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Advanced Classification of Ionospheric Troughs in the Morning and Evening Conditions

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Highlights:

- The separation of ionospheric troughs in the winter evening and morning ionosphere of the southern hemisphere was performed.
- The study is based on electron density measurements at CHAMP satellite altitudes of 405–465 km during 2000–2002.
- The main ionospheric trough was separated from poleward high latitude trough and from equarorward ring ionosperic trough.

Abstract: The separation and classification of ionospheric troughs in the winter evening and morning ionospheres of the southern hemisphere were performed using CHAMP satellite data for high solar activity (2000–2002). In the high-latitude ionosphere, the main ionospheric trough (MIT) was separated from the high-latitude trough (HLT). The separation was carried out using a thorough analysis of all the characteristic structures of the ionosphere in the framework of the auroral diffuse particle precipitation model. Two types of high-latitude troughs were identified: (1) a wide trough associated with zone II of diffuse precipitation on the poleward edge of the auroral oval and (2) a narrow trough of ionization, which is presumably associated with an electric field action. The poleward wall of MIT is as ever formed by diffuse precipitation in zone I on the equatorward edge of the auroral oval. The HLT and MIT separation is most difficult at the longitudes of the eastern hemisphere, where all structures are located at the highest latitudes and partially overlap. In the mid-latitude ionosphere, all the characteristic structures of the ionosphere were also identified and considered. MIT was separated from the ring ionospheric trough (RIT), which is formed by the decay processes of the magnetospheric ring current. The separation of MIT and RIT was performed based on an analysis of the prehistory of all geomagnetic disturbances during the period under study. In addition to the RIT, a decrease in the electron density equatorward of the MIT was found to be often formed at the America–Atlantic longitudes, which masks the MIT minimum. For completeness, all cases of a clearly defined polar cavity are also presented.

Keywords: main ionospheric trough; high latitude trough; ring ionospheric trough; low latitude trough; auroral diffuse precipitation

Citation: Karpachev, A. Advanced Classification of Ionospheric Troughs in the Morning and Evening Conditions. *Remote Sens.* **2022**, *14*, 4072. https://doi.org/10.3390/rs14164072

Academic Editor: Fabio Giannattasio

Received: 31 July 2022
Accepted: 18 August 2022
Published: 20 August 2022

1. Introduction

The ionization trough was discovered by Muldrew from the Alouette 1 data [1]. Muldrew identified it as the main ionospheric trough (MIT). MIT is located equatorward of the auroral oval. The results of numerous MIT studies are summarized in reviews [2–5]. Inside the auroral oval, another (high–latitude, HLT) trough was detected and studied in detail using the OGO 6 satellite data [6]. The so-called ring ionospheric trough (RIT) was later discovered equatorward at MIT [7]. RIT is formed by the decay process of the magnetospheric ring current and is typically observed in the recovery phase of a storm/substorm [8,9]. The multitudes of MIT and HLT, as well as MIT and RIT, partially overlap; therefore, the problem of trough separation arises in the region of the intersection. This problem was posed in prior studies [10,11] and elaborated in detail in a study by Karpachev [12]. However, this problem was not completely solved, so Liu and Xiong [13], processing a large dataset of CHAMP satellites, wrote: "There is no agreed quantitative definition of an MIT [14,15], as sometimes it is difficult to identify the individual mid-latitude trough from kinds of depletion structures extending along latitude, such as high-latitude trough and wave-like disturbances". An almost unambiguous solution to the problem of trough separation in the midnight ionosphere was obtained in a recent study by Karpachev [16]. Significant progress in the separation and classification of various structures of the midnight high-latitude and mid-latitude ionosphere has been achieved based on a thorough analysis of a large dataset of CHAMP satellites, which allows us to consider the phenomenon from different perspectives. As a result, two troughs were identified in the auroral ionosphere. A wide trough (HLT1) was identified in the framework of a simple visual model of diffuse auroral precipitation [17]. This model describes zone I of diffuse precipitation on the equatorward edge of the auroral oval and zone II on its poleward edge. It was determined that the precipitation in zone II forms the poleward wall of HLT1 and the precipitation in zone I forms the MIT poleward wall. This is the key point in separating MIT and HLT1.

The analysis is most effectively conducted in the framework of the longitudinal effect because the boundaries of both zones change with longitude by 2.5° in latitude [18], similar to the longitudinal variations in the MIT position. Analyzing the longitudinal variations of these structures, it was found that the problem of MIT and HLT1 separation is radically different in the western and eastern hemispheres. In the western hemisphere, MIT is located at lower latitudes than in the eastern hemisphere, and it is further removed from the auroral oval; therefore, it is quite simple to separate it from the HLT. In the eastern hemisphere, MIT shifts to high latitudes so that the region of its existence begins to overlap strongly with the statistical position of zone I of precipitation and the region of existence of HLT. Therefore, the separation of troughs in the eastern hemisphere was carried out according to the correspondence of the MIT poleward wall to the position of zone I and the HLT1 poleward wall to the position of zone II of precipitation. In addition, the trough minimum position relative to zone I was also monitored. The second trough (HLT2), described in [6,19], is associated with the action of local electric fields [19]; therefore, it is narrow in latitude (3–5°) and can be observed in any region of the auroral oval.

Because MIT is observed equatorward of the auroral oval, it is, by definition, a sub-auroral trough. The RIT is formed equatorward of MIT; therefore, it can be defined as a mid-latitude trough. RIT is formed even after a slight increase in geomagnetic activity and can be observed for a long time (sometimes two days) at latitudes of 53–57° GMLat [8,9]. Therefore, the frequency of RIT occurrence is determined by the degree of perturbation of the ionosphere, which is higher under high solar activity. The separation of MIT from RIT is also a difficult problem, but we can use the separation method carefully developed earlier [8,9]. It consists of the following: If MIT and RIT are observed simultaneously, then the equatorward trough is defined as the RIT. If there is one trough, its dynamics in prehistory must be considered. If the variations of the trough position correspond to the MIT model constructed in terms of the Kp index [20], then it is defined as MIT. If the trough is much more equatorward than the model position, then this is the RIT. However, there may be controversial cases that must be considered carefully. This will be shown below.

