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Key Points:

- The enhanced thermospheric density during the storm makes main contribution to the storm time degradation of Swarm orbit
- Estimating drag parameter with shorter interval largely suppress the negative effect of enhanced atmospheric drag on the orbit estimation
- Less improvement is observed after correcting the high-order ionospheric effects during the storm

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The Influence of Geomagnetic Storm of 7-8 September 2017 on the Swarm Precise Orbit Determination

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Abstract We analyze a recent geomagnetic storm event on 7-8 September 2017 to investigate the impact of geomagnetic storm on the precise orbit determination (POD) of Swarm constellation. The storm time performance of POD is analyzed. The quality of Swarm orbits are severely degraded during the storm main phase on 8 September and the maximum precision degradation reached over 10 cm. The enhanced thermospheric mass density at Swarm altitude during the storm enlarges the atmosphere drag for low Earth orbit satellites, which makes main contributions to the storm time degradation of Swarm orbit. This negative effect of enhanced atmosphere drag on the orbit estimation is mostly suppressed by estimating a more frequent atmosphere drag parameter. The higher-order ionospheric effects on the POD of Swarm are also analyzed. The vertical total electron content derived from the Swarm onboard Global Positioning System receiver presents a larger enhancement on the dayside at low latitude and midlatitude during the storm main phase. This leads to an increase in the high-order ionospheric effects, especially in the second-order terms. No evident precision improvement is observed after correcting the high-order ionospheric effects. The results demonstrate that during this geomagnetic storm, the enhanced thermospheric neutral density serves as a stronger error source than the enhanced ionospheric plasma density for the low Earth orbit satellite orbit determination processing.

1. Introduction

The fluctuation of the solar wind and interplanetary magnetic field (IMF) can trigger strong disturbances in the Earth's magnetosphere via the ejection of high-energy charged particles and electromagnetic radiation, which is usually called geomagnetic storm. The input of enhanced solar wind and magnetospheric energy can alter physical and chemical characters of the ionosphere-thermosphere system due to their dynamical coupling, further leads to an ionosphere and thermosphere storm (Buonsanto, 1999). During the storm, the high-latitude electric fields originated from magnetosphere can rapidly penetrate into lower latitudes (e.g., Astafyeva et al., 2015; Huang et al., 2007; Lei et al., 2014; Zhong et al., 2016). Meanwhile, the energy input at the auroral or subauroral regions heats the thermosphere and drives equatorward neutral winds and traveling atmospheric/ionospheric disturbances (e.g., Huang et al., 2012; Ritter et al., 2010; Xiong et al., 2015). The disturbance wind circulation further sets up disturbance dynamo electric field at middle and low latitudes (Scherliess & Fejer, 1997).

Low earth orbit (LEO) satellite refers to the satellites distributed in the orbit with an altitude of 300–1,500 km (Montenbruck & Gill, 2000), which have been widely used for many earth observational missions. These Earth observing LEO missions are usually equipped with space-borne Global Navigation Satellite Systems (GNSS) receivers to achieve a high-accuracy orbit (e.g., Bock et al., 2011; Kang et al., 2006; van den IJssel et al., 2015; Yoon et al., 2009). At altitudes of LEO satellites, the operation of onboard GNSS receiver can be easily degraded or interrupted by ionospheric scintillations, particularly during the extreme space weather events, such as solar flare or geomagnetic storm. During storm period, the ionosphere alters significantly from its quiet-time behavior and raises the risk of the degradation of GNSS signal amplitude or failure to acquire signals in severe cases, which has been reported by many studies (e.g., Cerruti et al., 2006; Chen et al., 2005; Kintner et al., 2007). The degraded GNSS signals can reduce the availability and reliability of GNSS-based precise orbit determination (POD) technique and increase the dilution of precision.

