AGU PUBLICATIONS

Radio Science

RESEARCH ARTICLE

10.1002/2014RS005413

Key Points:
- Observation of ionospheric hole made by a North Korean rocket
- The Russian GNSS was used for the first time to observe ionospheric hole
- The exhaust plume of the third-stage engine was observed

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Citation:
Nakashima, Y., and K. Heki (2014), Ionospheric hole made by the 2012 North Korean rocket observed with a dense GNSS array in Japan, *Radio Sci.*, *49*, 497–505, doi:10.1002/2014RS005413.

Received 28 FEB 2014
Accepted 18 JUN 2014
Accepted article online 24 JUN 2014
Published online 10 JUL 2014

Ionospheric hole made by the 2012 North Korean rocket observed with a dense GNSS array in Japan

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Abstract A dense array of Global Navigation Satellite System (GNSS) receivers is useful to study ionospheric disturbances. Here we report observations by a Japanese GNSS array of an ionospheric hole, i.e., localized electron depletion, made by water vapor molecules in the exhaust plume of the second-stage engine of the Unha-3 rocket launched from North Korea, on 12 December 2012. The Russian GNSS was used for the first time to observe such an ionospheric hole. The hole emerged ~6 min after the launch above the middle of the Yellow Sea, and its size and depth suggest that the Unha-3 is slightly less powerful than the 2009 Taepodong-2 missile, also from North Korea. Smaller-scale electron depletion signatures appeared ~10 min after the launch above the southern East China Sea, which is possibly caused by the exhaust plume of the third-stage engine.

1. Introduction

Booker [1961] first detected a localized reduction of ionization by the exhaust plume of the Vanguard II rocket with ionospheric sounding in 1959. *Mendillo et al.* [1975] found a sudden decrease in total electron content (TEC) after the 1973 Skylab launch by measuring the Faraday rotation of radio signals from a geostationary satellite and suggested that the exhaust of the rocket chemically influenced the ionosphere. They modeled the process in which water (H_2O) and hydrogen (H_2) molecules in the exhaust plume caused the localized electron depletion or an ionospheric hole. Nowadays, active experiments using ground incoherent scatter radars and in situ probes on satellites are often performed to understand ionospheric responses to chemical agents in the exhaust [e.g., *Bernhardt et al.*, 2001, 2005, 2012].

In 1990s, deployments of continuous Global Positioning System (GPS) receivers started in various regions close to boundaries of tectonic plates to study crustal deformation. Because GPS can also measure TEC along the line of sight by comparing the two L band carrier phases, dense GPS networks became a useful tool for two-dimensional mapping of ionospheric irregularities [e.g., *Maeda and Heki*, 2014]. Using GPS network in North America, *Calais and Minster* [1996] caught the shock wave signature of the ascending space shuttle. *Furuya and Heki* [2008] found the electron depletion signature using a dense network of continuous GPS receivers in Japan after the 2006 launch of an H-IIA rocket.

The so-called Taepodong-1 and -2 multiple-stage ballistic missiles were launched from Musudanri, on the eastern coast of North Korea, on 31 August 1998 and 5 April 2009, respectively. In both cases, their first stages splashed down onto the middle of the Japan Sea, and the second stages flew over northeastern (NE) Japan [e.g., *Brumfiel*, 2009]. For these missile launches, *Ozeki and Heki* [2010] detected ionospheric holes and inferred that the thrust of the 2009 missile was ~6 times as large as the 1998 missile by numerically simulating the ionospheric hole formation with a similar approach to *Furuya and Heki* [2008].

A new rocket, called Unha-3, was launched from Tongchangli, the launch pad on the Yellow Sea, coast of North Korea, on 12 December 2012, at 00:49:46 UT, and reportedly has put a satellite into an orbit [*Ministry of Defense*, 2013]. *Kakinami et al.* [2013] studied the ionospheric disturbances caused by this rocket using GPS stations in Japan, Korea, and Taiwan. They found short-period disturbances with V-shaped distribution 6.5–7.5 min after the launch in the northern part of East China Sea, caused possibly by shock waves excited by the rocket. They failed, however, to identify the ionospheric hole signature because no GPS satellites were in a suitable part of the sky at the time of the launch. In this study, we report the ionospheric hole found above the Yellow Sea made possibly by the second-stage engine of the 2012 Unha-3 using the Russian Global Navigation Satellite System (GLONASS; Global'naya Navigatsionnaya Sputnikovaya Sistema). We will compare the size and depth of the ionospheric hole with past examples by the Taepodong-1 and -2 launches. We will also discuss the ionospheric hole made possibly by the third-stage engine of the Unha-3.

