Data Screening and Quality Analysis for Kinematic Orbit Determination of CHAMP Satellite

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ABSTRACT

Kinematic orbit determination of the Low Earth Orbiters (LEO) based on GPS observable offers a viable alternative to the predominantly dynamic orbit determination approaches. Since kinematic orbit determination (OD) requires neither dynamic force models nor the physical properties of the LEO, the OD procedures are much simpler and computationally efficient than the dynamic OD approach. However, the quality of kinematic POD strongly depends on the quality and continuity of GPS data, and the geometry between the GPS satellites, LEO and the ground stations.

The main purpose of this paper is to present the analysis of the GPS data quality and the data prescreening procedures for the kinematic orbit determination of the CHAMP satellite (German **CHA**llenging **M**inisatellite **P**ayload, launched on July 15, 2000). Since, as mentioned above, the accuracy of the kinematic orbit determination highly depends on the configuration of GPS satellites as well as the ground stations, the discussion and the test results related to various configurations are presented.

Since kinematic method displays a strong dependence on the data quality and continuity, the data prescreening is of a major importance. The prescreening of the data is mainly composed of detection of cycle slips (CS) for CHAMP and the ground stations. Two test quantities, namely the one-way ion-residual of phase and phase/range linear combinations, as well as wide-lane combination are used for the CS detection. While the ground stations show less than 3 % of cycle slips, CHAMP shows much higher number (about 5.5%) of cycle slips for the period of 24 hours, based on the test data analyzed here. It should be mentioned however, that the classical methods of CS detection were found not fully reliable for a LEO moving very fast (CHAMP: ~7.6 km/sec) in the middle of the ionospheric layer. In order to analyze the reliability of the classical method of CS detection in that case, a dynamic solution was used as a true reference. The CS analysis, their effect on the continuity and the quality of the orbit, the effects of the geometry as well as the elevation cut off and processing batch length on the final kinematic orbit accuracy are presented in this paper.

1. INTRODUCTION

With the proliferation of GPS technology and the development of the GPS receivers suitable for space applications such as, for example, Motorola Demonstration Receiver (GPSDR) placed onboard the Topex/Poseidon mission (launched in 1992), Trimble TANS and TANS Vector, Ashtech SB24, and JPL TurboRogue and subsequently BlackJack, to name only a few, were placed onboard several space missions, including the space shuttle and minisatellite missions, with the primary objectives of the spacecraft precision orbit determination (POD), georeferencing remote sensing data, gravity field modeling or atmospheric sounding. The rationale behind using GPS in these applications is that GPS provides, at a relatively low cost, (1) an independent means of positioning data collected at high rates, and (2) complementary data to supplement other techniques (for example in gravity modeling, where augmenting GPS POD with satellite-to-satellite tracking, altimeter or a gradiometer data leads to the improvements in these estimates).

This paper addresses one of the space applications of GPS, namely the orbit determination in kinematic mode using GPS carrier phase observable in triple-differenced mode. The kinematic approach offers the simplicity, independence of the force models, low number of unknowns (especially in the triple-difference approach), and much lower computational load, as compared to the dynamic/reduced dynamic approaches. Decimeter to sub-decimeter accuracies (1D RMS) are feasible, as presented here, however the method displays a strong dependency on the geometry. Consequently any portions of the trajectory with weak geometry will result in low accuracy, and any gap in GPS data will introduce a discontinuity in the trajectory, as there is no force model to bridge the gap. Consequently, data screening and CS removal are crucial when using kinematic POD method.

The details of the method implemented in our software, P-KOD (**P**recision **K**inematic **O**rbit **D**etermination), derived as an extension of the OSU triple-difference approach to GPS orbit determination (Grejner-Brzezinska, 1995; Goad et al., 1996; Kwon, 1997), are presented in (Grejner-Brzezinska et al., 2001a and 2001b; Kwon et al., 2002, this volume). In this paper the primary focus is on the data quality analysis, data screening procedure and the final orbit accuracy depending on the geometry (PDOP, Position Dilution of Precision), elevation angle and the data processing batch, based on the example CHAMP data set. CHAMP carries onboard a codeless, dual frequency, 12-channel BlackJack receiver with multiple antennas supporting spacecraft navigation, radio occultation and specular reflections. Details on CHAMP mission can be found on: http://op.gfz-potsdam.de/champ/index_CHAMP.html. More information about the BlackJack receiver can be found in (Kuang et al., 2001 and http://www.jpl.nasa.gov/releases/2000/blackjackgps.html)