Another consequence of geomagnetic storm is the increase of higher-order ionosphere effect, due to enhanced perturbations of plasma density at storm period. The ionosphere delay is one of the primary error sources for GNSS signals. Due to the dispersive characters of ionosphere, most part of ionosphere delay can be eliminated using a linear ionosphere-free (IF) combination of dual-frequency GNSS observations. The residual errors are the higher-order terms of ionosphere delay. The high-order ionospheric effects usually refer to the second-order (I_2) and third-order (I_3) ionospheric terms, which can be expressed as follows (Hernández-Pajares et al., 2007; Petrie et al., 2011):

$$\begin{cases} I_2 = \frac{7527.87c}{f_i^3} \int_{\text{rec}}^{\text{sat}} B \cdot \cos\theta N_e dl \\ I_3 = \frac{2437}{f_i^4} \int_{\text{rec}}^{\text{sat}} N_e^2 dl \end{cases}$$

where c is the speed of light in vacuum. f_i denotes the GNSS signal frequency. B is the module of the Earth's magnetic field. θ is the angle between the geomagnetic field vector and the propagation direction of GNSS signals. N_e represents the electron density. It can be seen that both second- and third-order terms are associated with the electron quantity along the signal path, which can be easily disturbed during the geomagnetic storm. Though the higher-order ionospheric terms contribute less than 0.1% to the ionosphere-induced error at quiet time, they can lead to range errors of a few centimeters during the extreme space weather event, like geomagnetic storm (Klobuchar, 1996). Hence, if the errors deriving from higher-order ionospheric effects have not been properly treated, they can affect significantly the performance of LEO POD estimates at storm periods.

For LEO satellite, atmosphere drag is one of the important nonconservative driving forces. The atmospheric density is highly correlated with the solar extreme ultraviolet (EUV) fluxes. During the geomagnetic storm, the Joule heating at auroral and subauroral regions makes more contributions to the increase of atmospheric density (Knipp et al., 2004). Therefore, the increased atmosphere density at storm periods can largely enhance the atmosphere drag force and perturb the trajectories of LEO satellites, leading to accelerated orbital decay for LEO (Lei et al., 2013; Nwankwo et al., 2015; Walterscheid, 1989). The drastic fluctuation of the atmosphere density will increase the difficulty of drag force modeling for LEO POD during geomagnetic storms.

In this paper, we focus on the performance of POD of Swarm constellation during the geomagnetic storm event on 7-8 September 2017. Several influence factors of LEO POD are analyzed and discussed in details. Section 2 describes the dataset and POD scheme. Then the geophysical conditions of the 7-8 September 2017 storm are provided in section 3. The storm time performance of Swarm POD is evaluated, and the impact of atmosphere drag and higher ionosphere effects is analyzed and discussed in section 4. The summary is given in section 5.

2. Dataset and POD Scheme

2.1. Data Set

Aiming at studying the geomagnetic field and its temporal evolution, Swarm mission was successfully launched by European Space Agency on 22 November 2013. The Swarm constellation consists of three identical satellites, namely, Swarm-A, Swarm-B, and Swarm-C. Swarm-A and Swarm-C are flying side by side with longitudinal separation of 1.4° at the altitude of about 460 km, while the Swarm B is cruising at higher nearly polar orbit of about 510 km. The orbit inclination is 87.35° for Swarm-A/C and 87.75° for Swarm-B. Their initial mass is 472 kg (e.g., van den IJssel et al., 2015). To achieve its designed aim, the Swarm spacecraft is equipped with seven different payloads, including Absolute Scalar Magnetometer (ASM), Electric Field Instrument (EFI), Global Positioning System (GPS) Receiver (GPSR), Vector Field Magnetometer (VFM), Star Tracker (STR), Laser Retro-Reflector (LRR), and Accelerometer (ACC).

