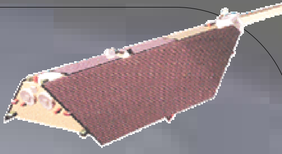
Near Real-time Kinematic Orbit Determination Using GPS



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Abstract

This paper presents a geometric approach to Low Earth Orbiter (LEO) orbit determination (OD) based exclusively on triple differenced GPS carrier phase observable. CHAMP (Challenging Minisatellite Payload; altitude ~ 450 km) mission data are used to present the accuracy, speed and efficiency of the processing algorithms, to discuss the methods of data screening as well as the effects of geometry on the orbit quality, and the final achievable accuracy including the limitations and the benefits of this method. The data screening for cycle slips is a particularly challenging procedure for LEO, which moves very fast in the middle of the ionospheric layer. It will be shown that SNR (signal to noise ratio) combined with the residual screening offers a good approach.

The triple difference method, entirely eliminating the ambiguity resolution, which by itself is a complicated and time consuming task for long-range kinematic GPS, renders the algorithms very efficient. This method has already demonstrated 15-30 cm 3D RMS of fit to the dynamic orbit used as a quality check for kinematic approach.

Introduction

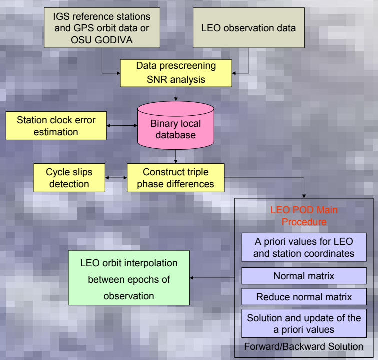
The availability of a full GPS constellation for the past number of years allowed continuous, three-dimensional and accurate position estimation, including space applications. The rich observing geometry provided by GPS has been used for trajectory determination of the low earth orbiters (LEO) using either dynamic, reduced dynamics or kinematic approaches. The rationale for kinematic approach to LEO orbit determination (OD) is the method's simplicity and short processing time, as well as the underlying fact that, particularly at lower altitudes, the actual trajectory may be closer to the precise GPS position estimates rather than the trajectory determined by the dynamics. Ultimately, the complicated irregularly shaped spacecraft on low earth orbits may be precisely positioned without using sophisticated force models, required especially for the dynamic method.

However, the kinematic approach has also some drawbacks related to its sensitivity to weak GPS/LEO/tracking stations geometry. Namely, for the weak geometry, the orbit quality degrades and cannot be bridged by the model, as used in the reduced dynamics/dynamic approach. The implementation of the dynamic method allows the use of either force models with additional parameters, or the replacement of the non-conservative forces with the accelerometer data sensed by the onboard accelerometer, supplemented by sensor error estimates in the state vector.

Varying tracking station geometry and their number along the LEO paths, have a profound impact on the overall orbit accuracy, especially in the geometric approach. Since our ultimate objective is to provide quality orbits supporting atmospheric limb sounding in near real-time (limited virtually by the tracking data availability), it is important that the distribution of the selected sub-set of the IGS tracking stations provides continuous and reliable solution. Naturally, even if the selected station coverage is sufficient, any data gaps on LEO will introduce a discontinuity in the kinematic trajectory.

Kinematic approach to LEO POD has been addressed in literature by, for example, Byun, S. H., 1998; Byun and Schutz, 2001; Bisnath and Langley, 1999; 2001).

Procedures of P-KOD



IGS reference stations and GPS orbit data or OSU GODIVA

LEO observation data

Data prescreening SNR analysis

Station clock error estimation

Binary local database

Cycle slips detection

Construct triple phase differences

LEO POD Main Procedure

A priori values for LEO and station coordinates

Normal matrix

Reduce normal matrix

Solution and update of the a priori values

Forward/Backward Solution

LEO orbit interpolation between epochs of observation

Figure 1. Procedures of P-KOD

Precise Kinematic Orbit Determination (P-KOD) is a triple-difference-based kinematic software designed for fast and automatic orbit determination of LEO. P-KOD GPS processing engine was derived from the dynamic orbit determination software, GODIVA, developed at the Ohio State University in mid-1990s (Grejner-Brzezinska, 1995; Goad et al., 1996; Kwon, 1997). The three major modules of the P-KOD algorithm are: (1) data pre-processing, (2) data reduction and least squares solution (main processing module), and (3) the post-processing module. Since kinematic solution is based exclusively on the measurements, the data containing cycle slips will significantly degrade the accuracy of the orbits. Thus, the most important procedure in the pre-processing step is the cycle slip detection.