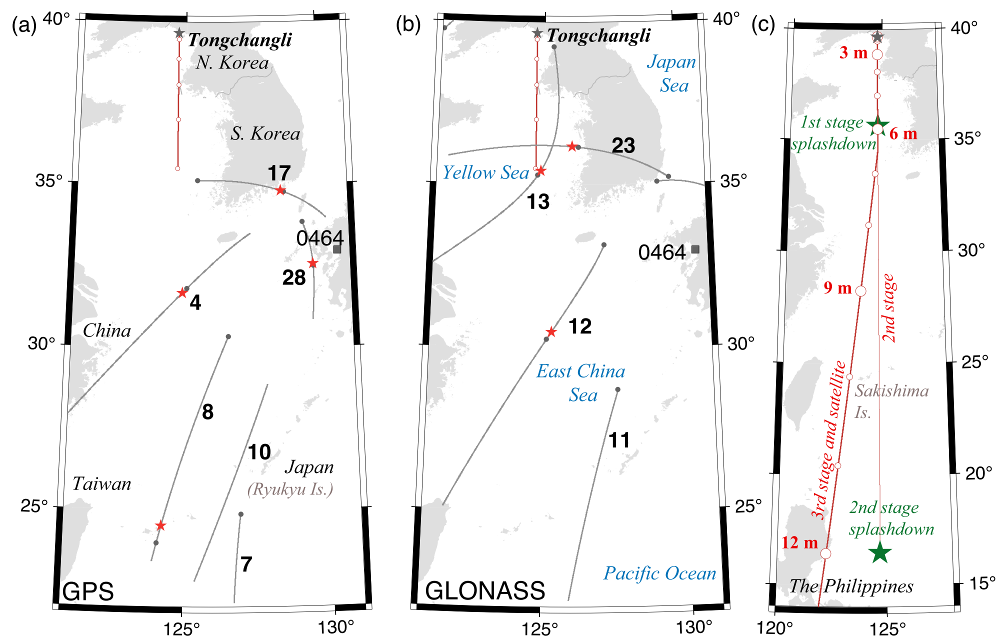

Figure 1. Track of SIPs for (a) GPS and (b) GLONASS satellites during a 2 h period (0–2 UT) encompassing the 12 December launch of the Unha-3 rocket from Tongchangli, North Korea. Ionospheric hole is expected to appear ~500 km south of the launch pad if the launch sequence is similar to the two predecessors [*Ozeki and Heki*, 2010]. SIPs of no GPS satellites are in the desired region, but GLONASS Satellite 13 has a just right SIP track. SIP is calculated assuming the ionospheric height of 280 km. Red stars on the SIP trajectories are the SIP positions when the electron depletion started (00:56 UT). (c) Approximate trajectory of the Unha-3 is shown. Splashdown points of the first- and second-stage rockets are shown with green stars. On the trajectory, time marks of 1 min (small open circles) and 3 min (large open circles) are given. The third-stage rocket slightly changed the azimuth and put the satellite into an orbit of inclination ~97° [*Ministry of Defense*, 2013].

2. Launches and Trajectories of Unha-3

The first test of the Unha rocket (Unha-2) ended as a failure on 13 April 2012, without reaching ionospheric height. The Unha-3 rocket was launched on 12 December 2012, as a three-stage rocket from Tongchangli launch pad on the Yellow Sea, coast of North Korea. The specifications of the rocket are not made available to public but are considered to be an improved version of the 2009 Taepodong-2 missile. In 2009, radar tracking data by the U.S. government suggested that the first two stages worked but the third stage has exploded without injecting a satellite into orbit [*U.S. Northern Command*, 2009]. In the 2012 Unha-3 launch, however, the rocket is believed to have successfully put a satellite, called Kwang-myong-song 3-2, into a polar orbit with inclination 97.4°. The satellite has the perigee and apogee height of 499.7–584.18 km and an orbital period of 95′ 43″, although the satellite is not thought to be functioning [*Ministry of Defense*, 2013].

The first stage of Unha-3 fell within the predicted area in the middle of the Yellow Sea ~460 km due south of the launch pad, ~9 min after the launch. The South Korean force succeeded in recovering a part of the first-stage rocket from the sea. The Japanese *Ministry of Defense* [2013] published that the second- and third-stage rockets flew over the western part of the Ryukyu Islands (Sakishima Islands), southwestern Japan, 9–11 min after the launch. The second-stage rocket is considered to have fallen to the east of the Luzon Island, the Philippines, ~2600 km from the launch pad, ~16 min after the launch (Figure 1c).

3. GNSS Data Analysis

3.1. Isolation of TEC Anomalies From GLONASS Data

The Japanese dense network GEONET (GNSS Earth Observation Network) is composed of ~1200 continuous GNSS tracking stations and records L band carrier phases in two frequencies every 30 s. We downloaded the raw data on the day of the Unha-3 launch available online from the Geospatial Information Authority (GSI), Japan. Temporal changes of the differences between the two phases expressed in lengths can be converted into TEC by multiplying with a factor determined by the two frequencies.