The rationale behind the triple difference (TD) method used in P-KOD is its simplicity, low number of unknowns (no integer ambiguity involved), and the accuracy that is comparable to the double difference approach with float ambiguities. Since the ambiguity fixing is rather challenging for LEOs, it seems to be the right choice to select a method that does not rely on the ambiguity resolution. Moreover, even if some percentage of the ambiguities can be resolved (about 40% success rate was reported at the CHAMP 1st Science Meeting, January 22-25, 2002), the resolution process is very time consuming, while our primary goal is to provide the orbit with the smallest possible delay and still sufficient accuracy.

2. CYCLE SLIP DETECTION PROCEDURES AND THE TEST RESULTS

We have currently implemented two independent data screening routines, (1) based on testing the time differences of ionosphere-only linear phase combination (also called geometry free or ionospheric residual), and phase/code combination, (2) testing the ambiguity of undifferenced widelane combination and the ionospheric residual (Blewitt, 1990). Since TD technique does not resolve the ambiguities, it is crucial that the data editing is performed properly before the final positioning filter run is completed.

The testing quantities in the first method are 1st through 4th order differences of one-way ionospheric residual phase and phase/range combinations (equations 1 and 2), since the higher order differences can amplify the jump due to the cycle slip, acting as the high-pass filter. The testing quantity representing the variation of the ionospheric residual normally changes rather slowly with time, assuming relatively calm ionosphere. Thus, under normal ionospheric conditions, this testing quantity should be sensitive to cycle slips. Another testing quantity is the phase/range (R) combination (equation 2), where the ionospheric term is again assumed to display slow temporal variations, thus any significant jump in the tested quantity would indicate a cycle slip. Since this combination, including pseudorange measurement, has relatively higher noise as compared to (1), it is useful to detect larger cycle slips.

$$\Phi_1(t) - \frac{f_1}{f_2}\Phi_2(t) =$$

$$N_1 - \frac{f_1}{f_2}N_L - \frac{I}{\lambda_1 f_1^2}\left(1 - \frac{f_1^2}{f_2^2}\right) \qquad (1)$$

In equation (1), the variables on the right hand side are the linear combination of ambiguities N on L_1 and L_2, and the ionospheric term I; λ denotes a wavelength of L_1 (L_2), and f is the frequency of L_1 (L_2) signal.

$$\lambda\Phi(t) - R(t) = \lambda N - 2\Delta^{Iono}(t) \qquad (2)$$

The second cycle slip detection method that we have currently implemented in P-KOD, is based on the testing of the ambiguity of undifferenced widelane linear combination and the ionospheric residual, so it is an extension of method one. This method requires a quality pseudorange and assumes a smooth variability of the ionospheric residual. The testing quantities are the ionospheric residual defined in equation (1) and the widelane ambiguity $N_{1,-1}=N_1-N_2$, as defined in equations (3-4). Since the widelane has a longer wavelength, it is easier to identify possible CS, if the pseudorange is of good quality (except for ill-posed case when CS on L_1 and L_2 occur in such a combination that the change in $N_{1,-1}$ is equal to zero). Thus, the widelane ambiguity is tested first, and if the CS is indicated, the hypothesis is carried to the next step, which is the testing of the ionospheric residual.

$$\Phi_{1,-1} = \rho - \frac{I}{f_1^2}\frac{f_1}{f_2} + \lambda_{1,-1}(N_1 - N_2) \quad (3)$$

$$N_{1,-1} = \frac{\Phi_{1,-1} - R_{1,1}}{\lambda_{1,-1}} + m + \varepsilon \quad (4)$$

More details on CS detection methods implemented in P-KOD can be found in (Grejner-Brzezinska et al., 2001a and 2001b).