At longitudes of America and the Atlantic, a special structure is often recorded: a weak electron density minimum at the base of the MIT poleward wall and a deep minimum located much more equatorward. This structure is recorded in the evening more often than in the morning. The first minimum is located poleward of the average MIT position, whereas the second is, correspondingly, equatorward. Consequently, there is the problem of accurately determining MIT position, which is also discussed below.

Finally, to complete the pattern, the clearest cases of a polar cavity are also highlighted. However, a thorough analysis has not been conducted because, at most longitudes, the satellite did not reach the geomagnetic latitudes necessary for registration.

This work is an extension of the study of the irregular structure of the ionosphere in the early evening and early morning hours, based on the experience gained from the analysis of the midnight ionosphere [16]. In both studies, only the pattern in the southern hemisphere was considered. The southern hemisphere is much better suited for practicing this technique because there are a number of interesting effects in this hemisphere. This particularly applies to the longitudes of America.

2. Materials and Methods

The CHAMP satellite carried out in situ measurements of electron density *Ne* [21]. Variations in *Ne* are presented below in terms of plasma frequency *fp* ($Ne[\text{cm}^{-3}] = 1.24 \cdot 10^4 fp^2$ [MHz]). The CHAMP altitude has changed from ~450 km to ~300 km, which is close to the height of the F2 layer maximum. It revolved on a nearly polar orbit with an inclination of 87°. The CHAMP data time resolution of 15 s is less than 1° of latitude, which allows accurate determination of the minimum trough position. The CHAMP data are available on the website http://op.gfz-potsdam.de/champ (accessed on 12 January 2015).

In this study, CHAMP data for local winter conditions in the southern hemisphere were used. The data only for high solar activity with F10.7~180 sfu for the period of 2000–2002 and the evening (17–19 LT) and morning (05–06 LT) conditions were considered. About 1500 CHAMP passes in the winter high- and mid-latitude ionosphere for $Kp \leq 4$ were examined. The MIT is usually defined as a sufficiently deep decrease in electron density of at least ~30% relative to the top of the steep equatorward wall [3]. However, in the morning sector, the electron density usually monotonously falls to high latitudes without noticeable inflection on the equatorward wall, and the trough definition becomes uncertain. Therefore, we have not estimated the level of electron density decrease at the MIT minimum. The position of MIT was determined by the electron density minimum at several degrees equatorward of the base of the poleward wall [3]. In the morning, the poleward wall was almost always clearly defined. If the trough was poorly expressed or masked by ionospheric plasma irregularities on some satellite path, the position of its minimum was determined through coordination with well-expressed troughs on neighboring paths.

Stricter criteria were imposed on the selection of the HLT. The HLT is observed in the auroral oval, where the electron density is highly irregular and several density minima can be observed. Therefore, the HLT was recorded only in obvious cases wherein it was clearly structured and when its poleward wall did not extend beyond the poleward diffuse precipitation zone. Similarly, the polar hole was defined only as a broad minimum of the electron density at latitudes above the poleward precipitation zone. Finally, only pronounced troughs were recorded equatorward of MIT.

3. Structure of the Evening Ionosphere

Figure 1 shows the positions of the different structures in the winter evening (17–19 LT) ionosphere of the southern hemisphere in terms of geomagnetic latitude—geographical longitude. The following structures are presented in Figure 1: polar hole, HLT, MIT, RIT and specific equatorward minimum of electron density. To eliminate the dependence on geomagnetic activity, the positions of the MIT, RIT and HLT were reduced to Kp = 2 according to $\Lambda\text{corr} = \Lambda\text{c} - a(\text{Kp}(\tau) - 2)$, where Λc is the current position of the structure and the ***a*** factor is 2.0° for the MIT [20], 1.5° for RIT [9], and ~1.5° for HLT [6]. The Kp(τ) index was used because it considers the prehistory of geomagnetic activity development [22]. In the evening sector, the dependence of MIT position on local time is quite strong; it was also considered according to the model [20].

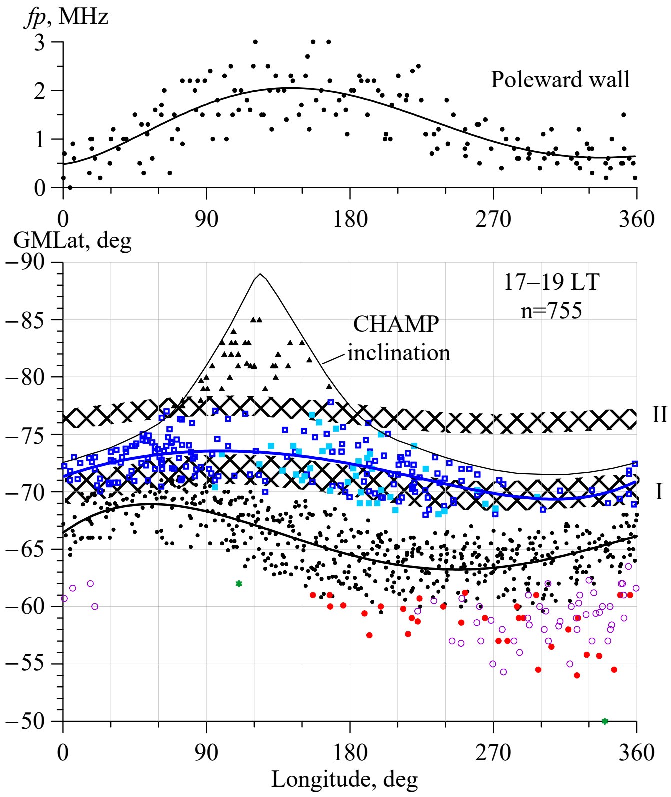

Figure 1. On the top: Longitudinal variations in the magnitude of the MIT poleward wall (dots and approximations). On the bottom: Longitudinal variations in the positions of main structures in the evening winter ionosphere of the southern hemisphere: polar hole (triangles), HLT1 (empty squares), HLT2 (filled squares), MIT (dots), RIT (red dots), equatorward density minima (purple circles), and low-latitude structures (green asterisks). The shaded latitude belts show diffuse auroral precipitation in zones I and II. The upper curve represents the CHAMP inclination equal to 87°.