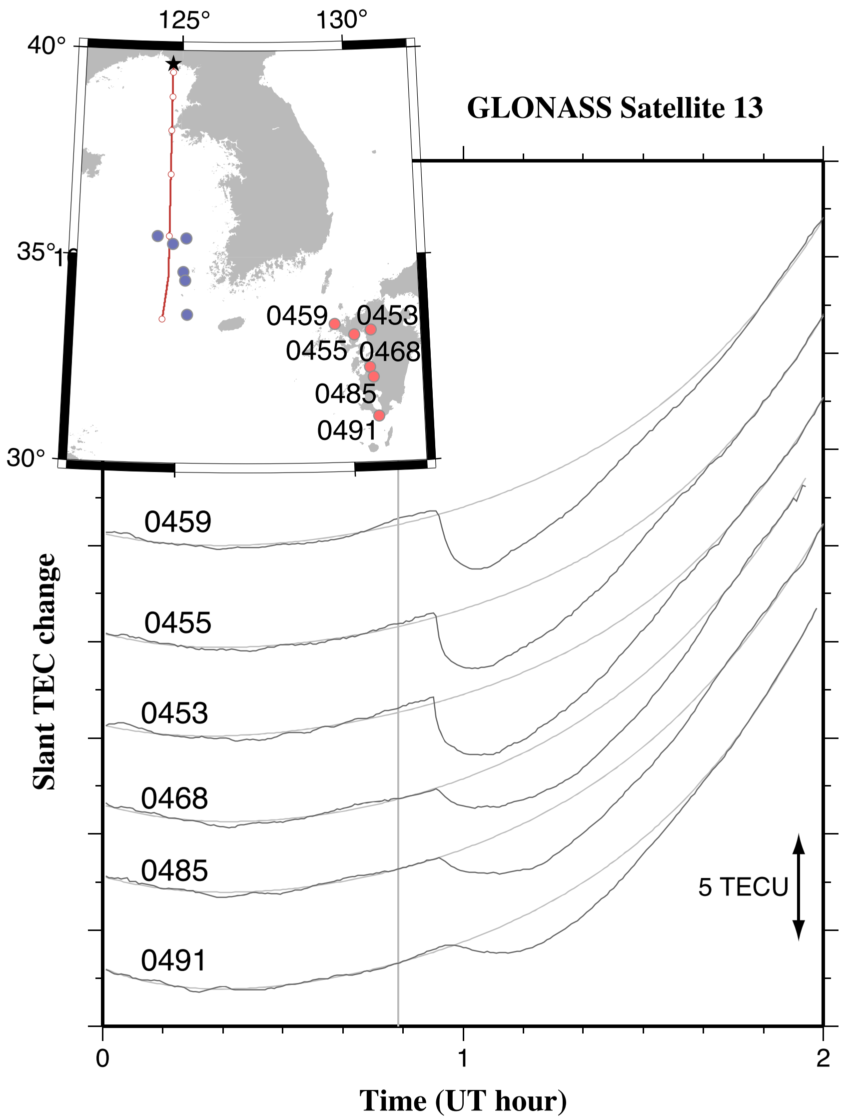

Figure 2. Raw time series (dark gray) of slant TEC changes on 00–02 UT, 12 December 2012, observed at six GNSS stations in Kyushu using the GLONASS Satellite 13. Positions of GNSS stations and SIPs at 00:50 UT are shown in the inset together with the trajectory of the first 6 min. Smooth light gray curves are the models estimated assuming that the VTEC changes as a quadratic function of time (0.93–1.70 UT is excluded; see text). Departures from the reference curves (TEC anomalies) are shown with color in Figure 3. Unusual TEC decreases start ~6 min after the launch of Unha-3 at 00:49:46 UT (gray vertical line).

If the ascent of the Unha-3 is similar to the Taepodong-1 and -2, ionospheric hole made by the second-stage engine is expected to appear in the *F* region 400–500 km south of the launch pad. As shown in Figure 1a, however, no GPS satellites were available to observe the ionosphere above that area with GEONET. *Kakinami et al*. [2013] did not find significant electron depletion signatures with GPS and inferred that the depletion was not strong enough. However, this was simply a geometry problem, i.e., GPS satellites were not in positions suitable for the detection of the ionospheric hole using stations in Japan.