Our analysis of CS detection in 24 hours of CHAMP data (with a 30 second data sampling rate) collected on June 15, 2001 indicate that the two methods presented above provide rather low (below 50%) success ratio. The reference CS detection procedure was performed using the GFZ (GeoForschungsZentrum Potsdam) rapid science orbit (RSO; good to ~10 cm 1D RMS). Epoch-by-epoch triple difference residuals were formed and screened with a tolerance of 20 cm. This data screening procedure was considered correct, and the results from the above two data screening approaches were compared to the reference results (at the common epochs, defined by TD approach). In addition, we also used the UNAVCO software TEQC to detect the cycle slips, with a success rate of about 43%, as compared to the detected reference set of cycle slips (http://www.unavco.ucar.edu/data_support/software/teqc/teqc.html).

The total number of TD observations for the 500-epoch period, for which the CS detection results were compared among the methods listed above, was 34374 (that includes 65 ground tracking stations and the CHAMP satellite), with a total of 1657 CS detected. The analyzed CS detection approaches reported much higher number of CS, with only a certain percentage (below 50%) coinciding with the "true" CS events. Table 2 presents the summary characteristics for CS events for the entire 24-hour data span of June 15, 2001.

The results of our analysis clearly indicate that the classical methods of CS detection do not work very reliably at the CHAMP altitude. The satellite is moving very fast (~7.9 km/s) in the middle of the ionospheric layer; also, the rapid motion of the satellite causes rapid changes in the tracking geometry, providing relatively short passes on the continuous phase observations. Moreover, the classical methods of ambiguity resolution, working in general very well, also for long-range cases, rely on smoothly and slowly changing ionosphere, while the current state of ionosphere still shows a significant activity. All these components together cause the lower than expected success rate for the ambiguity resolution by the classical methods.

# of Epochs with no C/S	2007
# of Epochs with C/S	873
Total # of Epochs	2880

Total No. of Observations	166495	
Number of C/S	Total = 9495 (5.7%)	
	CHAMP	Stations (65)
	9226 (5.5%)	269 (0.2%)
	97% of all CS	3% of all CS

Table 1. Cycle slip detection summary statistics.

Based on the results displayed in Table 1 it can be concluded that the majority of cycle slips happen at the CHAMP altitude, while the ground tracking stations exhibit rather low rate of cycle slips (about 3% of all CS that represents about 0.2% of ground station data).

The CSs, the weak geometry due to insufficient number of available observations, as well as the data gaps that the BlackJack receiver experiences occasionally, cause the singularities (discontinuities) in the kinematic solution. These discontinuities cannot be bridged, since no force models are involved in the OD process. The only solution is to interpolate between the neighboring continuous sections of the trajectory, but this method will give an acceptable solution only for very short gaps. Table 2 presents the discontinuity summary characteristics for a 24-hour data set of June 15, 2001.

Singularity	Duration	# of epochs
1	0253 ~ 0255	3
2	0678 ~ 0682	5
3	0752 ~ 0753	2
4	1080 ~ 1080	1
5	1314 ~ 1314	1
6	1392 ~ 1392	1
7	1904 ~ 1904	1
8	2394 ~ 2395	2
9	2792 ~ 2792	1
SUM		17

Table 2. Orbit singularity (discontinuity) summary statistics for June 15, 2001.

3. EFFECTS OF GEOMETRY AND THE ELEVATION ANGLE ON THE FINAL CHAMP ORBIT

As already explained, the kinematic OD approach strongly depends on the strength of the geometry (PDOP). Thus, the total number of ground stations and their distribution, as well as the number of GPS observations practically control the quality of the final solution. In our standard approach, we implement the data from about 65 globally distributed ground stations, however, their distribution is not uniform, as can be observed in Figure 1. Europe and North America are very well covered in terms of the tracking stations; however, Asia, Africa and naturally the oceans have much worse coverage, which results in a weaker configuration when the LEO flies over those regions. The examples of the weak geometry are illustrated in Figures 2a and 2b, while Figures 3 and 4 display the geometry change over the course of 24 hours for June 15, 2001 (that corresponds to ~15.3 orbital revolutions).

Since the solution quality in the kinematic OD approach depends strongly on the data quality and geometry, as already explained, naturally the number of observations available per epoch is of a major importance. The number of observations can be increased by lowering the elevation angle cut off, and for CHAMP it can be lowered to 0º. However, one has to examine the signal to noise ratio (SNR), especially for the lower satellites, to ensure that only quality data enter the solution. Examination of SNR also supports the CS detection, by eliminating the data with low SNR. Table 3 presents the summary statistics of the RMS of fit of the final kinematic orbit to RSO obtained from the two different data sets, (1) with elevation cut off for CHAMP at 5º and the ground stations at 10º, and (2) with elevation cut off for CHAMP at 0º and the ground stations at 10º. Clearly, some quality data can be obtained for cut off angle of 0º, which improves the 3D RMS of fit to RSO by about 1.5 cm.

