Small-Scale Ionospheric Irregularities of Auroral Origin at Mid-Latitudes during the 22 June 2015 Magnetic Storm and Their Effect on GPS Positioning

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Received: 16 April 2020; Accepted: 14 May 2020; Published: 15 May 2020

Abstract: Small-scale ionospheric irregularities affect navigation and radio telecommunications. We studied small-scale irregularities observed during the 22 June 2015 geomagnetic storm and used experimental facilities at the Institute of Solar-Terrestrial Physics of the Siberian Branch of the Russian Academy of Sciences (ISTP SB RAS) located near Irkutsk, Russia (~52°N, 104°E). The facilities used were the DPS-4 ionosonde (spread-F width), receivers of the Irkutsk Incoherent Scatter Radar (Cygnus A signal amplitude scintillations), and GPS/GLONASS receivers (amplitude and phase scintillations), while 150 MHz Cygnus A signal recording provides a unique data set on ionosphere small-scale structure. We observed increased spread-F, Cygnus A signal amplitude scintillations, and GPS phase scintillations near 20 UT on 22 June 2015 at mid-latitudes. GPS/GLONASS amplitude scintillations were at a quiet time level. By using global total electron content (TEC) maps, we conclude that small-scale irregularities are most likely caused by the auroral oval expansion. In the small-scale irregularity region, we recorded an increase in the precise point positioning (PPP) error. Even at mid-latitudes, the mean PPP error is at least five times that of the quiet level and reaches 0.5 m.

Keywords: small-scale irregularities; ionospheric scintillations; spread-F; S4; geomagnetic storm; precise point positioning

1. Introduction

Small-scale ionospheric irregularities affect radio telecommunications, because those irregularities can scatter electromagnetic signals [1]. The most pronounced effect is observed when the irregularity scale is of the radiowave’s first Fresnel zone $\sqrt{\lambda z}$ (where $\lambda$ is the signal wavelength, $z$ is the distance to the irregularity). The scattering leads to radio signal amplitude scintillations that deteriorate the quality of global navigation satellite system (GNSS) operation. In the extreme case, irregularities may even cause losses-of-lock [2] and interrupt positioning services.

Intensive amplitude scintillations and GNSS signal losses-of-lock are usually observed in the high-latitude and equatorial ionosphere [3–8], where irregularities are effectively generated. Equatorial small-scale irregularities are usually seen as spread-F on ionograms. Hence, a long-term history of irregularity observations is provided by ionosondes [9–11]. At the same time, there are
studies showing that such irregularities could exist in the mid-latitude ionosphere [12–14]. The auroral oval broadening is a reason for an irregularity to be generated at the middle latitudes [15,16]. Another reason is a large-scale ionospheric structure (including traveling ionospheric disturbances (TIDs) [17]) that appeared outside the mid-latitude region and traveled down to mid-latitudes. For example, an equatorial super plasma bubble can penetrate into the mid-latitude ionosphere [18] and produce small-scale irregularities that manifest themselves as the GPS losses of phase lock [19]. However, there is no large amount of amplitude scintillation data at mid-latitude. This is due to a small number of facilities at the mid-latitudes and insufficient coverage of the radio observations.

Several approaches have appeared recently to overcome this problem. One of them concerns indirect measurements. The Low Frequency Array (LOFAR) project [20] reveals a promising capability. Another approach is measuring scintillations of discrete space radio sources by incoherent scatter radars. The latter approach has been developed at the Institute of Solar-Terrestrial Physics of the Siberian Branch of the Russian Academy of Sciences (ISTP SB RAS) [21] and enables researchers to obtain unique data.

The small-scale irregularities (the first Fresnel zone scale) almost do not affect the carrier phase. It is due to power-law dependence of ionospheric irregularities amplitudes. Yeh and Liu [1] showed that only irregularities with the size 10−10 2 times greater than those of the first Fresnel zone have a noticeable effect on the phase. It is conventional to study small-scale irregularities with instruments operating at wavelength within the meter-decimeter range. However, such an approach provides the information only on a small part of the irregularity spectrum. To get a comprehensive study, one should employ instruments capable of sensing various part of the irregularity spectrum simultaneously.

The 22-23 June 2015 geomagnetic storm was “an anomalously intense event with large magnetic fields” [22]. It was one of the most intense storms of solar cycle 24 [23]. A number of significant papers have described and analyzed this event. Astafyeva et al. [23] observed an extreme enhancement of the electron density Ne and vertical total electron content VTEC in the Northern (summer) Hemisphere. They concluded that the extreme topside response was the result of a combination of the prompt penetration electric fields, disturbance dynamo, and the storm-time thermospheric circulation. Astafyeva et al. [24] studied global the ionospheric and thermospheric effects of the storm. They found that dayside neutral mass density increased by three to five times as compared to the quiet time level. Astafyeva et al. [25] studied the equatorial electrodynamics. They found an increase in the eastward electric field and in the upward E×B drift on the dayside (which led to rapid strong enhancement of the VTEC and electron/ion density), as well as downward vertical drift with a decrease in the VTEC and in the plasma density on the nightside. Singh and Sripathi [26] studied small-scale structures in the equatorial region. They suggested that the westward penetration of the electric field into the equatorial sector during the local midnight caused an abrupt decrease in the virtual height to ~200 km and suppressed plasma bubbles in the Indian sector. Comprehensive analysis was carried out by Piersanti et al. [27] who showed an increase in the ionospheric polar convection and an expansion of the lower boundary of the convection region toward low latitudes (from 60°N to 50°N).

