Large ionospheric TEC depletion induced by the 2016 North Korea rocket

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Abstract

A rocket called Kwangmyongsong-4 was launched from North Korea at 00:30 UT on February 7, 2016. We investigated ionospheric total electron content (TEC) depletions induced by the rocket using the Global Navigation Satellite System (GNSS) stations in South Korea. A sudden depletion in TEC variations appeared ~6 min after the rocket launch. The drops in slant TEC exceeded 17 TEC unit (TECU) and those in vertical TEC were approximately 7 TECU. It is remarkable that the TEC drop by the 2016 Kwangmyongsong-4 rocket is larger (almost by three times) than that by the 2012 Unha-3 rocket. There are the differences of the background TEC values at the 2012 and the 2016 cases. These results suggest that the difference of the background electron density affects the magnitude of TEC depletion. The horizontal velocity of the rocket was 1.6 km/s, which was estimated from horizontal distances with an initial time of TEC disturbances. However, the 2012 Unha-3 rocket (~2.5 km/s) moved faster horizontally than the 2016 Kwangmyongsong-4 rocket. Furthermore, when the rocket moved from high latitudes to low latitudes, TEC disturbances reduced gradually, and then, the depletion persisted for a longer time at the west side (the right side of southern direction).

Keywords: Ionosphere; Rocket launch; Total electron content; Neutral winds

1. Introduction

Ionospheric total electron content (TEC) is easily disturbed by many factors such as geomagnetic storms, solar activity and major earthquakes (Jakowski et al., 2002; Immel et al., 2003; Tsurutani et al., 2004; Fedrizzi et al., 2005; Mannucci et al., 2005). Many studies reported that ionospheric disturbances can also occur due to rocket launches (Noble, 1990; Calais and Minster, 1996; Li et al., 1994; Afraimovich et al., 2002; Ding et al., 2014; He et al., 2015; Park et al., 2016). Booker (1961) observed TEC depletion in the F region with ionosondes after the 1959 Vanguard II rocket launch. Mendillo et al. (1975) reported that a sudden TEC depletion was also observed by analyzing radio signals from a geostationary satellite after the 1973 Skylab launch.

North Korea has conducted many rocket and missile launches for two decades. A localized ionospheric disturbance induced by North Korea’s rocket or missile launches has been reported (Ozeki and Heki, 2010; Kakinami et al., 2013; Nakashima and Heki, 2014; Lin et al., 2014). Recently, ionospheric TEC depletion induced by rocket exhaust gas has been mainly detected by the ground-based Global Positioning System (GPS) stations. Ozeki and Heki (2010) observed ionospheric holes and TEC depletion from ballistic missiles of North Korea the 1998 Taepodong-1 and the 2009 Taepodong-2, using a Japanese GPS network. They inferred that the 2009 rocket was lar-
ger than the 1998 rocket by the numeric simulation to the formation of ionospheric hole. Kakinami et al. (2013) detected the V-shaped disturbance triggered by a rocket launched from North Korea on 12 December, 2012 using a dense GPS network in Taiwan, Japan, and South Korea. However they suggested that TEC depletion was not detected during this event because plasma depletion was weak in the topside ionosphere. Later, Nakashima and Heki (2014) detected TEC depletion using data of Russian GLONASS satellites, obtained from the GNSS stations in Japan.

A plasma depletion is caused by the chemical reaction of rocket exhaust molecules, primarily H\textsubscript{2}O and H\textsubscript{2}, with O\textsuperscript{+} the dominant F\textsubscript{2}-layer ion. The molecular ions (H\textsubscript{2}O\textsuperscript{+}, H\textsubscript{3}O\textsuperscript{+}, and OH\textsuperscript{+}) are produced by this reaction and recombine rapidly with electrons in the ionosphere (Mendillo et al., 1975). Furuya and Heki (2008) reported the formation of an ionospheric hole by numerically simulating the plasma depletion process.

Recently, North Korea launched a new rocket called the ‘Kwangmyongsong-4’ from the Sohae space center at 00:30 UT on February 7, 2016. In the present study, we report ionospheric TEC depletions induced by the 2016 Kwangmyongsong-4 launch. TEC values derived from a dense GPS network in South Korea are used to analyze the depletion properties in the local ionosphere. We also estimate the rocket’s trajectory and its horizontal velocity using the initial time of TEC depletions. We compare amounts of TEC depletion between the 2012 Unha-3 and the 2016 Kwangmyongsong-4. In addition, the relation between TEC changes observed along the trajectory of rocket and the neutral wind velocities is suggested.