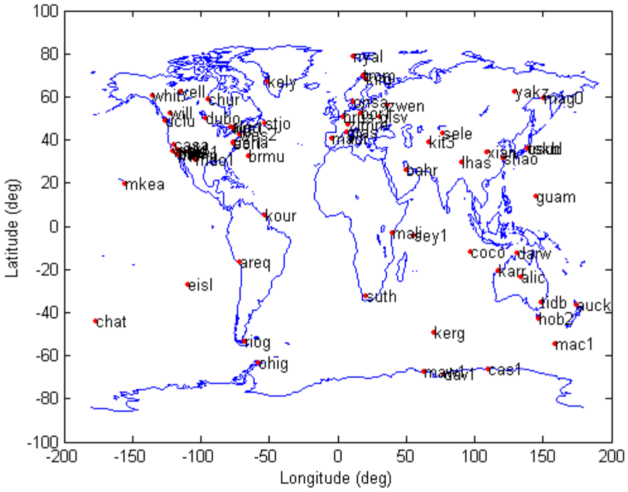

Figure 1. Distribution of selected ground stations for kinematic LEO POD.

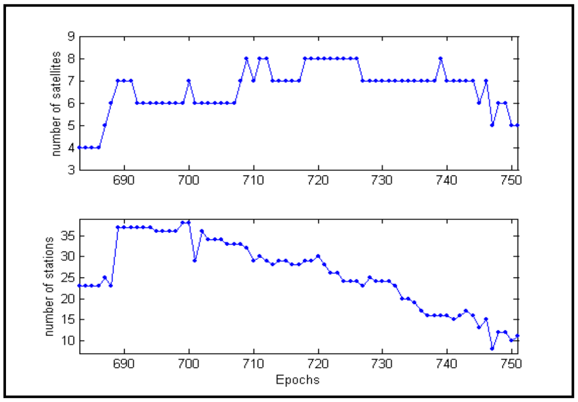

Figure 2a. Example of a weak geometry.

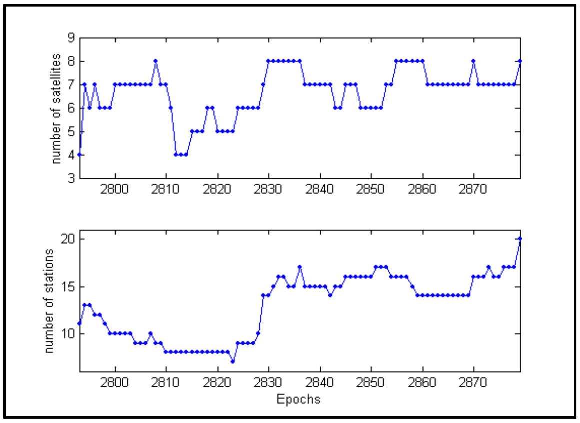

Figure 2b. Example of a weak geometry.

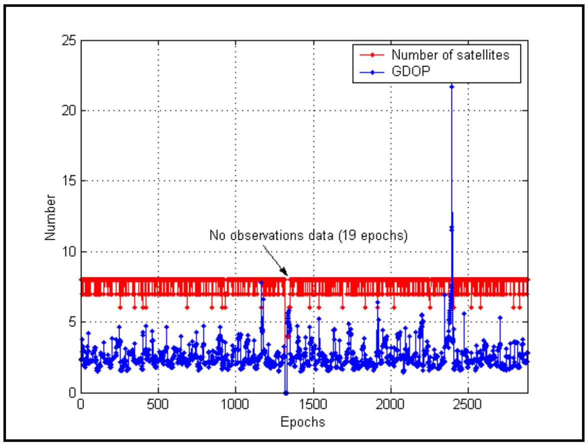

Figure 3. Epoch-by-epoch GDOP and the number of GPS satellites for CHAMP 24-hour data set, June 15, 2001.