Geomagnetic storms and TIDs are also known as sources for GPS positioning quality deterioration. GPS scintillations lead to a range error in GNSS due to diffraction [28]. Deep signal fades that appear during small-scale irregularities effect result in navigation outages [29]. Luo et al. [30] studied several strong storms during solar cycle 24, including the 17 March 2015 St. Patrick storm. They reported that the precise point positioning (PPP) error was less than 0.32 m at mid-latitudes.

In this paper, we study small-scale structures at mid-latitudes during the 22 June 2015 magnetic storm. The mid-latitude irregularity formation mechanism is not quite clear. We have tried to fill the knowledge gap by recording new scintillation data in different frequency bands at mid-latitudes. The data help to reveal physical mechanism for the irregularity generation in the mid-latitude ionosphere. Another point is to reveal how the irregularities affect GPS precision during the storm.

2. Experimental Facilities and Data
We used the ISTP SB RAS facilities to comprehensively study small-scale irregularities. We employed the S4 index [31] to study amplitude scintillations and $\sigma_\phi$ [32] to study phase scintillations. We used the spread-F [33] width to study irregularities within the ionosonde wavelength range. The S4 index is the signal intensity $E$ standard deviation normalized to the average signal intensity:

$$S4 = \frac{\sqrt{\langle E^2 \rangle - \langle E \rangle^2}}{\langle E \rangle}.$$

(1)

The $\sigma_\phi$ index is simply the carrier phase $\phi$ standard deviation:

$$\sigma_\phi = \sqrt{\langle \phi^2 \rangle - \langle \phi \rangle^2}.$$

(2)

The spread-F width is the measure of trace broadening on an ionogram near the ionosphere peak.

Below, we describe the instruments and data:

1) Ionosonde DPS-4 [34] enabled us to measure the spread-F width. We used the ionosonde located in Irkutsk – IR352 (52.3°N, 104.3°E; red star in Figure 1), at ~48° magnetic latitude. We manually scaled the ionograms to obtain the spread-F width. The ionosonde antenna is not typical. This did not enable us to measure the directions of signal receiving. During the geomagnetic storm, the ionosonde in Irkutsk was operating with a 15-min cadence. Additionally, we analyzed data from the ionosondes in Norilsk—NO369 (69.4°N, 88.1°E), Yakutsk—YA462 (62.0°N, 129.7°E), Mohe—MH453 (52.0°N, 122.5°E), and Moscow—MO155 (55.47°N, 37.3°E). As the ionosonde records the spread-F within ~3–10 MHz at 200–300 km, the irregularities that primarily affect the ionosonde signal have sizes 2.5–5 km.

2) Irkutsk Incoherent Scatter Radar (IISR) [35]. The IISR is located next to Irkutsk (52.9°N, 103.3°E; red star in Figure 1), at ~49° magnetic latitude. Its radiation pattern center is at 52.6°N, 102.9°E. The IISR receivers enabled us to measure scintillations of discrete space radio sources, when they crossed the radar sector of view [21]. In our experiments, we recorded the Cygnus A signal. Cygnus A is the most powerful radio galaxy in our part of the Universe. Cygnus A emits in a broad frequency band including the IISR frequency band (154–162 MHz). We should note that the radiation pattern is shown for the chosen frequency. By changing the frequency, we changed the radiation pattern, and thus could track the radio source [21].

Unfortunately, during the storm, the IISR was operating in passive mode. So, we have no corresponding electron density profiles or ion velocities. The highest temporal resolution for measurements in the passive mode is of the order of seconds. We used the 4.5-s resolution data. The integration time for the S4 index calculation is 1 minute. Since the IISR operates at ~150 MHz, at 100–300 km, the size of the irregularities primarily affecting the IISR signal amplitude is 400–800 m.

3) GPStation-6 specialized GPS/GLONASS receiver. The receiver is located in Irkutsk (52.3°N, 104.3°E; red star in Figure 1), at ~48° magnetic latitude. GPStation-6 receiver enabled us to measure the amplitude scintillations intensity, S4, and phase variations, $\sigma_\phi$ [36]. The data sampling rate used for the S4 and $\sigma_\phi$ calculation is 50 Hz (0.02-s resolution). The integration time for the S4 and $\sigma_\phi$ is 1 minute. The S4 and $\sigma_\phi$ measured by GPStation-6 were transformed into equivalent vertical values [37]. The GPStation-6 receives signals within the L1 and L2 bands for all the GPS/GLONASS satellites. There is an option with some satellites to receive a third frequency band, L5 and L3 for GPS and GLONASS, respectively. As receivers operate at ~1.6/1.2 GHz (L1/L2) at 100–300 km, the size of the irregularities primarily affecting the navigation signal amplitude is 100–300 m.
Additionally, we used the total electron content (TEC) variations obtained by using the dual frequency GPS/GLONASS phase measurement. The technique for the TEC calculation is well-known [38–40].