An analysis of the structures of the high latitude ionosphere was conducted using a model of auroral particle precipitation constructed from DMSP satellite data recorded in both hemispheres [17]. The model agrees well with other statistical models of auroral electron precipitation in the nighttime conditions [23–25]. There are no data in the literature regarding the dependence of the position of the diffuse precipitation zones on longitude in the evening sector. However, because the position of MIT showed a pronounced longitudinal effect [12], we preserved the shape and amplitude of the longitudinal effect in the auroral precipitation in the same form as revealed in the interval of 21–03 MLT [18] and used it to analyze the structure of the midnight high-latitude ionosphere [16]. For the southern hemisphere, these boundaries are presented in Figure S2 (in Supporting Information) according to [18]. The equatorward and poleward boundaries of the auroral oval experience synchronous longitudinal variations with an amplitude of ~2.5°. In Figure 1, zones I and II of the diffuse precipitation taken from Figure S1 are shaded. The average (for all longitudes) position of the equatorward boundary of the auroral precipitation oval corresponds to model [17] for Kp = 2. The upper thin curve in Figure 1 depicts the CHAMP satellite inclination. The satellite inclination of 87° does not limit the observations of the discussed structures, except for the polar hole. However, polar hole cases are shown in Figure 1 solely for completeness of the pattern; only unambiguous cases were selected.

The longitudinal variations in the MIT position are quite confidently determined from the CHAMP data in the evening (correlation coefficient $r = 0.72$, standard deviation $\sigma = 1.8°$). The amplitude of the longitudinal effect reaches ~6°, which is greater than at midnight [16]. At longitudes of the eastern hemisphere between 0° and 120°E, the MIT is located farthest from the pole; thus, this region overlaps with zone I of diffuse precipitation, even when considering the assumed longitudinal effect in the position of this zone. Even more important is that the clearly expressed MITs in this region are superimposed on well-defined HLTs. Regardless, the problem of separating MIT and HLT in the evening sector is more complicated than in the midnight sector and requires detailed consideration. Figure 2 shows several examples of the structure of the evening ionosphere, which require careful analysis. The shaded bars in Figure 2 show zones I and II of diffuse precipitation, which positions correspond to the current values of the longitude and Kp index. In some cases, the zones are slightly shifted to better compliance of the structures on the grounds that CHAMP provided the current data, and the precipitation model is statistical.

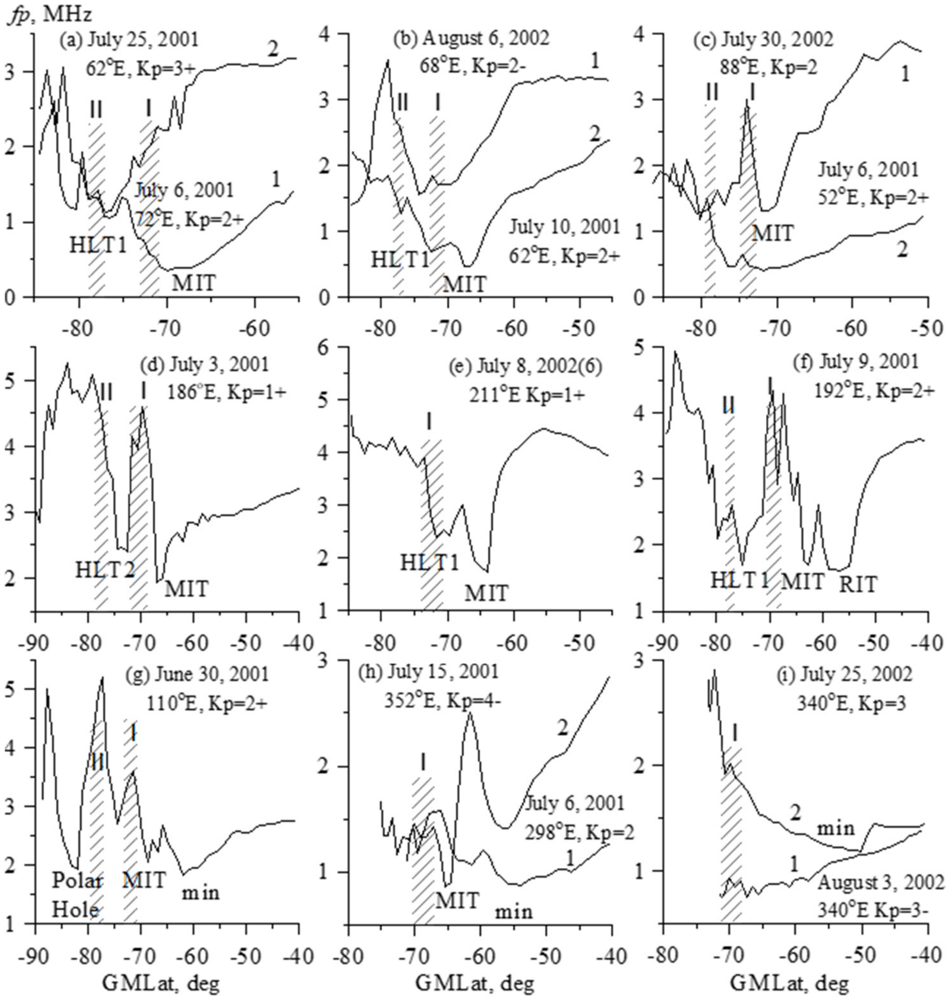

Figure 2. Characteristic examples of ionospheric troughs at different longitudes in the evening ionosphere. The shaded bars in (**a**) (zones I and II of precipitation) correspond to *fp* profile 1, i.e., Kp = 2+; the bar in Figure 2h corresponds to *fp* profile 1, i.e., Kp = 2.

The most difficult problem with the separation of MIT and HLT is observed in the eastern hemisphere at longitudes of 30–90°E, where the locations of MIT and HLT partially overlap. The weakly pronounced poleward wall of MIT at these longitudes (upper panel of Figure 1) complicated this problem. The data on the poleward wall were obtained during the quiet period from 10–17 July 2001.