The onboard dual-frequency GPS observations from Swarm satellite with a time interval of 1 s are used in this study, which can be freely downloaded via an ftp client at <ftp://swarm-diss.esa.int>. We perform the POD for all Swarm satellites based on the onboard GPS measurements to investigate the performance of LEO POD during the geomagnetic storm on 7-8 September 2017. These onboard GPS observations are

Table 1
Dynamics Model and Estimated Parameters for Swarm POD

Dynamics model	
Earth gravity	EIGEN6C (120×120)
N-body	JPL DE405
Ocean tide	FES 2004
Relativity	IERS 2010
Solid tide and pole tide	IERS 2010
Solar radiation pressure	Macro-model
Atmospheric density	DTM94 and estimating one drag parameter per 6 h
Estimated parameters	
Initial state	Position and velocity at initial epoch
Atmospheric drag	One constant parameter per 6 hr
Empirical accelerations	Piecewise periodical terms in the along-track, cross-track and radial components
Receiver clock error	Each epoch as white noise
Ambiguities	Each continuous arc

Abbreviation: POD, precise orbit determination.

also processed to extract the vertical total electron content (VTEC) by using the method described in Wautelet et al. (2017). The VTEC values are estimated together with differential code biases for satellites and receivers using the geometry-free combination of dual frequency pseudorange observations. Besides, the satellite laser ranging (SLR) data collected from the International Laser Ranging Service network (Pearlman et al., 2002) are also used to validate our orbit results.

2.2. POD Scheme

To obtain a high-accuracy orbit for LEO satellites, it is very important to describe perturbative forces with the proper models. Table 1 lists the details of dynamics model and estimated parameters for the Swarm POD. The dynamics model for LEO refers to conservative forces and nonconservation forces. In terms of the conservative forces, the gravity field is modeled by EIGEN6C (Förste et al., 2011) up to degree and order 120. We use IERS 2003 (McCarthy & Petit, 2003) to describe solid tide and pole tide, which is also used for computing relativity effects. FES 2004 (Lyard et al., 2006) serves as ocean tide model. Different from conservative forces, it is very difficult to accurately model the nonconservation forces (such as atmospheric drag and solar radiation pressure) due to its close connection with the geometric and physical information of LEO satellites as well as the space environment. Hence, additional force model parameters are usually estimated to compensate the model errors of nonconservation force. We used the macromodel described by Montenbruck et al. (2018) to compute the solar radiation pressure for Swarm satellites. Atmosphere drag is modeled using the same macromodel and the atmosphere density computed by DTM94 (Berger et al., 1998). In addition, a drag scale coefficient is estimated every 6 hr in order to describe the atmosphere drag more elaborately.

3. The geomagnetic storm of 7-8 September 2017

The intense geomagnetic storm, which consisted of two storms on 8 September 2017, is triggered by coronal mass ejection, which is the second strongest geomagnetic storm in the solar cycle 24 (Tassev et al., 2017). There was a series of M-class and X-class flares. In particular, the solar X1.3 flare occurred at 14:36 on 7 September 2017. Fig.1 shows the variation of geophysical and interplanetary parameters during the storm of 7–8 September 2017. The B_z component of IMF begins to turn northward at ~00:25 UT on 7 September. After a strong fluctuation for a long time, IMF B_z drops negative and reaches the minimum value of -31.09 nT at ~23:35 UT on 7 September. The velocity of solar wind suddenly increases from ~400 to ~600 km/s at midnight of 7 September and encounters the second increase from ~600 to ~800 km/s on 8 September. Affected by the intense variation of IMF and solar wind, the $SYM-H$ index reaches its first minimum excursion of -144 nT at ~01:05 UT on 8 September along with Kp index value of over 8. During the second decrease, $SYM-H$ values experiences second minimum values of -111 at ~17:05 UT on 8 September, while the Kp index exceeds 7. As shown in Fig.1d, the E_y components of the interplanetary electric field varies from -13 to 22 mV/m during the storm. The storm also generates disturbances to the