In addition to GPS, Russian GLONASS has become operational in 1990s. Recently, several other GNSS are being launched, e.g., Chinese Beidou and Galileo by the European Union. Receivers of the GEONET stations have been gradually replaced with the new ones capable of receiving multiple GNSS. In this paper, we analyzed the tracking data of GLONASS. At the time of the Unha-3 launch, 24 stations in Kyushu could track GLONASS (the number of stations has been increasing until now). From the viewpoint of TEC observations, GLONASS is different from GPS in two aspects, i.e., (1) individual GLONASS satellites employ slightly different carrier frequencies (GPS satellites use the same frequencies) and (2) the orbits of GLONASS satellites are

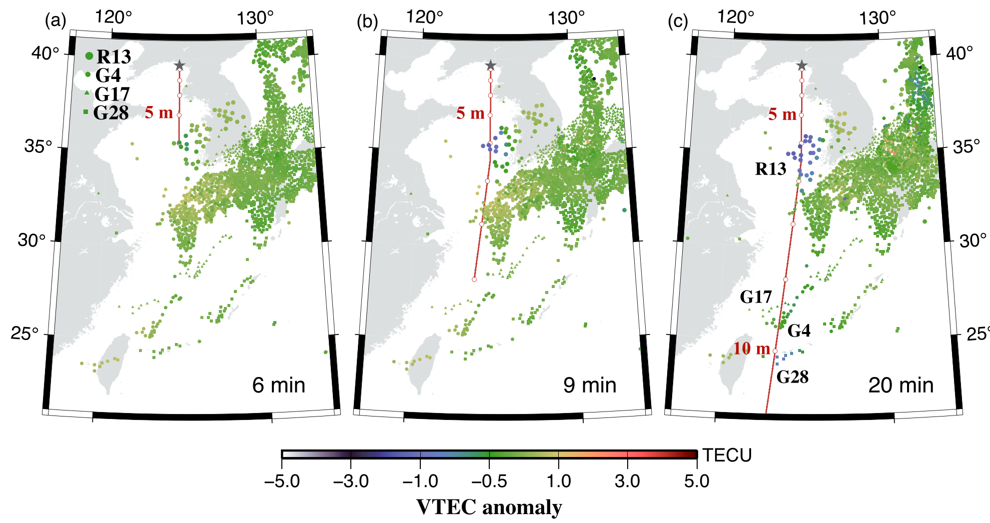

Figure 3. VTEC anomalies at (a) 00:56:00 UT, (b) 00:59:30 UT, and (c) 01:10:00 UT, which correspond to ~6, ~9, and ~20 min after the Unha-3 launch, respectively. Each dot corresponds to a GNSS satellite and receiver pair. Satellite numbers are shown in Figures 3a and 3c, and R and G mean GLONASS and GPS, respectively. Electron depletion appears in Figure 3a and grows in Figures 3b and 3c along the trajectory of the rocket. Numbers in red attached to white circles along the trajectory denote time in minutes after the launch.

broadcasted in the geocentric Cartesian coordinates and their time derivatives (those of GPS satellites are given in the Kepler elements). We slightly modified the software system used in the previous study for GPS [*Ozeki and Heki*, 2010] to be compatible with GLONASS.

3.2. Ionospheric Hole

First, we will have a look at pairs of GLONASS satellite 13 and GNSS stations located in Kyushu, whose line of sight (LOS) penetrates the *F* region ionosphere 400–500 km south of the launch pad (Figure 1b). Figure 2 (dark gray curve) shows the time series of slant TEC changes over a 2 h period including the Unha-3 launch. To isolate the negative TEC anomalies, we model the vertical TEC to change as a quadratic polynomial of time [*Ozeki and Heki*, 2010]. We estimated the model curve (light gray) excluding the period 0.93–1.70 UT, possibly influenced by the ionospheric hole, and considered the departure from the model as the anomaly. The anomaly is characterized by a sudden dip of ~5 TEC unit (TECU, 1 TECU = 10^{16} el m^{-2}) starting at 00:56:30 UT, ~6 min after the launch. The negative anomalies last for more than half an hour.