Two primary methods are currently implemented in our approach: (1) the cycle slips can be detected using the signal to noise ratio (SNR) included in the RINEX file for the LEO satellite, (2) the cycle slips can be detected and removed during the main estimation procedure by checking the level of triple difference residuals. This approach, however, applies only to the case when a good a priori orbit is available.

In the main processing module, the a priori LEO orbit is first computed based on double differenced pseudoranges. Then, the normal matrix accumulation and reduction are performed, and finally, the kinematic orbit is estimated by least squares batch solution. The primary observable used in P-KOD is the ion-free triple difference carrier phase combination. As already mentioned, the main advantages of using the triple difference carrier phase, are (1) short processing time, (2) no ambiguity fixing, and (3) no cycle slip fixing On the other hand, the complicated structure of the covariance matrix is a potential disadvantage of triple differencing. However, a fast decorrelation scheme, based on Cholesky's algorithm has been implemented (Grejner-Brzezinska, 1995; Grejner-Brzezinska et al., 2001; Kwon et al., 2002).

Cycle Slip Detection

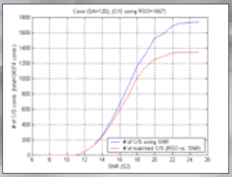


Figure 2. The comparison of cycle slips by SNR and RSO with fixed SA

SA	S2	# of C/S	# of matched C/S
120	22	1708 (5.0%)	1336 (80.6%)
121	22	1817 (5.3%)	1354 (81.7%)
122	22	1910 (5.7%)	1372 (82.8%)
123	22	1938 (5.6%)	1395 (84.2%)
124	22	1984 (5.8%)	1415 (85.4%)
125	22	2099 (6.1%)	1417 (85.5%)

Table 1. The comparison of cycle slips by SNR and RSO with fixed S2

One method of detecting cycle slips in P-KOD is through monitoring of the level of triple difference residuals if a good approximation of the orbit is available in the main processing module. In general, an approximated dynamic solution will suffice, while double differenced pseudorange solution cannot always provide a sufficient accuracy. Thus, if a good approximation is not available, cycle slips can be detected using SNR monitoring technique. Three types of SNR are available for CHAMP data: S1 and S2 corresponding to L1 and L2 carrier phase channels, and SA, corresponding to the C/A channel. Figure 2 illustrates the qualitative and quantitative assessment of CS detection using SNR. The "true" reference used for this analysis is the number of CS detected by the analysis of triple difference residuals using precise dynamic orbit (RSO, Rapid Science Orbit). It should be mentioned that finding the proper threshold of SA and S1 or S2 combination is not an easy task. Moreover, the selected cut-off values for one day, might not apply to another CHAMP data set. This variability of the SNR levels needs more attention.

Table 1 shows another example of different SNR combinations by varying SA with fixed S2 threshold. The number of cycle slips matched between SNR-based and the reference solutions varies from 80 to 85 percent, with SA ranging from 120 to 125. Effectively, if the RSO-based solution is considered "true reference," the SNR-based method seems too sensitive, and might discard too many data points, leaving off at the same time a number of real CS undetected.

Forward & Backward Filtering

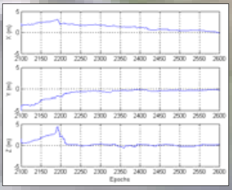


Figure 3. Difference between the estimated orbits and RSO after forward filtering

RMS of fit
RMS(x) = 0.745 m
RMS(y) = 1.029 m
RMS(z) = 0.866 m
RMS(3D) = 1.537 m

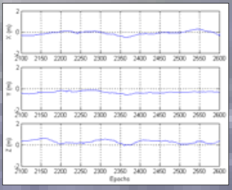


Figure 4. Difference between the estimated orbits and RSO after backward filtering

RMS of fit
RMS(x) = 0.173 m
RMS(y) = 0.098 m
RMS(z) = 0.154 m
RMS(3D) = 0.252 m

The orbit at the initial epoch should be provided to overcome the datum deficiency in the triple difference processing. If the fixed initial orbits are biased, it might take up to 120 seconds for the kinematic orbit to converge, as shown in Figure 3. Consequently, both forward and backward filtering should be applied in order to reduce the effect of the biased initial coordinates. The 3D RMS of fit to CHAMP RSO are 153 and 25 centimetre, respectively, after forward and backward filtering. The achievable accuracy can be even better than presented in Figure 4. If a strong geometry is available over a part of a pre-determined 500-epoch batch it can be processed separately, enabling a better final orbit quality as shown in Table 2.