Figure 1. Variations of the geophysical and interplanetary parameters during the storm of 7–8 September 2017. (a) The B_z component of the interplanetary magnetic field; (b) SYM-H index; (c) the velocity of solar wind; (d) interplanetary electric field E_y ; (e) AE index, and (f) 3-hour Kp index. The X1.3 solar flare occurrence time of 14:36 UT is indicated by black arrow, while the coronal mass ejection arrival time of 23:04 UT is indicated by the red arrow. The gray vertical dashed line represents the sudden storm commencement time. Main phase is marked with the blue vertical solid lines.

auroral region and pronounced increase of AE index can be recognized in the two main phases. During the storm of 7–8 September, the solar EUV flux proxy $F_{10.7}$ also presents a significant increase, which is not presented in Figure 1.

4. Results

4.1. The Impact of Thermosphere Total Density Perturbations on Swarm POD

First, the POD results are evaluated by overlap comparison. With the 30-hr orbit arc length, every two adjacent consecutive orbit arcs have a common 6-hr part, and the 6-hr overlapping orbit differences can be an indicator to evaluate the internal orbit consistency. In order to avoid the boundary effects on the overlap statistics, only 5-hr (from 21:30 of the first day to 2:30 of the next day) overlap differences are used in our study.

Figure 2a presents the root-mean-square (RMS) of 5-hr overlap differences for Swarm satellites during 5–12 September 2017. It can be seen that the orbit overlaps of all three Swarm satellites present good consistency except on 7–8 September, showing a total RMS value of better than 4 cm for Swarm-A/C and better than 2 cm for Swarm-B. It indicates that the observation model and force model we adopted are very suitable for Swarm POD during the magnetic quiet time. However, there is an evidenced orbit precision degradation during the geomagnetic storm. The 3-D RMS value of orbit overlap differences for Swarm-B can reach over 8 cm, while the orbit of Swarm-A and Swarm-C have a larger precision degradation and the 3-D RMS value

Figure 2. (a) The root-mean-square (RMS) of Swarm orbit overlap differences in the along-track, cross-track, and radial components. (b) The satellite laser ranging (SLR) residuals for Swarm precise orbit determination.

even exceeds 10 cm. The different levels of orbit degradation may be associated with the orbit altitude of Swarm satellites. However, it is worth to note that orbit overlaps indicate only the internal consistency or precision of orbit. Therefore, the SLR measurements from the International Laser Ranging Service are also employed to validate the accuracy of the Swarm orbit. Figure 2b shows the SLR residuals for all three Swarm satellites. The orbit of both Swarm-A and Swarm-C on 8 September have higher SLR residuals than those of the quiet days, and we found almost no evidenced degraded residuals for Swarm-B during the storm. This is consistent with the aforementioned result of overlap comparison. We found that all of these outliers are mainly observed on 8 September, which indicates that the degradation of orbit only occurs on the 8 September.

In the POD processing, most observation errors have been eliminated or weakened by the correction models or observation combinations, but there are still some residuals left. In general, with the high quality GNSS observations and the precise dynamic model adopted, the POD for LEO can usually show a good precision, which means that the residuals should be close to the noise level of observations after adjustment process. Though the observation residuals are not an absolute indicator to assess the orbit precision, it can still reflect the quality of orbit result to some degree. Figure 3 shows the residuals of IF carrier phase observations for Swarm-A (left panel) and Swarm-B (right panel). It should be noted that since there are two X-class solar flares (X2.2 at 9:10 UT and X9.3 at 12:02 UT) on 6 September, we take the residuals on 5 September as the quiet time level for comparison. We find that the residuals for 5 and 7 September are of comparable magnitude. However, a large increase in carrier phase residuals is visible from the end of 7th persisting to the whole 8 September, for both Swarm-A and Swarm-B. These increased residuals mainly appeared from 00:00 UT to 06:00 UT and from 12:00 UT to 15:00 UT, which covers the main phase of the two storms. It further demonstrates that the negative influence of geomagnetic storm on POD mainly occurs on 8 September.