The situation at problematic longitudes is considered below using individual characteristic examples. In Figure 2a, curve 1 depicts an example of a conventional MIT. Its minimum is located at quite a high latitude (−70°), but its poleward wall is definitely formed by diffuse precipitation in zone I. The MIT poleward wall is low, and the electron density minimum at −77° is apparently a sign of a high-latitude trough (HLT). Curve 2 depicts an example of a well-defined HLT with a minimum latitude of −76° (under Kp = 3+), i.e., deep inside the auroral oval. Its poleward wall is certainly associated with zone II of precipitation. This type of high-latitude trough has been defined as HLT1 [16]. The MIT on latitudinal *fp* profile 2 is completely filled, and only ionospheric plasma irregularities are observed at latitudes of its assumed minimum. This latitudinal *fp* profile is likely a consequence of the previous disturbance with Kp = 4+. Thus, the main criterion for the separation of MIT and HLT1 is the correspondence of the poleward wall of the trough to precipitation in zones I and II, respectively. The position of the trough minimum was also taken into consideration.

Figure 2b shows examples of the simultaneous existence of two electron density minima. Then, a lower-latitude minimum (<70°) corresponds to the MIT, and a higher-latitude one (>70°) refers to the HLT. The poleward walls of both troughs correspond to the related precipitation zones, although the MIT poleward wall is not pronounced in either case.

Curve 1 in Figure 2c represents a trough with a minimum at a very high latitude of −72° for Kp = 2. However, its poleward wall is clearly formed by precipitation in zone I, i.e., MIT. Of note that, in this case, MIT is located deep in the region of HLT existence. The latitudinal profile 2, as well as in Figure 2b, shows two *fp* minima. The equatorward minimum at latitude of −71.7° (under Kp = 2+) coincides with the MIT minimum on curve 1. However, its weak poleward wall is formed by only one *fp* value, i.e., it is not reliable. Therefore, this structure was attributed to the HLT, in which the poleward wall is located at latitudes of (−77–79°), i.e., at latitudes of zone II of diffuse precipitation. Thus, as the above examples show, the identification and separation of troughs in the challenge region at longitudes of 30–90°E was possible, although it required a thorough analysis of complex, controversial cases.

In Figure 2d, MIT and HLT are observed at the same time. However, in this case, the high-latitude trough is very narrow and deep. Such troughs were recorded onboard the OGO 6 satellite [6]. The authors of this study associated these troughs with the action of electric fields in the region of the high-latitude convection of ionospheric plasma. This trough can be defined as HLT2. In Figure 1, the approximating curve is determined for both HLT types. This curve shows the longitudinal effect in the HLT position, but it is distorted because, at most longitudes, the inclination of the satellite's orbit does not allow recording of the highest-latitude cases of HLT. (The HLT shown in Figure 1 sometimes goes beyond satellite inclination, which is associated with the reduction of the position of the troughs to Kp = 2).

In Figure 1, in the longitude range from 150° to 240°E, several HLTs are located at very low latitudes, equatorward of the polar oval. Such a case is presented in Figure 2e for HLT1. In this case, the MIT minimum and its poleward wall are much more equatorward than zone I of precipitation. We can deduce that zone I is located more equatorward at most longitudes than in Figure 1. However, this assumption cannot be verified without data on precipitation at all longitudes in the evening sector.

In Figure 2f, three troughs are observed simultaneously: HLT1, MIT and RIT. A well-expressed RIT was observed after a substorm with Kp = 5. The RITs in Figure 1 are indicated by red (filled) circles. The RIT is formed mainly in the western hemisphere. This is because the geomagnetic field in this hemisphere is weak, the precipitation of hot ions of the magnetospheric ring current is intense, and the trough is formed more often.

In Figure 2g, curve 1 shows the polar cavity at latitude of −82°, MIT at latitude of −68°, and the *fp* minimum at latitude of −61.5°. The polar cavity is observed at latitudes >78°; therefore it was recorded only at longitudes of the eastern hemisphere, where the satellite inclination allowed. The *fp* minimum is depicted by the green asterisk in Figure 1 at a longitude of 110°E. It clearly stands out from among other troughs, and the reason for its formation is unknown, although it is very clearly expressed.

Curve 1 in Figure 2h displays the structure often observed at the longitudes of America and the Atlantic, as discussed in the Introduction. This structure is characterized by a small *fp* minimum at latitude of −62° at the base of the MIT poleward wall and a deeper and wider minimum at latitude of −55°. This minimum makes it difficult to accurately determine the position of the MIT minimum. These equatorward electron density minima are marked in Figure 1 by purple circles. Figure 1 shows that both the RIT and the equatorward minimum are located in the same region, mainly in the western hemisphere. However, the RIT is formed after geomagnetic disturbance, and a structure with two electron density minima is formed under long-term quiet conditions. In addition, this structure has a specific shape.

Curve 2 in Figure 2h depicts a structure at a longitude of 352°E, formally similar to the structure represented by curve 1. However, the *fp* peak in this case is so pronounced that it represents a special independent structure. In other words, a question arises regarding the reasons for the formation of this peak. The structure in question was formed in a weakly disturbed ionosphere at Kp = 4−, but it is often observed at American longitudes under completely quiet geomagnetic conditions. The *fp* peak is located on the MIT equatorward wall so that the MIT minimum appears at a latitude of −65.3°. This peak forms a pronounced equatorward minimum at latitude of −57°, which can easily be mistaken for MIT with automatic and even manual data processing. However, even at Kp = 4−, this minimum is much more equatorward than the "normal" MIT, as shown in Figure 1.

The top panel in Figure 1 shows the longitudinal variations in the electron density on the top of the poleward wall derived with correlation coefficient r = 0.68, standard deviation σ = 0.43°, and amplitude A~1.5°. At small and especially large longitudes, the MIT poleward wall is surprisingly low. Another specific feature of the evening ionosphere at these longitudes is the slow decrease in electron density from middle to high latitudes, i.e., the small latitudinal gradient at the latitudes of MIT. This demonstrates curve 1 in Figure 2i. Latitudinal *fp* profile 1 was obtained on 3 August 2002 in the longitudinal sector of 340°E. The electron density slowly and almost monotonously decreases to high latitudes, showing neither a noticeable minimum nor a poleward wall. Such *fp* profiles are quite often observed at the discussed longitudes. Thus, in the evening, at small and large longitudes, the MIT as a structure is often not formed at all, neither its minimum nor the poleward wall. This is an unexpected fact that requires comprehension.