\[
I = \frac{1}{40.308} \frac{f_2^2 - f_1^2}{f_1^2 f_2^2} \left[ L_1 \lambda_1 - L_2 \lambda_2 + \text{const} + \sigma \phi \right],
\]

where \( L_1 \lambda_1 \) and \( L_2 \lambda_2 \) are the radio signal carrier phase ranges including ionospheric delay (m), \( L_1 \) and \( L_2 \) are a number of phase rotations at \( f_1 \) and \( f_2 \) frequencies; \( \lambda_1 \) and \( \lambda_2 \) are corresponding wavelengths; \( \text{const} \) is an unknown initial phase ambiguity (m); and \( \sigma \phi \) is a term corresponding to noise in phase measurements (m). By convention, 1 TEC Unit (TECU) = 10\(^{16}\) electrons/m\(^2\).

We used the data from 5172 receivers of the global and regional GPS/GLONASS receiver networks (see Acknowledgments), including the IGS [41], UNAVCO, SONEL, etc., as well as the regional data, like SibNet [42], CHAIN [43], EUREF [44] HIVE (https://hive.geosystems.aero/), etc. Blue dots in Figure 1 show the location of the used receivers.

Single cycle slips in the TEC data were eliminated by the formula:

\[
\text{TEC}(i) = \text{TEC}(-1) + \text{TEC}(i) - \text{TEC}(0) + \frac{\text{TEC}(-1) - \text{TEC}(-2)}{2} + \frac{\text{TEC}(1) - \text{TEC}(0)}{2}.
\]

where \( i \) is the time instance after a cycle slip, \( \text{TEC}(0) \) is the TEC value, when the cycle slip is recorded, \( \text{TEC}(1) \) corresponds to TEC records after cycle slip, \( \text{TEC}(-2) \) and \( \text{TEC}(-1) \) correspond to two TEC records before the cycle slip occurred. We used an approximation that the time derivative equals the mean derivative before the cycle slip and after it. A similar approach was used to eliminate loss-of-lock effects.

Variations in TEC within 15 min–3 hours correspond to TIDs and other wave-like ionospheric disturbances. As TEC variations, we considered detrended and filtered TEC values. We performed the following procedure [45]. We detrended TEC data based on smoothing spline. After this, we used the running average with a 10–20 min (20–60 min) window to filter variations corresponding to medium-scale travelling ionospheric disturbances. Thus, we obtained the TEC variations series \( dI \). We used a single layer model [46] as a mapping function to reduce TEC variations’ dependence on the elevation angle. We mapped the variations on the globe given the ionospheric pierce point location and obtain the global spatial distribution of TEC variations [40]. We marked each ionospheric
pierce point (at 300 km height) with the color corresponding to the TEC variation value. All calculations of TEC variations were performed by SIMuRG (https://simurg.iszf.irk.ru) [47].

5) To estimate the GPS precision, we calculated the station coordinates in the kinematic GPS dual-frequency precise point positioning (PPP) mode. For that purpose, we used the GAMP open-source software [48]. Receiver and satellite clock offsets were considered in GAMP PPP solution by applying IGS precise satellite orbit and clock products. In addition, using linearized equations of original pseudorange and carrier phase observations, GAMP considers line-of-sight (LOS) ionospheric delay, receiver non-calibrated code delay, receiver and satellite non-calibrated phase delays, and zenith wet delay. We used a dual-frequency PPP model, in which the receiver non-calibrated code delays are absorbed by both receiver clock offset and LOS ionospheric delay parameters. The 24-hour median values of X, Y, Z coordinates for a station were regarded as reference positions. The positioning error was calculated as the difference between the reference and the instant position

$$\sigma = \sqrt{\Delta X^2 + \Delta Y^2 + \Delta Z^2}. \quad (5)$$

By using the worldwide GNSS network, we can obtain the accuracy of the positioning distribution similar to that in [49].

3. Results

3.1.22. June 2015 Geomagnetic Storm

The storm is related to active region (AR) 12,371 on the Sun according to the SOHO LASCO CME catalog (https://cdaw.gsfc.nasa.gov/CME_list/; SOHO—the Solar and Heliospheric Observatory, LASCO—the Large Angle and Spectrometric Coronagraph, CME—Coronal Mass Ejection). The AR produced several CMEs. The 22 June 2015 magnetic storm is mainly due to ~1350 km/s Halo CME that appeared at 2:36. The CME with kinetic energy of ~9.0 $\cdot$ 10$^{31}$ erg (http://cdaw.gsfc.nasa.gov/CME_list/) is associated with an M2.7 flare with maximum at 02:34 UT. On June 22, a cluster of shocks passed the Advanced Composition Explorer (ACE) spacecraft at 17:58 UT [22]. Figure 2 presents time series of the data to help tracking storm evolution. We see a sharp increase in the proton density (Figure 2c) and a sudden storm commencement (SSC) (Figure 2a) at ~05:45 and ~18:30 UT on June 22, when the shocks hit the Earth’s magnetosphere.