The above results suggest that the precision of Swarm orbits can indeed be degraded during the geomagnetic storm and the level of orbit degradation is related to the orbit altitude. The orbit of the lower flying pair (Swarm-A and Swarm-C) is severely perturbed, while the higher flying Swarm-B satellite has a relatively smaller orbit degradation. During the geomagnetic storm, the thermospheric mass density at Swarm altitudes can perform a noticeable increase, which varies with latitude, altitude, and local time. This denser thermosphere results in a stronger drag force, especially for the lower pair Swarm satellites, and the variation of total density will increase the difficulty of drag force modeling (Montenbruck & Gill, 2000). This might explain the orbit degradation of centimeter level or even decimeter level during the geomagnetic storm on 7-8 September 2017. Another possible explanation is that the higher-order ionospheric terms have not been taken into consideration during the POD process. Its impact on Swarm POD will be discussed in section 4.2 subsequently.

Figure 3. The time series of residuals of ionosphere-free (IF) carrier phase for Swarm-A and Swarm-B on 5, 7, and 8 September 2017.

The in situ thermospheric mass density product is provided as Level-2 products for the Swarm mission. The thermospheric density is computed from nongravitational accelerations based on POD data only. Figure 4 shows the variation of thermospheric density at the orbit altitude of Swarm-A and Swarm-B deriving from Swarm level-2 product from 5 to 12 September, 2017. As shown in Figure 4a, an evidenced density increase can be found at different orbit altitude on 8 September during the storm and the increase of density at the Swarm-B location is much smaller than that of Swarm-A due to the lower density at the higher altitude.

Figure 4. (a) The thermospheric density from Swarm level-2 DNSxPOD_2_ product during 5-12 September 2018. (b) The thermospheric density and SYM-H index in 7-9 September 2017.

Figure 5. The result of precise orbit determination with the modified scheme. (a) The root-mean-square (RMS) of Swarm orbit overlap differences in the three components. (b) The time series of overlap differences for (top) Swarm-A, (middle) Swarm-B, and (bottom) Swarm-C for 8 September 2017.

Figure 4b displays the variation of total density and *SYM-H* index during the 7–9 September. The total density of thermosphere fluctuates more tremendously during the storm compared with the quiet time. There are two noticeable peaks in the thermospheric density at ~03:00 UT and ~15:00 UT on 8 September. The peaks present a strong correlation with the decrease in the *SYM-H* during the two storm main phases. This explains why the carrier phase residuals increase in this period of time.

As described above, the estimated drag scale parameter with 6-hr interval in the previous scheme cannot describe the drastic fluctuation of total density properly. Hence, we modified the scheme of POD for Swarm and the drag scale parameter are estimated more frequently with the interval of 30 min. Figure 5 shows the reprocessed POD result. It can be seen that the Swarm orbits achieve a similar precision as the orbit result with the 6-hr drag parameter. It indicates that the 6-hr drag scale parameter can already model the atmosphere drag force effectively in the quiet time. After refining the POD scheme, the orbit precision of Swarm satellite get a remarkable improvement during the storm, which is comparable to that of the quiet time (see Figure 5a). From Figure 5b, there are no evidenced biases between the consecutive orbit arcs. The improvement in the orbit overlap differences is due to the reduction of the amplitudes, and the precision improvement in the along-track and radial components play a dominate role. The residuals of carrier phase are also reduced to the level of quiet time (see Figure 6).

As shown in Figure 7, the outliers in the SLR residuals on 8 September have disappeared when estimating the drag parameter with higher time resolution. The result demonstrates that the increased thermospheric density will negatively influence the quality of LEO orbit if it is modeled improperly during the geomagnetic storm and suggests that the drag parameter estimation with shorter interval should be employed during the storm.