Latitudinal *fp* profile 2 in Figure 2i was obtained on 25 July 2002 under almost the same conditions in the same longitude sector. However, the latitudinal *fp* profile differs sharply from the usual profile at these longitudes. It is characterized by a high electron density at high latitudes, which quickly drops toward the equator. As a result, MIT is not observed, but a well-defined minimum is formed at an extremely low latitude of −50°. The whole structure of the ionosphere on this path looks strange. This structure has been recorded in the evening sector only once; a low latitude minimum is also marked by a green asterisk in Figure 1 at a longitude of 340°E and latitude of −50°. A possible explanation is associated with a strong particle precipitation equatorward of the "normal" boundary of diffuse precipitation, that is, at the latitudes of the MIT minimum, which is consequently filled with ionization [26]. A minimum latitude of −50° is probably a consequence of the formation of a subauroral polarization steam (SAPS) [27]. The study [27] provides an example of the formation of a trough at a latitude of 53°, according to the Millstone Hill radar and the DMSP F13 satellite measurements on 12 April 2001. The deep trough was formed under the action of the western component of the plasma drift, driven by a northward electric field. Thus, Figure 2h,i demonstrates the presence of problems in the identification of MIT at large longitudes in the western hemisphere.

As shown above, the main problem in the eastern hemisphere is the separation of high-latitude cases of the MIT from low-latitude cases of the HLT. The main criterion for separation is the correspondence of the MIT poleward wall to the precipitation in zone I and the HLT1 poleward wall to the precipitation in zone II. The solution to this problem was presented in sufficient detail above in the analysis of Figure 1. However, it is worth demonstrating this solution once again based on a very illustrative example obtained on 1 August 2001. Figure 3 on the left shows the longitudinal variations in the position of the troughs and both zones of diffuse precipitation. The Kp index varied in the period under review from 2− to 4−. To eliminate dependence on geomagnetic activity, the data were reduced to Kp = 2. Figure 3 shows that, in the western hemisphere, the trough minimum is located equatorward of the auroral oval of the precipitation and, by definition, is the MIT.

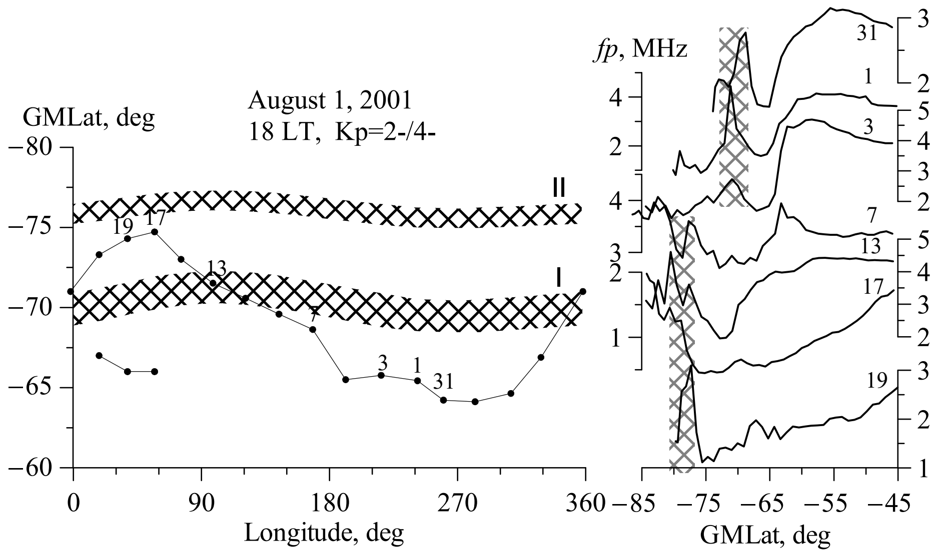

Figure 3. (**Left**): Longitudinal variations in the trough position on 1 August 2001. Precipitation zones I and II are hatched. (**Right**): Latitudinal *fp* profiles for the paths marked on the left.

Examples of the latitudinal cross-sections of the MIT are shown in Figure 3 on the right for paths 31, 1 and 3. The trough on these paths is clearly expressed; its poleward wall exactly corresponds to zone I of precipitation at a latitude of approximately −70°. In the eastern hemisphere, the troughs on paths 13–23 are located inside the auroral oval and by definition belong to the HLT. Examples of well-formed HLTs are shown on the right for paths 13, 17 and 19. Their poleward walls are located at latitudes of 76–80°, i.e., they are formed by precipitation in zone II. Path 7 is transitional; the poleward wall of the trough corresponds to zone II of precipitation, and the electron density minima at its wide bottom corresponds to both MIT and HLT. On paths 17 and 19, weak variations in ionospheric plasma are observed in the latitudinal region at approximately −66°, which can be assessed as a sign of MIT. On the other paths in the eastern hemisphere, there are no even weak manifestations, i.e., MIT has not formed in the eastern hemisphere. If the MITs in the western hemisphere combine with the HLTs in the eastern hemisphere into a single branch, there will be strong longitudinal variations in the trough position with an amplitude of ~11°. Note, however, the artificial character of the longitudinal effect in this case.

In Figure 2h, curve 2 depicts a specific structure, which is characterized by a shallow electron density minimum at the base of the poleward wall and a well-expressed minimum, which is much more equatorward than the "normal" minimum of the MIT. Because this structure is quite often formed at longitudes of America and the Atlantic (purple circles in Figure 1), it is worth considering its formation in detail. Figure 4 on the left shows the longitudinal variations in the trough position for quiet conditions (Kp varied from 1− to 2+) for the period of 4 July 2001. Both zones of diffuse precipitation are plotted in Figure 4. The thick curve shows the average position of MIT, which is highlighted in Figure 1. The numbers of characteristic satellite paths are indicated. The classic MIT is observed on path 14, and its poleward wall is formed by precipitation in zone I. In the eastern hemisphere, MIT is located slightly above the average position. MIT gradually enters zone I of precipitation, and on path 20, it transforms into HLT1, the poleward wall of which is already formed by precipitation in zone II. The MIT on path 20 did not manifest in any way, as in the previous event, at the same longitude (Figure 3).