2. Data and TEC calculations

Several agencies in South Korea have operated approximately 160 permanent GNSS stations and related facilities. In the present study, we used GPS data obtained from the Korean GNSS network (KGN) which has a spatial resolution of approximately 40 km. GPS data are available from the National Geographic Information Institute website (gnss.ngii.go.kr). Some of GNSS stations in the KGN are selected to monitor TEC variations in the ionosphere. Considering their data qualities and the spatial distributions, we have chosen 64 GNSS stations that are equipped with a dual-frequency receiver. The geodetic receivers in the GNSS stations provide data sampled every 30 s.

The methods to extract the TEC in the ionosphere by using the dual-frequency GPS signals have been described in the literature review (Lanyi and Roth, 1988; Klobuchar et al., 1994; Sardon et al., 1994; Mannucci et al., 1998; Jakowski et al., 1999; Otsuka et al., 2002). Dual-frequency GPS data are used not only to eliminate the influence of the ionosphere, but also to calculate precise TEC values. TEC in the ionosphere imposes a dispersive delay on the GPS signals. It can be easily calculated with ‘geometric-free linear combination’, which is formed by taking the difference between the phase and code measurements at the two GPS frequencies (f\textsubscript{1} \sim 1575.42 MHz and f\textsubscript{2} \sim 1227.60 MHz):

\[ P_4 \equiv P_2 - P_1 = I \left( \frac{f_2^2 - f_1^2}{f_1^2 \cdot f_2^2} \right) + d_r + d_s \quad (1) \]

\[ L_4 \equiv L_2 - L_1 = I \left( \frac{f_2^2 - f_1^2}{f_1^2 \cdot f_2^2} \right) + (\lambda_1 N_1 - \lambda_2 N_2) + d_r + d_s \quad (2) \]

where \( P_1 \) and \( P_2 \) are the pseudoranges of the GPS signals, and \( L_1 \) and \( L_2 \) are the carrier phases converted to distance units. \( \lambda_1 \) and \( \lambda_2 \) are the wavelengths of the two GPS signals, respectively. \( N_1 \) and \( N_2 \) are phase ambiguities. Ionospheric TEC from the two combinations, \( L_4 \) and \( P_4 \), can be easily computed. However, the TEC data derived by subtracting measurements at different frequencies include the hardware-related biases (\( d_r \) and \( d_s \)) for the receiver and satellite. Therefore, these hardware biases should be considered in the TEC estimation and can seriously affect the accuracy of the TEC data in the ionosphere (Mannucci et al., 1998; Meza, 1999). To extract the hardware biases from the TEC data, we adopted the weighted least squares estimation approach based on the GPS network employed by Choi et al. (2013).

To perform the conversion from slant TEC (STEC) to vertical TEC (VTEC), a suitable mapping function employed in Greiner-Brzezinska et al. (2004) is used. In addition, the time differenced TEC variations are considered to estimate the rocket’s velocity and its trajectory.

3. TEC disturbances

It is well known that TEC in the ionosphere can be reduced by 50% within ten minutes after the rocket launch and can persist over one hour (Zinn and Sutherland, 1980). As localized ionospheric disturbances could be possibly related to geomagnetic storms, we preferentially considered geomagnetic conditions. During the launch time of the Kwangmyongsong-4, the value of the three hourly averaged Kp index was 0+, and the disturbance storm time (Dst, Kyoto) index was ~2 nano-Tesla. It is noted that geomagnetic conditions were very quiet at the launch time on February 7, 2016. Therefore, we do not consider a potential relationship to geomagnetic activity.

To examine ionospheric TEC depletions induced by the Kwangmyongsong-4 rocket on February 7, 2016, data from a dense GPS network in South Korea were used. Only two GPS satellites were observed over the western sea of South Korea around the time of the launch. The trajectory of the rocket was nearly southward from the launch site, known as the Sohae space center. Fig. 1 shows trajectories of sub-ionospheric points (SIP) of GPS PRN 15 and PRN 20. The motion of the PRN 20 satellite was perpendicular (eastward) to the rocket’s flight path, and PRN 15 satellite
moved approximately from southwest to northeast. In Fig. 1, the Korean GPS network marked as red-circles is composed of 64 permanent GPS stations.