4.2. The Impact of Higher-Order Ionospheric Effects on Swarm POD

In the POD processing, the carrier phase and code observations are usually combined to the IF linear combination to eliminate the first term of the ionospheric delay, while the higher-order effects (second- and third-order ionospheric terms) are neglected. This is mainly based on the fact that the first ionospheric effects play a dominating role in the ionospheric delay on the GNSS signals. However, the remaining second- and third-order ionospheric effects can contribute to GNSS observational errors on an order of centimeters (Wang et al., 2005). In this section, we mainly focus on the variation of higher-order ionospheric effects during the geomagnetic storm of 7–8 September 2017 and its influence on the Swarm POD. As Swarm-A and Swarm-C fly side by side at the same altitude, they are in a similar condition of space environment. So here we discuss only the GNSS measurements from Swarm-A and Swarm-B.

Figure 6. The time series of residuals of ionosphere-free (IF) carrier phase for (left) Swarm-A and (right) Swarm-B with the modified precise orbit determination scheme.

The second-order ionospheric term is a function of the Earth's magnetic field at the intersection of the ionospheric pierce point and total electron content (TEC; Bassiri & Hajj, 1993). We compute the second-order effects (I_2) on the range for the L1, L2 frequency and IF combination, respectively, using IGRF12 model (Thébault et al., 2015) and the VTEC deriving from onboard observations. The results are shown in Figure 8. Because of fast motion of LEO, the arc length for every GPS satellite is shorter than that of ground stations. Compared with second-order effects in the L1 frequency, the second-order effect in the L2 frequency presents a larger value due to the lower frequency of L2. Similar to the thermospheric density, there is a strong correlation between the increase of second-order effect and the decrease of $SYM-H$ index. The largest increase in the second-order effect can be found in the period of 21:00 UT on 7 September to 03:00 UT on 8 September, especially in the L2 frequency. Compared with Swarm-A, the second-order term of Swarm-B shows a slight increase in the L2 frequency during the storm, which may indicate a smaller ionospheric response to the storm at the orbit altitude of Swarm-B. Although the effect of second-order ionospheric term on the IF combination is reduced after combination, the increase of second-order effect on the IF combination is still visible for Swarm-A during the storm and the maximum value can reach over 1 cm. However, different from Swarm-A, almost no evident increase of second-order effect can be observed in the IF combination for Swarm-B during the storm.

Figure 7. The SLR residuals for the modified Swarm precise orbit determination.

The third-order ionospheric term can be expressed as a function of the maximum electron density and TEC (Bassiri & Hajj, 1993). The third-order ionospheric effects (I_3) during the storm are also computed, and the results are shown in Figure 9. For most part of the storm period, the third effect on the IF combination is less than 1mm. However, the values of the third-order ionospheric effect on the IF combination exceed 4 mm during the first storm main phase.

The result above indicates that the GPS observations errors of higher-order ionospheric effects indeed get an increase during the geomagnetic storm and the second-order effect is the main contributor. The increase of second-order ionospheric effect mainly occurs in the period of from 21:00 UT of 7 September to 03:00 UT 8 September, which covers the main phase of the storm. Hence, we will only focus on the ionospheric response to the geomagnetic storm during this period in the study. In the 7–8 September storm, the Swarm-A satellites crossed the equator at ~10:16 LT (ascending) and ~22:16 LT (descending) and Swarm-B satellite at ~15:47 LT (ascending) and 03:47 LT (descending). Figure 10 shows the variations of VTEC computed from the onboard GPS observations for Swarm-A and Swarm-B in the morning and afternoon sectors,

Figure 8. Second-order ionospheric terms based on the vertical total electron content generated from onboard observations and IGRF12 model.

Figure 9. Third-order ionospheric effect on the Global Positioning System observations of Swarm.