RMS [m]	Batch length [epochs]	
	500	250
X	0.14	0.06
Y	0.18	0.09
Z	0.11	0.09
3D	0.25	0.14

Table 2. The RMS of fit to RSO as a function of batch length/geometry

Orbit Overlap Analysis

Another measure of the quality and consistency of the orbit estimation is the RMS of fit of the overlapping portions of the satellite trajectories. Three separate solutions were obtained using the forward and backward filtering: (1) where the initial coordinates were precisely known (forward solution only), (2) where only approximated initial coordinates were known (one full iteration), and (3) where only approximated initial coordinates were known (two full iterations). Two batches, overlapping by 300 epochs were processed, and the RMS of fit of these two consecutive batches is presented in Table 5 for all three solutions. Relatively small RMS of fit shown in table 2 indicates high internal accuracy of the kinematic solution.

Table 3. RMS of fit of the overlapping orbits

Solution	X [m]	Y [m]	Z [m]	3D [m]
1	0.02	0.06	0.09	0.11
2	0.05	0.08	0.14	0.17
3	0.07	0.03	0.10	0.13

Processing Time

		Number of epochs		
		300	400	500
Number of stations	40	10	11	14
	50	12	14	17
	60	15	16	20

Table 4. Processing time in minutes (cycle slips detected during the data reduction using the approximated dynamic orbit).

		Number of epochs		
		300	400	500
Number of stations	40	15 (1.57)	19 (1.82)	28 (2.13)
	50	18 (1.77)	25 (2.08)	33 (2.45)
	60	23 (2.02)	30 (2.38)	39 (2.80)

Table 5. Processing time in minutes (cycle slips detected during the pre-processing using SNR). The numbers in parenthesis represent the time used to clean the data.

Drawbacks

It should be emphasized again that a reliable cycle slip detection routine is necessary to support any near real-time application. The average percentage of cycle slip occurring in CHAMP data is ~5-6 percent, which is 10 times higher than for the ground receiver data. Therefore, a successful cycle slip detection and removal is crucial to the final orbit accuracy. As indicated earlier, depending on the level of SNR threshold selected, the number of detected CS will vary, affecting ultimately the quality of the final orbit. For example, using the combination of 123 and 22 for SA and S2, respectively, which seems the optimal combination in this test data (June 15, 2001), a data set was cleaned and used for orbit determination. This solution provided a less smooth orbit with a 3D-RMS of fit to RSO of 33 cm. It is about 32 percent decrease in accuracy as compared to the solution with cycle slips detected using a good approximated orbit.

Consequently, to clean the orbit from the remaining spikes due to undetected CS a smoother can be applied using either a 9-th degree polynomial or a sliding 20-epoch wide window. The sliding window seems to provide better results, while a polynomial might alter the shape of some portions of the trajectory. After the smoothing step, the 3D RMS of fit to the reference dynamic orbit was reduced to 28 cm, representing only about 12 percent worse accuracy as compared to the solution obtained from data cleaned using RSO.

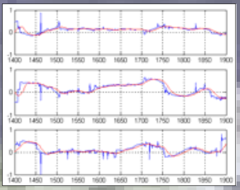


Figure 5. Orbit before and after smoothing

RMS of fit to RSO of the smoothed orbit
RMS(x) = 0.092 m
RMS(y) = 0.220 m
RMS(z) = 0.154 m
RMS(3D) = 0.283 m

Summary

Based on the study presented here, the following conclusions can be drawn:

(1) Kinematic triple difference POD works well for good geometry – better than 30 cm 3D RMS of fit is achievable.

(2) The method, based on a least squares filter/smoother is simple and efficient.

(3) Since there is no force model-dependence, the method can be applied to any platform, whose motion is controlled by GPS.

(4) The P-KOD processing time is short, as indicated in Tables 3-4, which indicate the method suitability for near real-time application.

(5) Weak geometry can pose significant problems; the solution might needs more iterations, while the accuracy can decrease significantly.

(6) Cycle slip cleaning is not an easy task – LEO operates under high dynamics in the middle of the ionospheric layer.

(7) SNR helps in the detection of cycle slips, however, more work needs to be done on the SNR threshold selection.

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