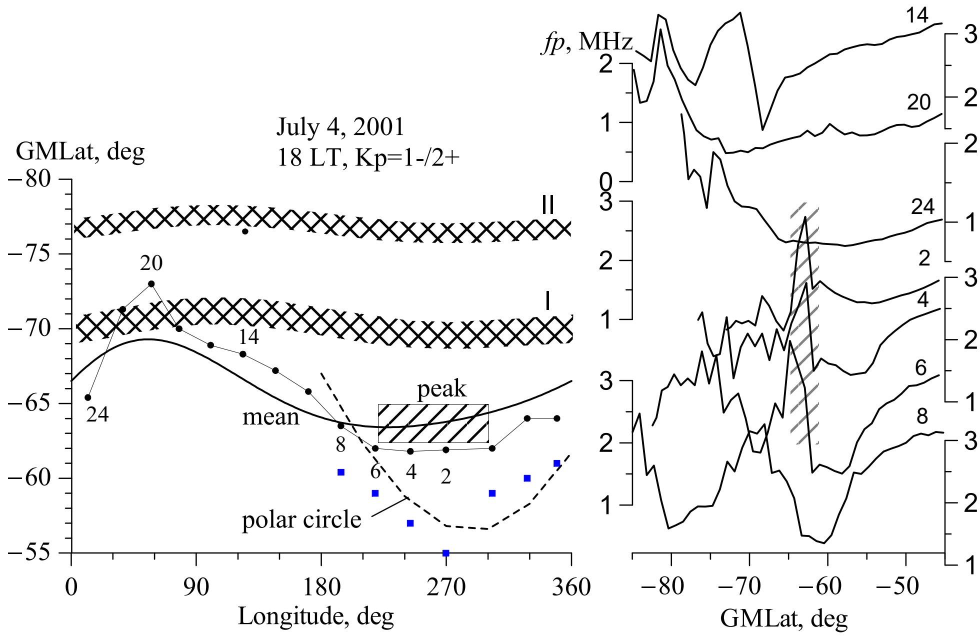

Figure 4. On the **left**: longitudinal variations on 4 July 2001 in the MIT position (black circles) and equatorward density minimum (blue squares). The average position of MIT (from Figure 1) is shown by a thick curve, and the polar circle is a dashed curve. Hatching shows the position of both zones of precipitation and the plasma density peak. On the **right**: *fp* latitudinal cross-sections for the paths indicated on the left.

A remarkable structure was formed in the western hemisphere. On paths 2, 4 and 6, a well-expressed ionospheric plasma peak is observed at latitudes of 62–65°, which is much more equatorward of the zone I precipitation. This peak defines the steep poleward wall of the trough. The appearance of plasma peaks distant from the auroral oval may be due to two reasons. Sufficiently strong particle precipitation sometimes occurs in the evening sector equatorward of the stable boundary of diffuse precipitation, i.e., already inside the trough [26]. The resulting peak of ionization can be amplified and shifted further to the equator by the zonal drift created by the SAPS [27], as the SAPS flows developed nearby. A small minimum *fp* is observed at the base of the poleward wall. Its position is plotted in Figure 4 as the MIT minimum because we have no other way to determine the position of the trough; it is masked by the well-defined equatorward minimum of *fp*. On path 2, this minimum is located at a latitude of −55°, which does not correspond to the minimum of the "normal" MIT at all. Then, this minimum shifts to high latitudes up to −61° on path 8. As a result, an ordinary MIT with a poleward wall formed by zone I precipitation was observed on path 8.

The dashed curve in Figure 4 shows the position of the polar circle at a geographic latitude of −66°. Thus, the observed minimum *fp* is obviously associated with the decay of electron density during the polar night. Automatic data processing of the MIT position has been frequently used recently. It is clear that any program will take the equatorward minimum as the minimum of MIT in Figure 4. Then, the longitudinal variations in the trough position, considering paths 20 and 22, will reach 18°, and the average position of MIT in the western hemisphere will be underestimated. There is a serious problem in determining the position of MIT because such a situation, as in Figure 4, is observed quite often. In the study by [2] on a large set of ISIS 1 and Injun 5 satellite data, it was determined that the minimum MIT was located 2–5° away from the auroral oval. This is true for the average position of the trough (the bold curve in Figure 4). However, in this case, even the base of the poleward wall is 6–7° away from the auroral oval. Thus, we were forced to take the minimum *fp* at the base of the poleward wall as the minimum of MIT.

4. Structure of the Morning Ionosphere

Figure 5 shows the longitudinal variations in the position of the main structures of the morning ionosphere. The designations are the same as in Figure 1. The CHAMP data for 05–06 LT were used. They were selected in the interval of Kp < 4 and were again reduced to Kp = 2. The longitudinal variations in the MIT position from the CHAMP data are less confidently determined in the morning (r = 0.55, σ = 2.1°) than in the evening because of the small amplitude A~4°. Longitudinal variations in the electron density on the MIT poleward wall (upper panel) were obtained during the quiet period from 3 July to 12 July 2001. These variations in the morning sector, as well as in the evening, are reliably revealed (r = 0.65, σ = 0.50°, A~1.5°).

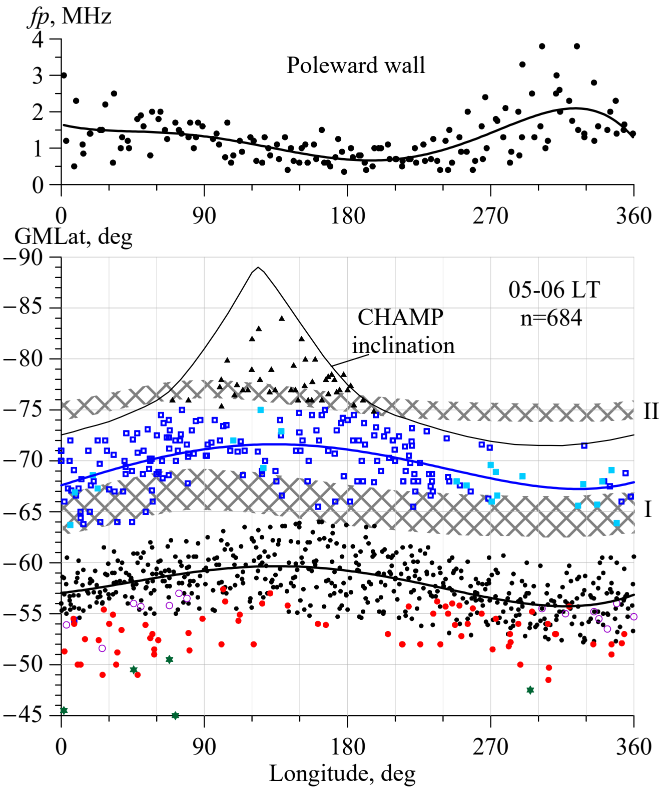

Figure 5. The same as in Figure 1, but for 05–06 LT.