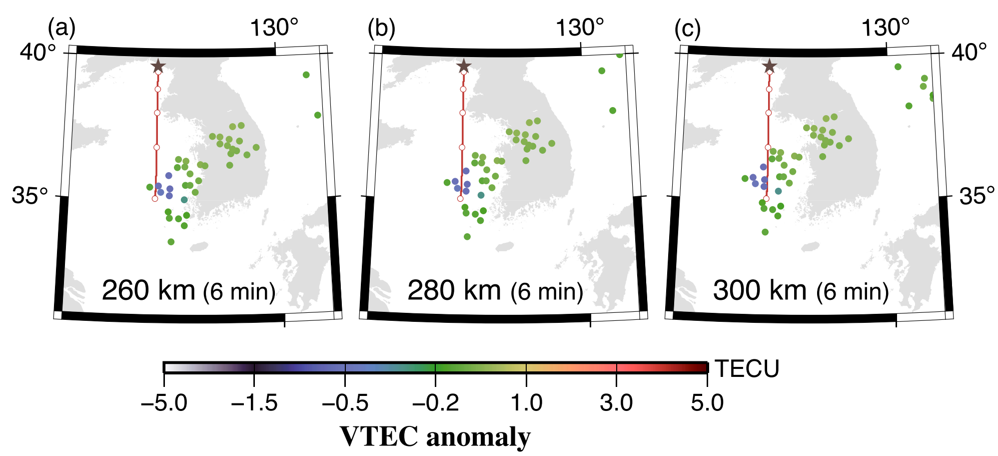

Figure 4. Because SIP positions depend on the assumed height of the ionosphere, it can be used to constrain the height of the observed anomaly. SIPs of the hole ~6 min after the launch should overlap with the trajectory, and this is better achieved by assuming the ionospheric height of (b) 280 km rather than (a) 260 km and (c) 300 km.

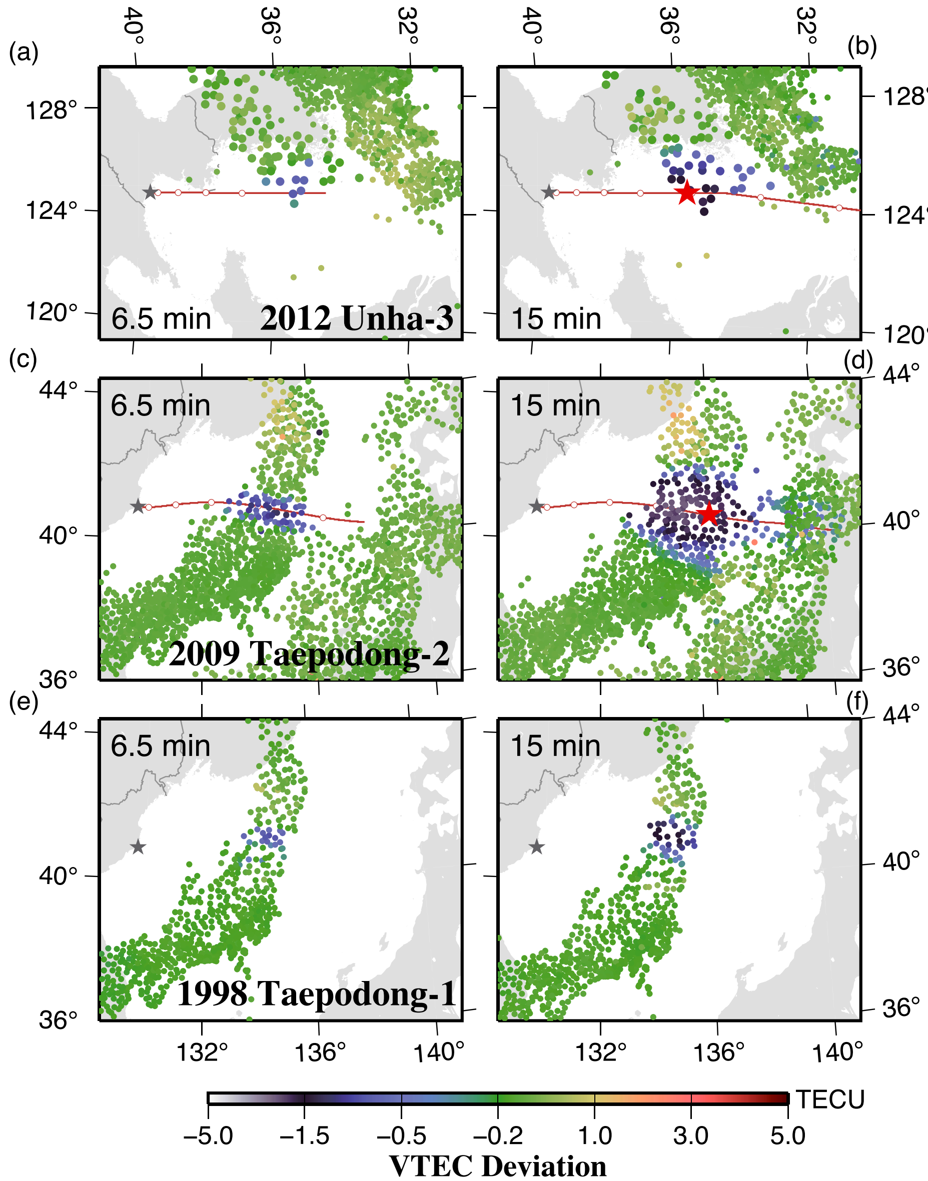

Figure 5. The ionospheric hole made by the (a, b) 2012 Unha-3 is compared with those by the (c, d) 2009 Taepodong-2 and (e, f) 1998 Taepodong-1 [*Ozeki and Heki*, 2010]. In Figures 5a and 5b, we plot the map taking the north-south direction in the horizontal axis so that the positions and the sizes of the ionospheric holes can be compared with each other.