The data presented in Figure 2 (Bz component of the interplanetary magnetic field (IMF), H-SYM index, AE-index, and proton density) were retrieved from the OMNI database (ftp://spdf.gsfc.nasa.gov) [50]. The spread-F (Figure 2c, red line) was measured based on the Irkutsk ionosonde data. As the shock hits the 22 June 2015 magnetosphere at 18:30 UT, we see the storm onset as a SSC, and the H-SYM index starts decreasing. The proton density changed from 12 cm$^{-3}$ (before the shock) to 52 cm$^{-3}$ (after the shock). The H-SYM had a local minimum (135 nT) at 20:15 UT. After 20:15 UT, the magnetosphere was recovering. The recovery of the magnetosphere lasted until 00:50 UT, when Bz turned south again, and the proton density decreased to ~9 cm$^{-3}$. The minimal H-SYM was observed at 04:25 UT with the value of ~207 nT. We should note that the substorm occurred before the storm. The AE-index shows an increase after 14 UT on June 22. H-SYM dropped to ~50 nT at ~16:15 UT.
Figure 2. Evolution of the 22 June 2015 geomagnetic storm from the OMNI data. Panel a: H-SYM index (black line) and the interplanetary magnetic field (IMF) Bz component (blue line). Panel b: AE-index. Panel c: solar wind proton density (black line) and spread-F width (red line). Spread-F data are provided for the Irkutsk ionosonde (52° N, 104° E).

3.2. Spread-F and Scintillations

Figure 3 shows the experiment geometry. The left panel shows the GPS ionospheric pierce points (IPP) at 300 km as black lines with 10–20 minute TEC variations superimposed, red curves, at 19:30–20:30 on 22 June 2015. The vertical segment in the right bottom part of panel (a) shows 0.5 TECU variations. The data shown are measured by the ISTP SB RAS station within the SibNet. The TEC variations are shown only for four satellites (PRN15, PRN20, PRN21, PRN22). The right panel shows the geometry in details. Black lines show the GPS IPP (the same as on the left panel). Gray lines show the IPP of Cygnus A at 100, 250, and 400 km for the IISR location that is 60 km away from the ISTP SB RAS station. Filled gray region and filled blue region are approximate radiation patterns (at 250 km) of the ionosonde and of the IISR, respectively. The ionosonde was not capable of measuring the direction of the received signals during the interval of interest. Thus, we only can attribute the spread-F data to somewhere in the gray region. Figure 3 allows us to see that the measurements are almost in the same region.

We observed the spread-F on 22 June 2015 (Figure 2b) rather than on 23 June 2015. Note that, when the 22 June 2015 H-SYM is minimal at 04:25 UT, there was no noticeable spread-F (Figure 2b). There were occasional black-outs that prevented reliable processing of the ionograms. However, when there is no black-out, there is still no spread-F on the ionograms. The solar wind proton density at this time was even smaller than that of the quiet time. This leads to a smaller energy input into the auroral region; hence, no large-scale disturbances exist and no small-scale irregularities are generated.
Figure 3. Experiment geometry. Panel (a) shows the GPS IPP (black lines) at 300 km and 10–20 min total electron content (TEC) variations (superimposed red lines) within 19:30–20:30 UT on 22 June 2015. Panel (b) shows the geometry in details. Black lines show the GPS IPP at 19:30–20:30 UT. Gray lines show the Cygnus A ionospheric pierce point at 100, 250, and 400 km. On both panels, the filled grey region is the ionosonde approximate radiation pattern, the filled blue region is the IISR approximate radiation pattern. Vertical segment in the right bottom part of the panel (a) shows 0.5 TECU variations.

Figure 4 shows the spread-F width time series from the ionosondes in Irkutsk (a) as well as in Yakutsk, Mohe, and Moscow (d). Panel b shows phase scintillations $\sigma_{\phi}$ calculated by using observations from all the visible GPS satellites (all the GPS satellite data are mixed here), and Cygnus A radio signal amplitude scintillations (c). The 22 June 2015 data are plotted for 15:00 – 24:00 UT. On the panel c, we also show the 24 June 2015 data (grey) as a quiet time reference. Dashed-dotted line shows the angle $\gamma$ between the “IISR – Cygnus A” line of sight and the Earth magnetic field calculated based on the IGRF−12 model [51].

We see the spread-F enhancement 19:45 UT through 21:15 UT in Irkutsk. After the magnetic storm onset, the spread-F was at the background level for an extra hour. The background was ~0.08 MHz, while the maximal spread-F width was 0.46 MHz at 20:15 UT. We also observed a $\sigma_{\phi}$ increase for ~19:30–19:50 UT. The $\sigma_{\phi}$ mean value was 0.07 rad, with ~0.1–0.2 rad during the enhancement. We did not observe any significant increase in the GPS/GLONASS navigation signal amplitude scintillation. During the time interval presented in Figure 4, the S4 index did not exceed the background level, and, hence, we do not show the GPS/GLONASS S4 here.

Unfortunately, there are no observations from the Norilsk ionosonde during the storm. Black-out caused by strong absorption in the D-region started shortly after the SSC and prevented collecting useful information from the ionograms. However, we were able to retrieve the data for the ionosondes (see Figure 4d) in Yakutsk (blue line), Mohe (black line), and Moscow (red line).