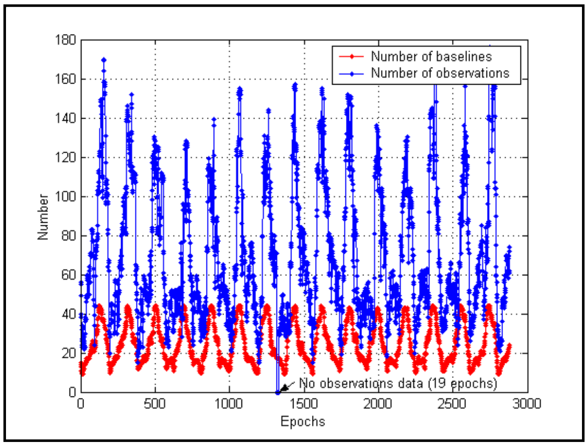

Figure 4. Total number of TD observable and number of baselines per epoch for CHAMP 24-hour data set, June 15, 2001.

RMS$_x$ [m]	RMS$_y$ [m]	RMS$_z$ [m]	RMS$_{3D}$ [m]
0.137	0.205	0.103	0.267
Cutoff angle 5° (LEO), 10° (Stations)			

RMS$_x$ [m]	RMS$_y$ [m]	RMS$_z$ [m]	RMS$_{3D}$ [m]
0.141	0.179	0.109	0.253
Cutoff angle 0°(LEO), 10° (Stations)			

Table 3. Effects of the elevation angle cut off on the final orbit quality.

4. EFFECTS OF THE PROCESSING BATCH SIZE ON THE FINAL CHAMP ORBIT

In P-KOD, the GPS data processing is initiated at the selected starting epoch, and the normal equations can be accumulated until the discontinuity is encountered in the data. Thus, the length of the processing batch can vary, and theoretically, if there are no discontinuities, the OD process can be performed in one step for the entire 24-hour span. However, the longer the batch size, the more unknowns are accumulated (X, Y, Z changes in CHAMP coordinates per epoch) and the larger the normal matrix to deal with. Thus, to increase the numerical efficiency and the processing speed, we separate the 24-hour orbit into several batches, usually of 500 epochs (separated by 30 s) in duration. Naturally, if the singularity happens during the batch, the two separate batches are processed. Using a 500-epoch batches to process the data from CHAMP and 65 ground stations, the total processing time on a 1.8 GHz processor amounts to about 2 hours. Using a 250-epoch batches allows for the reduction of the processing time by the factor of four.

The processing time reduction is not the only benefit of the shorter batch size. If the PDOP is very strong for some portions of the pre-selected 500-epoch batch, it may be beneficial from the accuracy stand point to process that portion separately, to take a full advantage of the low PDOP and high number of observables. Table 4 and Figure 5 both illustrate an example of the benefits of using shorter batch size. The comparison of two solutions based on 500-epoch and 250-epoch batch length indicate that the first 250 epochs obtained from a 250-epoch solution fit much better to the reference solution, as opposed to the same 250 epochs obtained from the combined 500-epoch solution. Figures 6 and 7 illustrate the number of TD observations and the baseline number, as well as the number of GPS satellites for the portion of the trajectory analyzed in Table 4 and Figure 5. It can be observed that the number of satellites/baselines and thus TD becomes somewhat lower in the second part of the 500-epoch period presented (especially the last 150 epochs, i.e., the last orbital revolution shown here), which results in worse fit to RSO by the end of the longer batch, as compared to the first 250 epochs.

Batch length	500 [epochs]	250 [epochs]
RMS$_x$ [m]	0.1415	0.0618
RMS$_y$ [m]	0.1788	0.0921
RMS$_z$ [m]	0.1091	0.0894
RMS$_{3D}$ [m]	0.2528	0.1425

Table 4. Effects of the size of the processing batch on the final orbit quality.

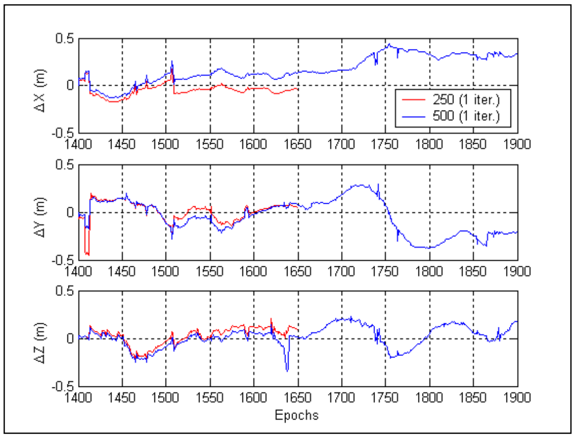

Figure 5. Effects of the size of the processing batch on the final orbit quality.