Figure 10. The variation of topside vertical total electron content (VTEC) measured by Swarm-A and Swarm-B spaceborne receiver in the (left) morning sector and (right) afternoon sector. The UTC of equator crossings is presented above each satellite track. The each subfigure of bottom panel shows the latitudinal profiles of Δ VTEC variation (subtracted by the quiet-time reference) for each ascending track marked by numbers 1, 2, 3, and 4 during the period of 21:00 7 September to 3:00 8 September. The red line presents the corresponding Δ VTEC variation during the storm.

respectively. The average VTEC values of 4 and 5 September are regarded as quiet time level because the low geomagnetic activities on both days. From Figure 10, one can notice that the first small storm time VTEC enhancement was observed in low-latitude region at both altitudes shortly after IMF B_z turned southward at ~ 21 UT 7 September (see track 1 for both satellites), which is associated with the prompt penetration electric field when the IMF B_z component is southward. Afterward, the VTEC enhancement began to extend to midlatitude and high-latitude region. For Swarm-A, the VTEC enhancement shows a symmetric variation with respect to the magnetic equator and there are two peaks corresponding to the two crests of equatorial ionization anomaly. The largest VTEC increase of $\sim 400\%$ with respect to quiet time is observed when Swarm-A satellite pass over the Northeast Asia and Australia regions during the storm main phase (see track 3). As shown in Figure 1, the variation of IEF E_y indicates that there is a prompt penetration of electric field into low-latitude and midlatitude regions during the main phase of the storm, which is the main contributor of N_e increase. For the afternoon sector, the distribution of VTEC storm time enhancement is quite different from that in the morning sector. The increase of VTEC at low latitudes in the southern hemisphere is larger than that in the northern hemisphere (NH) at 21–23 UT 7 September, and afterward a VTEC enhancement is visible at midlatitudes in the NH before the storm. Along with the sharp decrease of $SYH-H$, the largest VTEC enhancement occurs from $\sim 00:54$ UT to $\sim 01:36$ UT on 8 September (see track 3). VTEC in the NH presents a stronger enhancement than that in the southern hemisphere during the storm main phase, especially at the mid latitudes.

To investigate the storm response of the topside ionosphere in the evening and pre-sunrise regions, we also analyze the VTEC from Swarm-A and Swarm-B data in the descending tracks. As shown in the Figure 11, The VTEC enhancement on the nightside is much smaller than that on the dayside. In the evening sector, VTEC in the low-latitude region has a slight enhancement and presents a clear one-peak structure (see

Figure 11. The same as Figure 10 but for Swarm-A and Swarm-B in the (left) evening sector and (right) presunrise sector.

track 1 for Swarm-A). Along with IMF B_z dropping to its minimum value of -31.09 nT at $\sim 23:35$ UT on 7 September, there is a small VTEC depletion at the low latitude and midlatitude in the NH. At later UTs of the main phase, the VTEC mainly shows relatively larger increase in the low- and high-latitude region (see track 3 and 4). For the presunrise sector, an evident growth of VTEC is observed from 0:00 UT 8 September. These increases are generally symmetric with respect to the magnetic equator and mainly occur at the low altitude.

In order to analyze the higher ionospheric effects of storm time on the Swarm POD, we directly correct the ionospheric effects on the raw GPS observations and then perform the POD with refined strategy. The corresponding results are listed in the Table 2. Although the higher ionospheric effects have a noticeable increase during the storm, the result of both overlap comparison and carrier phase residuals indicates that almost the same precision has been achieved for Swarm-A and Swarm-B, no matter whether or not the higher ionospheric effects are taken into consideration. This indicates that the storm time N_e enhancement can indeed enlarge the ionospheric effects, but its magnitude is still very small and almost has no influence on LEO POD.

In addition to the geomagnetic storm, there are also a series of M-class and X-class solar flares happened on 7-8 September 2017. The enhanced fluxes of solar energetic particles, the X-ray emission as well as the EUV and ultraviolet (UV) fluxes during solar flares, can cause increased ionization in the ionosphere exhibiting as a sudden enhancement in the ionospheric TEC. Besides, Le et al. (2012) also found that the X-class solar flares can induce an average enhancement of 10–13% in the thermospheric mass density at latitudes 50°S – 50°N , and this enhancements sometimes are seen within ~ 4 hr after the flare onset. Since the several flares happened during the storm on 7-8 September, it is difficult to separate the influences from the solar flares or storm on the observed thermosphere density enhancements that further affects the POD performance of LEO satellites.