Fig. 2 shows STEC and VTEC time series derived from five GPS stations (HONC, INJE, CHCN, HCHN and CHLW) with the GPS PRN 15 satellite from 00:00 to 02:00 UT on February 7, 2016. Kwangmyongsong-4 blasted off from the launch site at 00:30 UT. TEC depletions appeared ~6 min after the launch and then gradually recovered in half an hour. Clear TEC depletions are seen at 00:36 UT after the launch of the rocket. From the STEC time series in Fig. 2a, we clearly detect TEC depletion with a maximum value of TEC \( /C24 \) 17 TEC unit (TECU, 1TECU \( /C24 \) \( \approx \) \( 10^{16} \) electrons/m\(^2\)). The VTEC value is converted from STEC using a simple mapping function. Changes in VTEC show a decrease of approximately 7 TECU. Although VTEC changes are relatively smaller than the STEC changes, a clear signature of VTEC depletion was also observed in a relatively short time. The abnormally large TEC decrease occurred rapidly at 00:36 UT.

Sharp TEC decreases derived from the rocket launch can be explained from the chemical reactions. The rocket exhaust gases consist of molecules, predominantly \( \text{H}_2\text{O} \) and \( \text{H}_2 \). A diagram of the chemical sequence is illustrated in Eqs. (3) and (4):

\[
\text{H}_2\text{O}^+ + e^- \rightarrow \text{H} + \text{OH} \quad (4)
\]

\[
\text{H}_2\text{O} + \text{O}^+ \rightarrow \text{H}_2\text{O}^+ + \text{O} \quad (3)
\]

The \( \text{H}_2\text{O} \) molecules react with \( \text{O}^+ \) ions and then form \( \text{H}_2\text{O}^+ \) ions. The \( \text{H}_2\text{O}^+ \) ions formed in the chemical reaction Eq. (3) react rapidly with \( e^- \) electrons in the ionosphere. The reaction of Eq. (4) is faster than the direct recombination of \( e^- \) with \( \text{O}^+ \). Therefore, the molecular ions and the electrons can be rapidly removed by the process of the chemical reactions.

Fig. 3 shows the distance-time diagram of differed TEC variations induced by the Kwangmyongsong-4 rocket launch. Weak TEC decrease appears at approximately 200 km in a horizontal distance. The maximum occurrence of TEC depletion is located within a horizontal distance of approximately 400–600 km from the launch site. The horizontal velocity of the rocket is estimated from horizontal distances with the initial time of TEC depletions. Therefore, the horizontal velocity of Kwangmyongsong-4 was calculated to approximately 1.6 km/s. If a vertical motion of the rocket is known or considered simple, its velocity is assumed to be 2–3 km/s.

A previous rocket called ‘Unha-3’ blasted off from North Korea at 00:49 on December 12, 2012. It was a southward launch which is similar to Kwangmyongsong-4 from the same launch site. The launch time of Unha-3 is approximately 19 min later than Kwangmyongsong-4. In the present study, to analyze characteristics of TEC changes with the distance after Unha-3 launch, GPS data in South Korea were also investigated. Fig. 4a presents
the trajectory of GPS PRN 17 over South Korea from 00:00 to 02:00 UT. The trajectory of GPS PRN 17 estimated on 12 December 2012 is almost similar to that of GPS PRN 20 estimated on 7 February 2016. Fig. 4b shows the differential TEC variations with time, as observed by GPS PRN 17. The horizontal distances are calculated between SIPs and the location of the rocket launch. As shown in Fig. 4b, sudden TEC changes are clearly identified at approximately 6 min after the onset time of the rocket launch. The horizontal velocity of Unha-3 is estimated as the slope of the red-dashed line in Fig. 4b. The red-dashed line indicates the first time occurrence of TEC depletions at selected GPS stations. The velocity of Unha-3 was approximately 2.5 km/s in the horizontal direction. Kakinami et al. (2013) reported that the western and eastern sides of the V-shaped TEC disturbances derived from Unha-3 rocket’s exhaust gases propagated at approximately 2.0 and 2.5 km/s. Our results are in good agreement with their results. They show that there is an obvious difference between the 2012 and the 2016 cases with different velocities. However, it is difficult to directly compare both of them. The horizontal velocity of Unha-3 is greater than that of Kwangmyongsong-4. If we assume that their performance (including the rate of fuel consumption and the chemical components of the fuel) is similar, this might suggest that the flight altitudes or the initial flight path angles are different between the 2012 and the 2016 cases. Presumably, Unha-3 may move toward southward at a lower altitude than Kwangmyongsong-4 in the first stage. As shown in Figs. 3 and 4b, the initial TEC disturbances induced by Kwangmyongsong-4 and Unha-3 appear at a distance of about 200 and 350 km, respectively. This reflects the fact that the 2016 Kwangmyongsong-4 has reached an altitude of ionosphere much faster than the 2012 Unha-3. Therefore, we also suggest that the velocity of Kwangmyongsong-4 has a greater vertical component than that of Unha-3.

