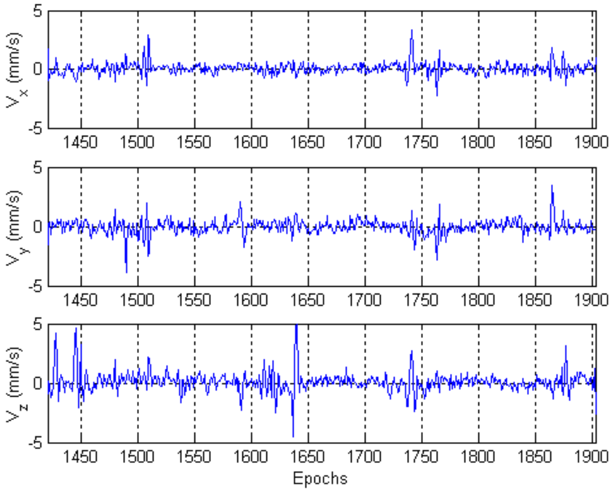

Figure 7. The difference between the RSO velocity and the derived velocity.

2.4 Discussion of the results

The number of observations at each epoch is the most critical factor in the kinematic OD for its complete dependence on the observations. If the number of the observation at an epoch is less than four, the orbit could not be calculated because of the singularity. On the date for the test data set, thanks to the 12-channel receiver on CHAMP, there is no epoch having less than four observations. There are, however, about 10 minutes of gaps in the data of June 15, 2001, caused by the gaps in receiver tracking. Most of the time, CHAMP tracked six or more satellites during that day. After excluding cycle slips, bad observations and taking triple differencing, however, 17 out of total 2880 epochs in 24 hr span appeared as singularities, separating the total span into 10 discontinuous segments (for details on cycle slip and data gap statistics see (Bae et al., 2002, this volume).

The ten segments spanning 24 hrs are processed to estimate orbit in separate batch. As seen in Table 3, it is found that each batch produces consistent results with accuracy ranged 20-50 cm in RMS except last segment. The reason for the poor result on last segment is the small size of the batch as well as bad geometry. In other words, we saw that at least 120 continuous epochs were necessary to overcome the effect biased first position (see Figure 5). Therefore, the convergence is not guarantied if the batch size is significantly smaller than 120, and the solution could easily approach to the local minimum.

Currently, the biggest problem should be solved for the application of the developed algorithm is to build a sound data pre-screening algorithm. It is found that the low signal to noise ratio from low satellites is the major element causing cycle slips on the phase data of CHAMP. Therefore, a procedure combining the information of the signal to noise ratio from CHAMP RINEX files and conventional cycle slip detection method should be developed for successful precise kinematic OD.

Table 3. RMS of fit of the 24 hr kinematic orbit to RSO.

# of segment and epochs	X (cm)	Y (cm)	Z (cm)	3D (cm)	# of iteration
1 (251)	4.3	15.0	14.7	21.4	1
2 (421)	9.1	25.7	18.4	32.9	2
3 (68)	11.1	7.5	26.6	29.8	13
4 (325)	11.3	20.8	16.1	28.7	1
5 (232)	20.4	6.0	19.0	28.6	3
6 (76)	20.3	7.1	17.9	27.9	1
7 (510)	18.4	18.7	16.3	30.9	1
8 (488)	22.9	12.0	29.4	39.1	1
9 (395)	26.5	17.9	35.1	47.5	2
10 (87)	6.6	27.0	88.4	92.9	1

A possible update on the modeling of the tropospheric effect could improve the accuracy on the estimated orbits. Basically, there are two ways for better tropospheric modeling. One is to model the tropospheric effect as a stochastic process and estimated at certain interval for each ground station, and the other is to implement the results from IGS centers estimated tropospheric scale factors. Other than the tropospheric modeling, optimal selection of ground stations for best accuracy and efficiency should be studied. Minimizing the number of ground stations with no degradation in accuracy will significantly improve the computational efficiency.

3. CONCLUSION AND RECOMMENDATIONS

An algorithm of the precise kinematic orbit determination for LEO using the triple differenced phases has been developed and applied to CHAMP. The three-dimensional accuracy of the estimated orbits and velocities derived through numerical differentiation are better than 30 cm and 1.5mm/sec, respectively. It is expected that better accuracy can be achieved by refined tropospheric modeling (for example, using IGS-provided tropospheric scaling factors) and the ground station configuration.

A big issue in the kinematic approach is to clean the data from LEO. Because of the low signal to noise ratio of the signal from low GPS satellites and the CHAMP fast motion through a mid-ionosphere of, the reliable detection of outliers and cycle slips was not possible using the conventional methods.

One of the advantages of performing the kinematic OD is that the developed common modules in OD procedures can be easily transferred to the reduced dynamic approach, which would allow for bridging gaps and weak geometry in the data. Since almost all the procedures such as database construction, clock estimation, and orbit estimation are common in both kinematic and reduced dynamic approach, much faster development of reduced dynamic OD, which is known to generate the best accuracy, is expected in the near future.

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REFERENCES

Bae, T.S., Kwon, J.H., Brzezinska, D. (2002): Analysis for Kinematic Orbit Determination of CHAMP Satellite, 2002 ION National Technical Meeting, San Diego, CA, January 28-30, 2002.

Bertiger, W.I. et al., (1994): GPS precise tracking of TOPEX/POSEIDON: Results and implications, *JGR*, Vol. 99, No. c12, pp. 24449-24464.

Byun, S.H., Schutz, B.E. (2001): Improving satellite orbit solution using double-differenced GPS carrier phase in kinematic mode, *Journal of Geodesy*, Vol. 75, No. 9/10, pp. 533-543.

Goad, C. C., Goodman, L., (1974): A Modified Hopfield Tropospheric Refraction Correction Model, presented at the Fall Annual Meeting of the American Geophysical Union, San Francisco, California, Dec. 12-17.

Goad C. C., Grejner-Brzezinska D. A., Yang M., (1996): Determination of High-Precision GPS Orbits Using Triple Differencing Technique, *Journal of Geodesy*, Vol. 70, pp. 655-662.

Grejner-Brzezinska D. A., (1995): *Analysis of GPS Data Processing Strategies: In Search of Optimized Routine of Orbit and Earth Rotation Parameter*

Recovery, Department of Geodetic Science and Surveying, OSU, Departmental Report No. 432.

Kwon, J. (1997): *The orbit determination software GODIVA at the Ohio State University*, Department of Geodetic Science and Surveying, OSU, Departmental Report, No. 438.

Tapley, B.D., et al., (1994): Precision Orbit Determination for TOPEX/POSEIDON, *J. Geophys. Res.*, Vol. 99, pp. 24383-24404.

Yang, M. (1995): *New GPS Measurement Modeling Technique for Orbit Determination and Precise Kinematic Positioning, Department of Geodetic Science and Surveying, OSU*, Departmental Report No. 431.

Zhao, C.Y., (1998): *The sensitivity of atmospheric temperature retrieved from radio occultation technique to orbit errors of GPS and LEO satellites*, GeoForschungsZentrum Potsdam, Scientific Technical Report STR98/23.