The spread-F is observed at all the stations. A strong spread-F appears at the similar time at Mohe and Moscow. Also, the time was close to that when we observed the spread-F at Irkutsk (20:15 UT, 22 June 2015). Small deviations for the Moscow station are explained by its slightly higher latitude than that of Irkutsk and Mohe. There is no noticeable spread-F appearance dependence on the longitude. At Yakutsk, the spread-F is observed early, which we attribute to a higher latitude of that station as compared to others. The above (Section 3.1) substorm results in spread-F at Yakutsk latitude before the main storm onset.
Figure 4. Effects of ionospheric irregularities on different-band radio signals. Panel a presents the spread-F at the Irkutsk ionosonde; panel b displays the $\sigma_F$ for the L1 GPS signal; panel c reflects the Cygnus A radio amplitude scintillations from the Irkutsk Incoherent Scatter Radar (IISR) data; panel d shows spread-F. Panel d shows data for the ionosondes in Yakutsk (YA462, 62.0°N, 129.7°E; blue line), Mohe (MH453; 52.0°N, 122.5°E; black line), and Moscow (MO155; 55.47°N, 37.3°E; red line) during the 22 June 2015 magnetic storm. The horizontal line on panel d shows 0.5 MHz. The black lines and the histogram on panels a-c show the 22 June 2015 data, the gray line on the panel c shows the 24 June 2015 data (reference day). The dashed-dotted line in panel c shows the angle $\gamma$ between the “IISR—Cygnus A” LOS and the Earth magnetic field. The dashed lines mark 19:30 UT, 20:15 UT, 21:30 UT.

The Cygnus A was observed within the radar field of view 17:00 through 22:00 UT. The Cygnus A signal scintillation index $S_4$ was calculated by using formula (1). Figure 4c shows the result. The black continuous line shows the 22 June 2015 data. On 22 June 2015, the $S_4$ first increase was observed between 18:30 and 19:30 UT. A similar increase was recorded on 24 June 2015, the day that was chosen as a reference day (grey line). The increase corresponds to the angle $\gamma$ minimum, i.e., it is the magnetic
zenith effect. Such an effect is regularly observed in the IISR scintillation data and fades quickly, when the angle between the LOS and the magnetic field exceeds 10° [52]. The highest S4 for Cygnus A was observed around 20:00 UT. It coincides with the time, when the enhanced spread-F was observed. The scintillation intensity dropped at 20:30 UT, while the spread-F lasted for an extra hour.

3.3. Precise Point Positioning

To estimate the GPS positioning accuracy, we calculated the PPP error (5) for the worldwide network. The dynamics for the PPP error spatial distribution can be found in the Supplementary Materials (Video S1). Figure 5 shows the average PPP error vs. latitude. The latitude bin size is 2.5°. PPP errors are averaged over −0°…180° (European-Asian sector, upper panels a-b) and −180°…0° (American-Atlantic sector, bottom panels c-d). The dashed line on panels b and d marks 18:30 UT. Panels a and c show the data for the reference day (21 June 2015, 172nd Day of the Year, DOY), while panels b and d show the data for the 22 June 2015 storm (173 DOY).

The results for the reference day show that the PPP error increases due to satellite geometry or data processing peculiarities. Such effects have similar patterns for both the storm and the reference days. For example, there is a PPP error increase at ~10UT in the Northern Hemisphere. Note that, over 0–1(2) UT, the quality of the PPP solution obtained by the GAMP software is significantly worse than that at other times. So, we do not consider this time. In Figure 5, the navy blue regions (zero values) mark lack of the data. Data gaps can be seen on both the reference and the storm days. One can see such patterns at the North Pole region, as well as at ~60°S, where there are no stations for calculations.

![Figure 5. Average precise point positioning (PPP) error (obtained by GAMP software) vs. latitude. The latitude bin size is 2.5°. The longitude region was 0°…180° (European-Asian sector, upper panels a-b), −180°…0° (American-Atlantic sector, bottom panels c-d). The dashed line on panels b and d marks 18:30 UT. Panels a and c show the data for the reference day (172 DOY), while panels b and d show the data for the 22 June 2015 storm (173 DOY).](image-url)
The typical average errors are less than 0.5 m (and even less than 0.1–0.3 m). From Figure 5, in the Northern Hemisphere after 18:30 UT (dashed line), one can see a sharp decrease in the PPP quality at 65–75°N. The error exceeded 0.5 m. So, we recorded a precision deterioration, which results in fivefold worse positioning accuracy. There is an equatorward “propagation” of the error with time. In the American-Atlantic sector (Figure 5d), we can observe such a “propagation” as far as ~50°N. The PPP error maximum appears at ~20 UT at this latitude. In the European-Asian sector, we observed a similar pattern with an increased error at ~20 UT, but not in such details due to fewer stations. There is a signature that propagated to the equatorial region in the Northern Hemisphere, but the effect is not so pronounced, and it is observed during the reference day.