Fig. 5 shows two-dimensional TEC variations for the same time epoch (at 00:38 UT) at different ionospheric altitudes of (a) 200 km, (b) 250 km, and (c) 300 km. SIP positions are dependent on ionospheric heights which are assumed to a thin layer. SIPs of GPS PRN 20 passing around the launch site have a fixed height of 200 km. TEC depletions are observed along the trajectory of the rocket. The first stage booster of the rocket fell into the western sea of South Korea at 00:32 UT. The South Korean military detected the rocket trajectory just minutes after the launch. However, it disappeared from the military’s radars. Information about Kwangmyongsong-4’s trajectory has not been released to the public because of this reason. As the rocket’s precise trajectory is not yet known, we estimate the rocket’s trajectory with different ionospheric altitudes. As observed in Fig. 5, the rocket’s trajectory at the altitude of (c) 300 km has not been available to the public; however, it is well consistent with useful information inferred from TV news and media (http://spaceflight101.com/north-korea-kms-4-launch-success/).

A V-shaped disturbance was also clearly observed in Fig. 5. When the shock wave produced by the rocket’s
body exceeds the sound speed, the V-shaped disturbances are generated by the shock wave. As shown in Fig. 5, however, the V-shape signature was not well revealed from the east side (the left side of southern direction) of the trajectory due to the geometry of GPS satellites. It was clearly observed at the west side. Furthermore, TEC depletions at the west side of the trajectory last for a relatively longer time compared to the east side. This could be related with the neutral wind effect.

To investigate the detailed quantitative analysis for TEC depletions, Fig. 6b displays the time series of the differenced TEC changes derived from eight GPS stations during the Kwangmyongsong-4 passage. The GPS stations marked as red circles are located on a similar longitude (127°E) with different latitudes in Fig. 6a. SIP for GPS PRN 15 is calculated by assuming the ionospheric height of 300 km. The largest TEC change occurred at ‘skma’ station which is the northernmost site in Fig. 6a. The TEC change was relatively small at ‘jeju’ station, which is located on the southernmost station in South Korea. Therefore, it is noted that TEC changes reduced gradually from the high latitude to low latitude. The exhaust gases from the rocket’s second stage rapidly diffuse in the ionosphere. The interaction between the exhaust gases and the electrons in ionosphere causes local TEC depletion within several hundreds of kilometers. The smaller TEC changes...
over the southern propagation of the Kwangmyongsong-4 rocket might be associated with the exhaust effusion’s reduction or neutral wind effect.

4. Discussion

Fig. 7 presents the slant TEC changes induced by Unha-3 launch between 00:00 and 02:00 on 12 December 2012. This is obtained from three GPS stations (MKPO, CHJU and JEJU) with the GPS PRN 17 satellite. Sudden TEC depletions of about 5 TECU are clearly observed at 00:55 UT. Nakashima and Heki (2014) analyzed STEC changes using observables from GLONASS satellites. They reported that STEC depletions observed by the GLONASS satellite were approximately 5 TECU at approximately 6 min after the launch. Our results are in good agreement with the results reported by Nakashima and Heki (2014).