Figure 3 shows the map projection of the emergence and development of the ionospheric hole by this rocket launch. We show vertical TEC (VTEC) anomalies, derived by multiplying the slant TEC (STEC) anomalies by cosine of the incident angle of the line of sight with a thin layer at altitude of 280 km (the height of the rocket ~6 min after the launch; see the next paragraph). They show three different epochs, i.e., 00:56:00 UT, 00:59:00 UT, and 01:10:00 UT, which correspond to ~6.0, ~9.0, and ~20.0 min after the launch, respectively. The dots show subionospheric points (SIP), ground projection of ionospheric piercing point (IPP) of line of sight. In calculating IPP coordinates, the ionosphere is assumed as a thin layer at the inferred height of the hole (i.e., not at the height of the maximum electron density). Their colors are dominated by green (normal), with some yellow/red and blue dots indicating positive and negative anomalies, respectively.

A distinct negative TEC anomaly (ionospheric hole) emerged ~6 min after the launch (Figure 3a). The hole expanded in the middle of the Yellow Sea (around 35°N, 124°E, ~500 km south of the launch pad; see Figure 3b). Next, we try to constrain the altitude of this hole. The distance between SIP and the ground GNSS

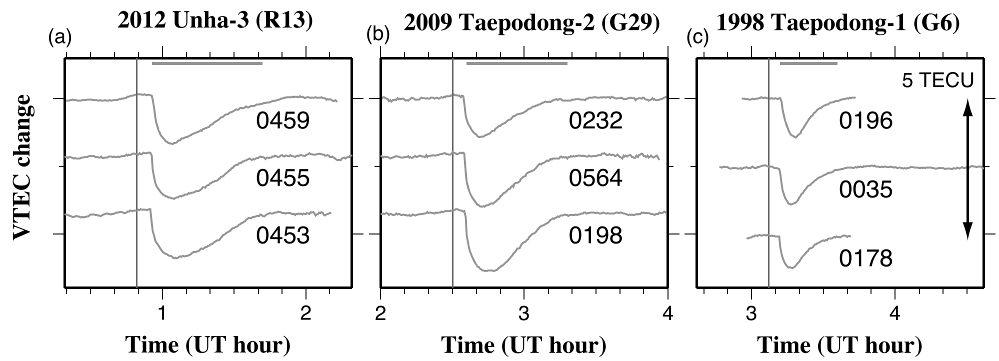

Figure 6. VTEC anomaly time series over 2 h time windows at three GNSS stations for the ionospheric holes made by the (a) 2012 Unha-3, (b) the 2009 Taepodong-2, and (c) the 1998 Taepodong-1 launches from North Korea. For the positions of the stations and SIP, see Figure 2 of this paper for the 2012 Unha-3 and Figures 7 and 11 of *Ozeki and Heki* [2010] for the 2009 and 1998 Taepodong cases, respectively. Vertical TEC values at the time of the launches are 15.0 TECU, 11.3 TECU, and 23.7 TECU for the three cases according to the Global Ionospheric Map. Horizontal gray bars at the top indicate the time intervals excluded in deriving the reference curves.

station depends on the assumed height of the thin ionosphere, i.e., lower altitudes make SIP closer to the station, or vice versa. *Ozeki and Heki* [2010] determined the hole altitude by correlating the hole images derived by two different satellites. Here we assume that the Unha-3 flew due south from the launch pad and examine which IPP height makes the hole signature coincide with this trajectory. Figure 4 compares SIPs calculated with ionospheric altitudes of 260 km (a), 280 km (b), and 300 km (c). The negative anomalies best coincide with the trajectory in (Figure 4b), i.e., the second stage of Unha-3 should have reached ~280 km when it traveled ~500 km from the launch pad. Because time lag between the missile passage and the hole formation is very small (see simulation results in *Furuya and Heki* [2008] and *Ozeki and Heki* [2010]), this would have happened ~6 min after the launch.

4. Comparison With the Earlier Missiles

Furuya and Heki [2008] simulated the development of ionospheric holes by the 2007 H-IIA launch by chemical reaction between the water vapor molecules and ionospheric ions and reproduced the observed ionospheric hole formation. *Ozeki and Heki* [2010] followed the same procedure and inferred numerically that the thrust power (assumed proportional to the number of water molecules per second in the exhaust) of the 2009 Taepodong-2 is 6 times as large as the 1998 Taepodong-1.

Figure 5 compares the ionospheric holes of the three cases of North Korean missiles/rockets drawn with the same scale for the same time epochs, i.e., 6, 10, and 20 min after the launch. Because the third case (2012 Unha-3) was a southward launch from western North Korea, the maps for this case (Figures 5a and 5b) were rotated counterclockwise by 90° to facilitate the comparison. In all the cases, ionospheric holes appear ~6 min after the launch with similar distances from the launch pads. Because these holes were made by the second-stage engines, the launch sequences of the first and second stages would have been similar.