4. Discussion

Using the data from Figure 4, we can conclude that, during the geomagnetic storm, 500–5500 m small-scale irregularities were present in the ionosphere. The absence of the GPS/GLONASS amplitude signal scintillations means that there were no intensive irregularities with corresponding scales. The ionospheric irregularity amplitude exponentially decreased as the irregularity size decreased [1,53]. That is why there were no significant 100–300 m irregularities.

We also examined mechanisms for the existence of such intensive small-scale irregularities. We had two hypotheses. The first possible mechanism is an expansion of the auroral oval toward mid-latitudes, so we would observe auroral phenomena at mid-latitude stations. Particle precipitation results in local increases and decreases in the plasma density more than 10 km wide. Such structures can be cascaded into smaller scales through instability processes and turbulent diffusion [54]. The 0.1–30 km irregularities are generated at high latitudes mainly due to ExB instability [55]. Also, the thermomagnetic instability can produce F-region 1 km-scale irregularities at high-latitudes [56].

The second mechanism suggests generation of small-scale irregularities due to passage of a medium-scale (MS) TIDs [57]. For example, generating medium-scale irregularities due to the large-scale disturbance passage was mentioned by Astafyeva et al. [16]. Astafyeva et al. [16] found medium-scale 2–10 min irregularities, when a well-distinguished strong disturbance of the 40-min time scale passed by. There are a number of papers by G.G. Bowman focusing on the spread-F caused by TIDs. Bowman and Mortimer [58] showed that, during the passage of a large scale TID, the average ionospheric F2 layer height rises. Bowman [17] showed that the spread-F observed in equatorial regions several hours after increased geomagnetic activity is directly related to ionosphere height rise. Studies by Farley et al. [59] indicated that a favorable condition for the instability growth is induced rise of the ionosphere height. The “rise-in-the-ionospheric-layer-height” mechanism, which makes the spread-F observable at equatorial stations, may also produce the spread-F at mid-latitudes [58]. In fact, gravity waves are the prevailing source for both MS TIDs and small-scale irregularities [60]. Gravity waves induce currents that drive plasma instability.

To find a proper mechanism, we used, first, the OVATION model data and the SuperDARN data to estimate the oval boundary dynamics and its correspondence with the observed small-scale irregularity appearance. Second, we studied the global distribution of TEC variations. On the one hand, the global TEC variations maps can reveal TID origin and propagation. On the other hand, the maps provide some evidence of small-scale structure development. Third, we analyzed the changes in PPP error over the globe. An increase in the PPP error and its localization can provide additional information about the source of the recorded small-scale irregularities.

To study oval expansion we used the OVATION prime energy flux data (not shown here) (http://iswa.gsfc.nasa.gov; https://sourceforge.net/projects/ovation-prime/) [61]. For the time interval of interest, the oval boundary did not reach 52°N for the Asian sector. However, the OVATION is a model and cannot represent the actual precipitation (especially during such intensive storms). Based on SuperDARN data, Piersanti et al. [27] studied the polar convection for this very storm and concluded that the auroral oval expanded to ~50°N (we should note that it is magnetic latitude). We also used the SuperDARN data to study this expansion in detail. The data are available at http://vt.superdarn.org/[62]. Figure 6 shows the maps for the electric potential from SuperDARN for
18:30 UT (a), 18:40 UT (b), 19:00 UT (c), 19:30 UT (d), 20:00 UT (e), 20:30 UT (f), 21:00 UT (g), 21:30 UT (h). Green dashed curve shows the Heppner–Maynard boundary.

From Figure 6 one can see that, after 18:30 UT, the expansion of auroral oval started. In the Irkutsk sector (look for Lake Baikal at the map bottom), the Heppner–Maynard boundary reached 50° magnetic latitude at ~19:00 UT and persisted at this position until ~21:30 UT. Over that time, the boundary approached and then moved away from the facilities without reaching them. However, the boundary was very close to the radiation patterns of the instruments that we used (Figure 3). The ionosonde has wider radiation patterns. So, it was able to record more reflections from small-scale structures due to the expanded oval than the Irkutsk incoherent scatter radar was. The difference in the observation time seems to be related to the radiation pattern difference. This point proves the hypothesis that the oval expansion is the reason for generating small-scale irregularities.

Another hypothesis is that small-scale irregularities are caused by the passage of a large-scale disturbance. We assume that a small-scale irregularity source is originated in the auroral area and then travels down to mid-latitudes. To prove this, we used TEC variation maps (see Experimental Facilities). On these maps, the TEC variation amplitude is plotted. The point positions correspond to the ionospheric pierce points (300 km height). Figure 7 shows the 10–20 min TEC variations maps for 18:30 UT (a), 19:00 UT (b), 19:30 UT (c), 20:00 UT (d), 20:30 UT (e), 21:00 UT (f). Figure 8 provides similar maps, but for 20–60 min TEC variations. For reference, we provide the movies that illustrate the global spatial-temporal distribution of the 10–20 min and 20–60 min TEC variations for 17:00–24:00 UT at 1-min time resolution (see Supplementary Materials, Videos S2 and S3).