Table 2
The Result of POD for Swarm-A and Swarm-B After Correcting Higher Ionospheric Effects

Satellite	Date	3-D RMS of overlap differences (cm)		RMS of carrier phase residuals (mm)	
		Before correction	After correction	Before correction	After correction
Swarm-A	7 September	1.8	1.8	7.7	7.7
	8 September	2.6	2.6	7.9	7.9
Swarm-B	7 September	1.7	1.6	7.8	7.8
	8 September	1.4	1.4	7.9	7.9

The above results demonstrate that the orbit of three Swarm satellites indeed experienced a precision degradation during the storm and the orbit degradation only occurred on 8 September 2017. In fact, a smaller storm is also observed at ~00:45 UT on 7 September, along with a sharp increase of solar wind velocity. As shown in Figures 8 and 9, this storm contributes also to a clear increase in high-order ionospheric effects in the early time of 7 September. However, there is no evidenced orbital precision degradation on 7 September and Swarm constellation presents a similar orbit precision as that of quiet time (see Figures 2b and 3).

Furthermore, it is seen that the higher-order ionospheric terms have less effects on improving the Swarm orbit precision during the storm of 7-8 September. The similar results have been reported by Jäggi et al. (2015) for the GOCE mission. They found that the carrier phase residuals of GOCE reduced-dynamic POD show systematic errors around the geomagnetic equator and no significant reduction in systematic errors can be observed when high-order ionosphere corrections are applied, which indirectly indicates the negligible impact of higher-order ionospheric errors. However, the results of reduced-dynamic POD are not completely in agreement with the results of kinematic POD. Zehentner & Mayer-Gürr (2016) reported an improvement in orbit accuracy when estimating an individual slant TEC parameter in the kinematic POD processing to model the ionospheric influence, including high-order ionosphere effects. The different performances of high-order ionospheric corrections may be attributed to the methods of LEO POD that have been used. The kinematic POD is exclusively based on the onboard GNSS observations and is thus independent from dynamical models. It indicates that the kinematic POD is very sensitive to the quality of GNSS observations and any observations error can directly affect the precision of kinematic orbit result. In contrast, apart from the onboard GNSS measurements, the reduced-dynamic POD makes full use of dynamic models of LEO motion, which constrains the resulting satellites position. In reduced-dynamic POD, the constraint of dynamic models may reduce the influence of high-order ionosphere effects, which needs to be further investigated.

5. Summary

In this paper, we focus on the performance of the POD for Swarm constellation during the geomagnetic storm happened on the 7-8 September 2017. The influence of the thermosphere density perturbations and higher-order ionospheric effects on POD are analyzed and discussed. The main findings are summarized as follows:

1. The quality of Swarm orbit was largely degraded during the storm. From the SLR validation and residuals analysis, the negative influence of geomagnetic storm on POD mainly occurs during storm main phase. The magnitude of orbit degradation reached centimeter-level for Swarm-B and decimeter-level for the lower flying pair (Swarm-A and Swarm-C).
2. A noticeable perturbations in the thermosphere density can be observed on 8 September. The increased total density of thermosphere results in a stronger drag force, which is the main source contributing to the Swarm orbit degradation. This side impact can be largely suppressed by estimating a more frequent drag parameter coefficient (with every 30 min instead of every 6 hr). With the refined POD scheme, Swarm orbit can achieve a similar precision of few centimeters during the storm as that in the quiet time.
3. The absolute TEC enhancements during the storm main phase show larger magnitude on the dayside at low and middle latitudes that lead to an increase in the higher-order ionospheric effects at these regions. However, no evidenced orbital precision improvement is visible after correcting these ionospheric effects.

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