Figure 6 compares the TEC behaviors in the three launches as time series. The size and depths of the hole in the 2012 case (Figure 6a) is larger than the 1998 Taepodong-1 (Figure 6c). The background electron density was higher in the 1998 case (VTEC was 23.7 TECU) than in the 2012 case (15.0 TECU) according to the Global Ionospheric Maps [*Mannucci et al.*, 1998]. Needless to say, the number of water vapor molecules in the 2012 case should have been much more than the 1998 case.

The VTEC time series in the 2009 and 2012 cases look more similar (Figures 6a and 6b). The hole remains within a few tens of kilometers around the trajectory just after its formation [*Furuya and Heki*, 2008]. Hence, the amount of initial TEC drop would be sensitive mostly to the electron density around the height of ~300 km and is roughly proportional to VTEC (see Figure 8 in *Ozeki and Heki* [2010]). Considering that the VTECs were 11.3 and 15.0 TECU for the 2009 and 2012 cases, respectively, the exhaust gas of the 2012 Unha-3 would have included water vapor molecules less than the 2009 Taepodong-2 by ~1/4.

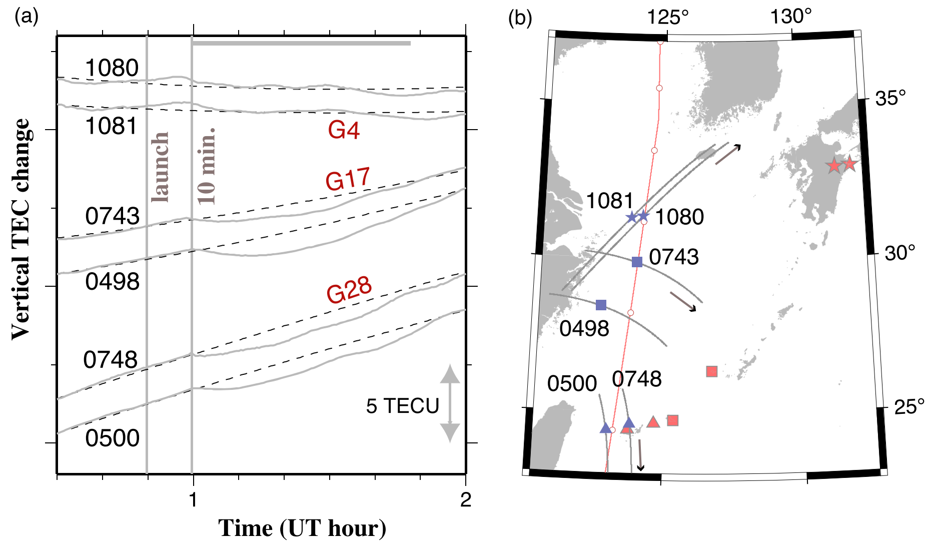

Figure 7. Time series of VTEC changes for (a) three GPS satellites, 4, 17, and 28. Quadratic polynomial functions (shown with dashed lines) are fit to the VTEC data 0.0–2.3 UT excluding 1.0–1.8 UT (shown as a gray bar at the top). G17 and G28 show clear electron depletion signatures starting 9–10 min after the launch. This is considered to be the ionospheric hole caused by the exhaust of the third-stage engine. (b) GNSS stations and SIP tracks are shown. SIPs were calculated assuming the ionospheric height of 400 km (G4), 450 km (G17), and 500 km (G28).

Although the hole signature lasts longer (~50 min) in the 2012 case (Figure 6a) than in the 2009 case (~35 min) (Figure 6b), we cannot consider the 2012 hole "larger" than the 2009 one. Because the SIP of GLONASS Satellite 13 moved toward SSW (Figure 1b), the line of sight would have kept penetrating the hole (elongated north-south) for a longer interval. In contrast, in the 2009 case, the southward moving SIP of GPS Satellite 29 has moved through the hole (elongated east-west) in a relatively short time. Considering the velocity of the IPP in the two cases, the horizontal dimension of the hole would be around 200 × 300 km elongated in the direction of the rocket ascent.

5. Ionospheric Hole Made by the Third-Stage Engine

In the case of the 1998 and 2009 launches, they failed to ignite the third-stage engines, and the third stage (possibly with payloads) splashed down to the Pacific Ocean east of NE Japan [*Brumfiel*, 2009]. A large advance in the 2012 launch is that they succeeded in separating and igniting the third-stage engine and putting a satellite into an orbit [*Ministry of Defense*, 2013]. Here we look for the electron depletion caused by the third-stage engine.