Note that the amount of STEC depletions induced by the 2016 Kwangmyongsong-4 in Fig. 2a is roughly three times greater than that of the 2012 Unha-3. From the large difference of STEC depletions between the 2012 and 2016 cases, the 2016 Kwangmyongsong-4’s exhaust gas would have contained a relatively large amount of water molecules compared to the 2012 Unha-3. Ozeki and Heki (2010) suggested that the amount of initial TEC depletion would be dependent on the electron density in the ionosphere. If we assume that their trajectories are very similar, such a difference can be caused by the background plasma.
density. As the next step, the background electron densities in both cases were calculated. We compared the background TEC values in the 2012 PRN 17 and the 2016 PRN 20. The resulting background TEC difference is presented in Fig. 8. The 2016 VTEC (≈18.6 TECU) is about twice as large as the 2012 VTEC (≈10.2 TECU). As SIP track of PRN 20 on February 7 2016 is very similar to that of PRN 17 on 12 December 2012 as shown in Figs. 1 and 4a, the difference of the background condition can affect the magnitude of TEC depletion.

Furthermore, the difference of the background TEC at different altitudes of the upper E-layer and the F-layer of the ionosphere may also affect the amount of TEC depletion (Mendillo et al., 1975). In Section 3, we suggested that the flight altitudes (pathes) of rocket reaching the ionosphere between the 2012 and the 2016 cases can be different. Park et al. (2016) reported that electron temperature in the daytime mid-latitude topside is anticorrelated with TEC depletions by analyzing the Swarm data. It is noted that the heating of electrons due to rocket exhaust can also affect TEC depletion.

TEC depletions induced by rocket exhaust are difficult to explain in association with any known factor. This is complicated with several components such as the chemical components of rocket’s exhaust, the amount of water molecules (H₂ and H₂O) diffused from the rocket, and the second stage’s performance of rockets, a difference on ionospheric conditions. However, obvious large difference of STEC depletions (see Figs. 2a and 7) suggests that the background electron densities are different at the 2012 and the 2016.

To analyze the properties of TEC changes at different latitudes as shown in Fig. 6b, the background neutral wind velocities at a specific location (35°N, 124°E) are calculated.
from the empirical horizontal wind model (HWM07) (Drob et al., 2008) in Fig. 9. The neutral wind velocities were derived from the HWM07 model at different ionospheric altitudes (200, 250, and 300 km) on February 7, 2016. A westward (zonal) wind velocity at the height of 300 km is approximately 120 m/s at 00:30–1:00 UT. Therefore, the exhaust gases from the rocket can be moved by a westward zonal wind. Fig. 10 presents the snapshots of the difference TEC changes with time after Kwangmyongsong-4 launch. Longer duration of TEC depletion is clearly observed as shown in square boxes in Fig. 10d–f. We suggest that the neutral wind can lead to TEC depletion for a longer time. This is evident that the exhaust gases of the rocket move with the neutral wind. In addition, a northward (meridional) wind velocity at 300 km is approximately 60 m/s. Therefore, the northward meridional wind can inherently dispute a southward propagation of the exhaust gases. However, the decrease in TEC depletions can be regarded as the background ionospheric effect during this event as the rocket’s altitude increases gradually with a southward propagation. In consequence, the difference of the electron density at different altitudes in the ionospheric F2 region, or a direction of the neutral wind may be related to TEC depletion induced by the rocket exhaust.

5. Conclusions

The rocket called Kwangmyongsong-4 was launched from the Sohae space center at 00:30 UT on February 7th, 2016, and its trajectory was nearly southward from the launch site. TEC depletions were observed along the rocket’s trajectory. An apparent reduction in GPS TEC appeared ~6 min after rocket launch. The drops in STEC of the 2016 Kwangmyongsong-4 exceeded 17 TECU. The largest STEC decrease of the 2012 Unha-3 was about 5 TECU. However, there were the large differences of the background electron densities at the 2012 (10.2 TECU) and the 2016 (18.6 TECU). The difference of the background condition affects the magnitude of TEC depletion.
depletion was observed at the west (the right side of southern direction). Interesting thing is that TEC depletion can be associated with the direction of neutral wind. Furthermore, we estimated a horizontal velocity of rockets between the 2012 and the 2016. The horizontal velocity of the 2012 Unha-3 was greater than that of the 2016 Kwangmyongsong-4. Therefore, the Kwangmyongsong-4 may have a greater vertical component than that of Unha-3.

In conclusion, TEC depletions induced by rocket launches have to consider in combination with several factors such as the chemical components, amount of the exhaust gases, plasma density in the ionosphere, the trajectory of rocket, performance of rocket and the neutral wind effect.

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References