There are always sporadic disturbances in the auroral oval that do not form any pronounced structures. We can clearly see this before the storm from Videos S2 and S3. After the storm onset at 18:30 UT, we see a large-scale well-defined negative disturbance that covers all longitudes. Later, we see a positive disturbance. We can see a long negative front at 19:30 UT reaching the northern part of the Irkutsk region. Maps of 20–60 min TEC variations show an extended sharp “edge” in the European-Asian region. The “edge” dynamics corresponds to that for the Heppner–Maynard boundary from the SuperDARN data.

The 10–20 min TEC variation dynamics (Video S2) show that, in the European-Asian region, the irregularities of the auroral origin (“irregularity cloud”) approached 50°N. The same spatial limit is seen from maps of 20–60 min TEC variations. This agrees with the results in Figure 2 (left panel), where TEC variations exceeding 0.1 TECU were recorded only for the IPPs located northward 52°N. These auroral-origin irregularities, presumably, are manifestation of delayed instability development in the auroral oval. The recorded TEC variations (Figure 2b, Figure 7, Figure 8) can be related to the movement of the boundary with an increased ionization level. We should also note that the polar cap features smaller TEC variations. Along with the propagation of the auroral–origin boundary, we can see the polar cap expansion.

After ~19:20 UT, we can observe an appearance of large-scale TID, close to the position of the “edge” related to the oval expansion. Thus, there were observed both auroral oval expansion and TID generation on the auroral oval boundary. We should note that it is difficult to definitely separate these two phenomena due to the complexity of the considered event.
Figure 6. Maps for the electric potential from the SuperDARN data for 18:30 UT (a), 18:40 UT (b), 19:00 UT (c), 19:30 UT (d), 20:00 UT (e), 20:30 UT (f), 21:00 UT (g), 21:30 UT (h). Green dashed curve shows the Heppner–Maynard boundary.
Figure 7. Maps of 10–20 min TEC variations for 18:30 UT (a), 19:00 UT (b), 19:30 UT (c), 20:00 UT (d), 20:30 UT (e), 21:00 UT (f). Scale is shown at the bottom in TECU units.
We recorded a TID in the Northern Hemisphere with an extended wave front. In Figure 7f, we see large positive TEC variations crossing the equator in the American region. According to the movie (see Supplementary Materials, Videos S2 and S3), the disturbance originated in the Northern Hemisphere, crossed the equator, and reached ~40°S. The disturbance, hence, travels more than 10,000 km from its source. The disturbance can be seen in the American and Australian longitude sectors, which implies that it is ~200° wide in longitude. It can be clearly identified in the American-
Atlantic region, especially, when it was reaching the equatorial region (see Figure 7e, Figure 7f). TID is also seen over the European region, and a part of its structure can be found over Northern Africa. It is difficult to clearly identify TID southward over the Northern African and Asian regions due to low data coverage.

Finally, we can compare the TEC variations maps with the maps for the PPP quality. The observed PPP error does not coincide with the sharp oval extension (Figure 6). The oval reached 50° magnetic latitude in the Asian sector quickly, while the PPP deterioration at such latitudes was recorded only at ~20 UT. However, TEC variation maps (Figure 7, Figure 8 and Movies S1, S2) also show a gradual propagation of irregularities from the oval. Moreover, in the American sector, we do not observe any “propagation” of the PPP error to the Southern Hemisphere, as we observe for TIDs. If the TID was the source for scintillations resulting in enhancement in PPP errors at mid-latitudes, we would expect to see an increase in PPP error along the TID propagation trajectory. However, we did not observe any “propagating” pattern (up to the Southern Hemisphere) in PPP error distributions. While this is not an incontrovertible conformation, it indirectly indicates that TID propagation is not a source for the increase in PPP error (and scintillations). In contrast, this is additional evidence in favor of the auroral oval expansion mechanism for the revealed small-scale irregularities.

Thereby, the auroral oval expansion and the development of small-scale structure seem to be a more preferable mechanism to produce the observed small-scale irregularities at mid-latitudes. The irregularities lead to increased phase scintillations of navigation signal. The increase is more pronounced at the start of the irregularity formation. Phase scintillations decay very quickly. We observed spread-F, Cygnus A signal amplitude scintillations, and GPS phase scintillations simultaneously. The spread-F width maximum was recorded after the GPS phase scintillations recover their background level. The ~2.5–5.5 km irregularities (ionosonde) seem to persist over the entire interval, when the spread-F is observed. The ~400–800 m irregularities (IISR) emerged after the GPS phase scintillations started and ended before the enhanced spread-F ended. We refer the absence of the GPS signal amplitude scintillations to the exponential shape of the irregularity spectrum. Consequently, the irregularities with the size proper for a significant effect on the navigation signal had too low amplitudes to affect the latter.

The results on the PPP error agree, in general, with those obtained by Luo et al. [30]. However, while Luo et al. [30] reported a <0.32 m PPP error, we recorded a higher error (>0.5 m) even at mid-latitudes. We recorded, at least, the GPS positioning error being five times increased at mid-latitudes during several hours of the storm.