Figure 7 shows the VTEC change time series of the three GPS satellites whose LOSs pass by the trajectory after the second-stage engine made the ionospheric hole in the middle of the Yellow Sea. The VTEC values have been converted from STEC using the interfrequency bias information derived by *Sakai* [2005]. *Kakinami et al*. [2013] constrained the altitude of the rocket in the northern East China Sea as 400–450 km. In Figure 7, SIP tracks have been drawn assuming 400 km (Satellite 4), 450 km (Satellite 17), and 500 km (Satellite 28). GPS Satellite 4 might show a vague signature of VTEC decrease 7–8 min after the launch, but it is not clear enough. This is consistent with *Kakinami et al*. [2013], who did not find the electron depletion signature with the GPS Satellite 4.

Figure 7, however, show rather clear electron depletion signature starting ~10 min after the launch for GPS Satellites 17 and 28 further to the south. Because it is the third-stage engine that was burning at this time, this would indicate the ionospheric hole made by the third-stage engine. Satellite 17 received at 0743 shows TEC drop starting ~9 min after the launch. The onset is a little later in 0498 because of the distance from the trajectory. However, the hole signature is stronger in 0498 than in 0743. It is possibly because the LOS of the former moved toward the center of the hole after the onset, while the LOS of the latter simply moved apart from the hole.

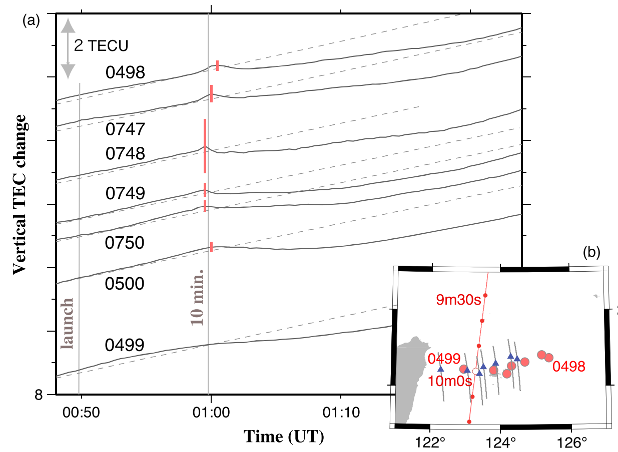

Figure 8. (a) Time series of vertical TEC changes observed at seven stations in the Sakishima Islands with GPS Satellite 28. Dashed lines are derived in the same way as Figure 7. Vertical separations between curves are nearly proportional to the longitude differences between the stations. Red vertical bars show the onset of the negative anomalies, and the length of the bars are proportional to the change of the rates between the 1 min intervals before and after the onset. (b) Onset is earlier in the stations with LOSs closer to the third-stage rocket trajectory. SIP tracks are calculated assuming the thin ionosphere as high as 500 km. Red circles on the rocket trajectories are 10 s time marks, and the large white circle shows the position at 10 min after the launch. Blue triangles on the SIP tracks are those at 10 min after the launch. In the westernmost station (0499), we could not see a sharp onset of the depletion.

In Figure 8, we compare onset times of the electron depletion in seven stations in the Sakishima Islands, western part of the Ryukyu Islands. The depletion seems to have started ~9.5 min in the central stations (e.g., 0748 and 0749), and it is ~1 min later in the easternmost station (0498). This time lag would reflect the time needed for water vapor molecules to diffuse from the rocket trajectory at the altitude of ~500 km. According to *Mendillo et al*. [1975], the water vapor molecules are tens of times as diffusive at 500 km altitude as at 280 km. However, further discussion (e.g., the consistency between the time lag and the diffusivity at this altitude) would be difficult because of the relatively long sampling interval at the GNSS stations (30 s) and the ambiguity in the trajectory altitude.

6. Conclusions

Here we studied ionospheric signatures of the three-stage rocket Unha-3 launched from North Korea on 12 December 2012, with a dense array of GNSS receivers in Japan. We summarize the results as follows.

1. Ionospheric hole slightly smaller than the 2009 Taepodong-2 was found with a GLONASS satellite. It emerged ~6 min after the launch as the region of negative TEC anomalies above the middle of the Yellow Sea.
2. Judging from the depth of the ionospheric hole (i.e., the amount of VTEC drops) and the background TEC, thrust power of the second-stage engine of the Unha-3 rocket would be ~3/4 of the 2009 Taepodong-2 missile.
3. The electron depletion signatures made by the third-stage engine of the Unha-3 rocket are confirmed to have been formed above the southern East China Sea and the Sakishima Islands starting 9–10 min after the launch.

Acknowledgments
We thank the three anonymous reviewers for their constructive comments and Geospatial Information Authority of Japan (GSI) for making GEONET data available online.

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