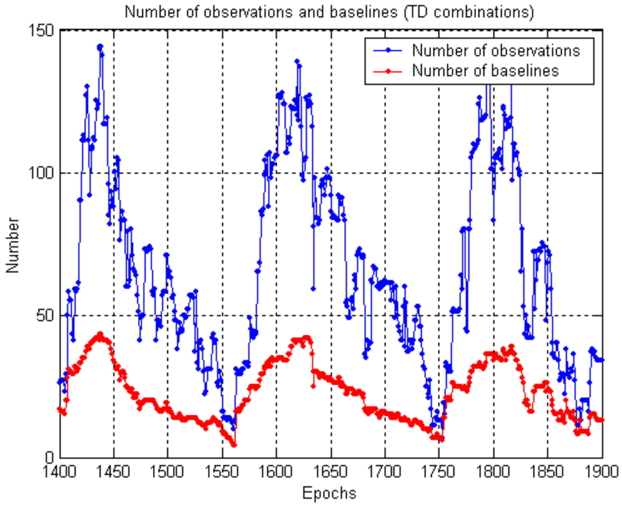

Figure 6. Total number of TD observations and baselines per epoch for CHAMP 500-epoch data set corresponding to Table 4.

5. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

P-KOD processing algorithms are very fast and the software package offers the flexibility and portability, as our operational platform is a standard PC. For example, if we select a 500-epoch batch length for the processing, the total processing time for a 24-hour CHAMP orbit using 65 ground stations, is about 2 hours (forward and backward) on a 1.8 GHz Pentium processor. If there are no singularities and the processing at every batch starts with the known position from the previous batch, the processing time is reduced to about 1 hour, as only forward processing is needed. For shorter batches, the processing time is even shorter (for example, 250 epoch batch selection results in four times faster processing time). Thus, even without the final tuning and still possible algorithmic optimization, we believe that we have reached the point where we can provide near-real-time kinematic LEO orbits. However, an improvement in CS detection is needed, to make the solution independent from the approximated dynamic orbit.

The currently demonstrated 3D RMS of fit to the dynamic GFZ orbit can reach 15-25 cm for a good PDOP, but it is very sensitive to the strengths of the geometry. It was also demonstrated that the currently achievable accuracy of kinematic orbits is sufficiently good to support atmospheric sounding however, the still existing discontinuities due to weak geometry need to be overcome. The most logical solution is the implementation of the reduced dynamics. The processing time, however, is expected to be longer than for the kinematic approach. Thus, the algorithmic optimization will be of major interest.

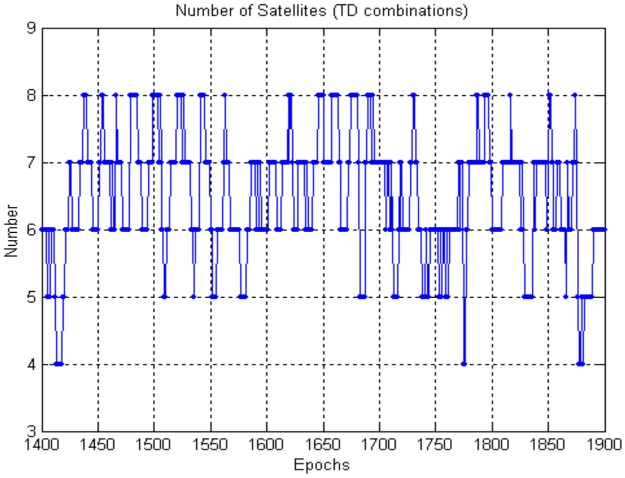

Figure 7. Total number of satellites per epoch for CHAMP 500-epoch data set corresponding to Table 4.

ACKNOWLEDGEMENTS

This project is supported by the NASA Goddard Space Flight Center NIP Award; OSU project number 740809.

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