Although in the position of the morning MIT, a weaker longitudinal effect was observed than in the evening; nevertheless, we retained the shape and amplitude of the longitudinal effect in precipitation in the same form as they were revealed for 21–03 MLT in [18]. The sharp difference between the morning and evening ionospheres is that MIT and HLT are separated by a large gap in the morning. Considering the results of the midnight ionosphere study [16], a trend can be identified: MIT is most closely located to the auroral oval in the evening, farther away from the oval at midnight, and even farther in the morning. Accordingly, the problem of separating MIT and HLT is most acute in the evening and simplest in the morning.

Examples of the most characteristic structures in the morning ionosphere are shown in Figure 6. Figure 6a shows an example of HLT1 recorded on 8 August 2002 at a longitude of 196°E. The poleward wall of the HLT is formed by precipitation at latitudes near −76°, which corresponds to zone II of precipitation. Only a slight decrease in electron density is observed at the latitude of MIT.

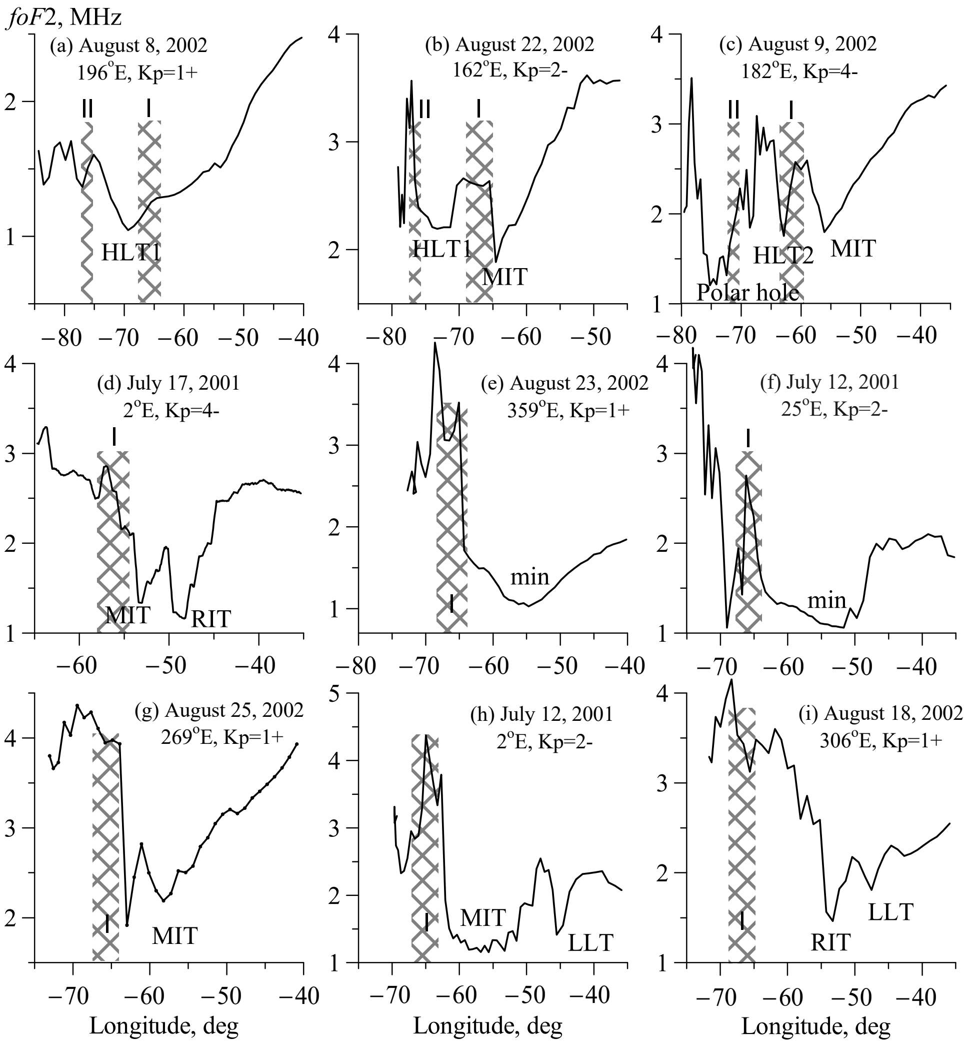

Figure 6. Characteristic examples of ionospheric troughs at different longitudes in the morning ionosphere.

At longitudes from 150° to 200°E, several MIT cases are located so high in latitude that their identification can be questioned. In Figure 6b, the minimum trough is located at a very high latitude of −64.6° for 5.0 LT and Kp = 2−. This is because the sharp minimum electron density corresponds to the base of a very steep poleward wall. However, the poleward wall is certainly formed by the precipitation in zone I, and this is MIT. Moreover, on this latitudinal *fp* profile, there is another high-latitude trough with the poleward wall located at a latitude of −78°, which corresponds to the precipitation in zone II.

Figure 6c clearly identifies three structures recorded on 9 August 2002 in the longitudinal sector of 182°E at Kp = 4−: the polar cavity, HLT and MIT. The high-latitude trough is quite narrow; therefore, it was assigned to HLT2. In Figure 5, it is located at the lowest possible latitude of −66° (reduced to Kp = 2), but it cannot be confused with MIT. Thus, even in the challenge longitudinal interval of 150–200°E, the MIT and HLT can be separated based on a thorough analysis. However, observing a trough path by path at longitudes of 120–210°E, the MIT can transfer into HLT and vice versa, and with a cursory analysis, it may not be noticed. This situation is demonstrated in Figure 3 for evening hours. The low poleward wall aggravates the problem, as well as in the evening sector.