5. Conclusions

We observed small-scale irregularities as the 22 June 2015 geomagnetic storm evolved. We used spread-F data from ionosonde, and the Cygnus A signal amplitude scintillation data from IISR. The most pronounced effect is observed when the irregularity scale is of the radiowave first Fresnel zone ∼√λz (where λ is the signal wavelength, z is the distance to the irregularity). An approximate distance z is ~100(IISR)/200(ionosonde)−300 km. As the ionosonde recorded F-spread within the 3–10 MHz band and the Cygnus A signal frequency is 150 MHz, the irregularity size is within ~0.5 km (IISR) and ~5.5 km (ionosonde) range.

The exponential behavior of the irregularity spectrum explains why we did not observe noticeable GPS/GLONASS signal amplitude scintillations. It also explains why the ionosonde signal scintillations were more pronounced than those of Cygnus A (received by IISR). In addition, a longer observation time of small-scale irregularities by the ionosonde may be connected to the radiation pattern difference (ionosonde has a wider radiation pattern than the IISR).

The spatial distribution of the TEC variations and the maps for the electric potential from the SuperDARN data revealed that small-scale irregularities are most likely caused by an the auroral oval expansion. Scintillations and the PPP errors at mid-latitudes increased, when the irregularity region with an increased level of the TEC variations approached the measuring facilities. At mid-
latitudes, the PPP errors exceeded the background level in the region of small-scale irregularities appearance over several hours by at least fivefold.

**Supplementary Materials:** The following are available online at www.mdpi.com/2072-4292/12/10/1579/s1, www.mdpi.com/xxx/s2, www.mdpi.com/xxx/s3; Video S1: Global dynamics for the GPS PPP error as derived from a ground-based GPS-receiver for 0 through 24 UT on 22 June 2015. The animation cadence is 1 min. The time (in UT) is shown on the top; Video S2: Global dynamics for the 10–20 min TEC variations as derived from a ground-based GNSS-receiver for 17 through 24 UT on 22 June 2015. The animation cadence is 1 min. The scale is on the right. The corresponding UT is shown in the animation title; Video S3: Global dynamics for the 20–60 min TEC variations as derived from a ground-based GNSS-receiver for 17 through 24 UT on 22 June 2015. The animation cadence is 1 min. The scale is on the right. The corresponding UT is shown in the animation title.

**Author Contributions:** Conceptualization and Methodology, Y.Y., R.V., K.R. Data curation and formal analysis: IISR – R.V., A.S. M.G.; Ionosonde – K.R., A.V.; GNSS – Y.Y., A.Y., A.K., A.V. PPP calculation and formal analysis, S.S. Investigation, Y.Y., R.V., K.R., A.V. Writing – Original Draft Preparation, Y.Y., A.A., R.V., K.R. Writing – Review & Editing, Y.Y., A.V., A.Y. All authors have read and agreed to the published version of the manuscript.

**Funding:** The research was supported by Russian Federation President Grant No. MK-3265.2019.5 and by Russian Foundation for Basic Research Grant No. 19-05-00889. The study is based on the data recorded by using the ISTP SB RAS Angara Multi-access Center facilities (http://ckp-rf.ru/ckp/3056/), including the Unique Research Facility Irkutsk Incoherent Scatter Radar (http://ckp-rf.ru/usu/77733/), under budgetary funding from Basic Research Program II.16.

**Acknowledgments:** The authors thank Alexandra Kustavinova for the graphical abstract made for the paper. We acknowledge the Scripps Orbit and Permanent Array Center, IGS [41], Bundesamt für Kartographie und Geodäsie (BKG) Data Center, WuHan University, Crustal Dynamics Data Information System (CDDIS), Korea Astronomy and Space Science Institute, National Geodetic Survey (Data from NOAA’s National Geodetic Survey (NGS) Continuously Operating Reference Station (CORS) network of Global Navigation Satellite System (GNSS) (https://www.ngs.noaa.gov/CORS/data.shtml), the UNAVCO Facility (supported by the National Science Foundation (NSF) and National Aeronautics and Space Administration (NASA) under NSF Cooperative Agreement No. EAR-0735156), Système d’Observation du Niveau des Eaux Littorales (SONEL), the EUREF Permanent Network Services [44], Geoscience Australia, the New Zealand GeoNet project (supported by EQC, GNS Science and LINZ), the State GPS network of the Republic of Bulgaria, Institut Geographique National, Instituto Geográfico Nacional, Instituto Tecnológico Agrario de Castilla y León, Geodetic Data Archiving Facility, Instituto Brasileiro de Geografia e Estatística, Canadian High Arctic Ionospheric Network [43] for the GPS/GLONASS data. We are grateful to the Industrial Geodetic Systems (HIVE) (https://hive.geosystems.aero/) and, especially, to S. Sorokin for the access to the GPS/GLONASS network data in Russia, which allowed us to significantly increase the TEC and PPP visibility in the addressed region. The authors acknowledge the use of AE, H-SYM, Bz, and the proton density data from the OMNI database; the ionosonde data in Yakutsk, Moscow, Mohe from GIRO database; the SuperDARN data, which is a collection of radars funded by national scientific funding agencies of Australia, Canada, China, France, Italy, Japan, Norway, South Africa, United Kingdom, and the United States of America; and the SuperDARN software and web tools available at Virginia Tech.

**Conflicts of Interest:** The authors declare no conflict of interest.

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