The structures of the morning ionosphere are located at much lower latitudes than in the evening. As a result, the satellite inclination makes it possible to record the HLT at almost all longitudes. Therefore, the approximating curve for the HLT in Figure 5 reproduces the longitudinal variations in the HLT position more adequately than in Figure 1 for evening hours. The polar cavity in the morning is also much more equatorward than in the evening and is often superimposed on the precipitation in zone II. However, a detailed analysis of the polar cavity was not included in the objectives of this study.

On 17 July 2001, under Kp = 4, two troughs were also recorded: MIT and equatorward RIT (Figure 6d). The RIT is formed much more often in the morning than in the evening [9], which confirms the comparison of Figures 1 and 5. The morning RIT is, as in the evening, observed more often at longitudes with a weak geomagnetic field. Figure 6d shows the case in which MIT and RIT are separated very clearly. However, this is not always observed; therefore, we must separate them by analyzing the prehistory of the dynamics of both troughs during geomagnetic disturbance, starting with the main phase of the storm/substorm, as mentioned in the Introduction.

Figure 6e shows two examples of a structure that is most often recorded in the evening (Figure 2h, curve 1), but it is sometimes observed in the morning at longitudes in America and the Atlantic. It is characterized by a high poleward wall (compare with Figure 6b), shallow minimum or inflection of *fp* at its base and a deep minimum of *fp* far from the poleward wall. This structure is discussed in detail in Figure 4. In Figure 5, the equatorward minima of electron density is marked with purple circles. There are much fewer of these minima than in the evening. They are usually located far equatorward from the MIT average position. In any case, this minimum masks the MIT minimum and makes it difficult to determine the true MIT position.

The structure in Figure 6f looks like the structure in Figure 6e. However, in this case, the *fp* minimum at the latitude of $-51.7°$ is more than $10°$ away from the base of the poleward wall and is accompanied by a sharp increase in *fp* to the equator. As a result, the structure in Figure 6f is similar to the structure that was observed in the evening in Figure 2i (curve 2) but is even more pronounced. In addition, in the evening, this structure is rarely observed; however, because the event repeats, a question arises about the mechanism of its formation.

In Figure 6g, two *fp* minima are observed in the longitudinal sector 269°E. The *fp* minimum at a latitude of $-58.2°$ corresponds exactly to the average position of MIT for Kp = 2 in Figure 5.

The minimum latitude of $-62.8°$ is located on the base of the steep poleward wall. The observed *fp* profile can be interpreted as an irregular structure at the bottom of the trough. However, the question remains as to why the deep minimum of the electron density is so often formed on the base of the sharp poleward wall of MIT.

The latitudinal *fp* profile in Figure 6h shows the deep and narrow low-latitude trough (LLT) on the equatorward wall of MIT at a latitude of $-45.5°$. Another such LLT was observed at a longitude of 72°E and latitude $-45°$ (see Figure 5). Troughs at such low latitudes are observed quite rarely and probably belong to troughs associated with hot particle precipitation from the inner radiation belt [28] or with the penetration of electric fields deep into the plasmasphere [29].

The structure in Figure 6i also defies unambiguous identification. A deep *fp* minimum is observed at a latitude of $-47.5°$. This is 4–5° equatorward than observed on previous days at the same Kp and LT values. This minimum was formed after a weak disturbance with Kp = 3+. Even after such a weak disturbance, the RIT is often formed. However, in this case, it cannot be stated unambiguously. Nevertheless, in Figure 5, this trough is defined as the RIT. Equatorward of RIT at latitude of $-47.5°$ another LLT is observed.

5. Discussion

The analysis of the localization of different structures of the high-latitude and mid-latitude ionospheres in terms of the longitudinal effect proved to be effective. This is because the positions of all structures, including the auroral oval of particle precipitation, experience quite strong variations with longitude. The MIT position changes with longitude by 6° in the evening and by 4° in the morning. The position of the boundaries of the auroral diffuse precipitation changes by 2.5°, according to the results, which was obtained so far only in one interval 21–03 MLT [18]. When variations in the position of the precipitation boundaries in the morning and evening sectors are revealed, the mutual location of the auroral oval and MIT can be clarified. However, we are confident that this will not fundamentally change the results of the analysis performed in this study.

In [2], the average distance of 2–5° between the auroral oval and MIT was determined. Now, we can refine this estimate. In the evening, MIT's average position is approximately 3° away from the equatorward border of diffuse precipitation, 4.5° at midnight [16], and as much as 6° in the morning.

Because MIT in the eastern hemisphere is located at a higher latitude than in the western hemisphere, the region of its existence in the eastern hemisphere is partly superimposed on zone I of precipitation and the location of the HLT. Therefore, the problem of MIT and HLT separation is most difficult at longitudes of 0–120°E in the evening and at midnight and 150–200°E in the morning. The problem is complicated by the fact that, at these longitudes, the poleward wall of the MIT is poorly expressed. Therefore, the main criterion for separating troughs is the correspondence of the MIT poleward wall to the precipitation in zone I and the HLT poleward wall to the precipitation in zone II. The position of the trough minimum also matters. All of this makes it possible to almost unambiguously separate MIT and HLT 1. However, to do this, we should carefully analyze each case because when observing path after path, situations arise when the MIT shifting to the pole transforms into HLT1 and vice versa. At the same time, only weak traces of MIT can be observed on the equatorward wall of HLT1, which is difficult to identify as a trough.

As for HLT2, the narrow trough described in [6] is most often observed at midnight, less often in the evening and even less often in the morning.

The polar cavity was recorded only where the inclination of the satellite allowed, i.e., at longitudes of 60–210°E. Analysis of the polar cavity was not a priority task; therefore, only obvious cases were recorded. The polar cavity was observed at latitudes above −76° in the morning and at those above −78° in the evening.

The RIT was also separated from MIT. For this purpose, the prehistory of the development of all, even weak disturbances, was considered. RIT is more often observed in the morning than in the evening. In the evening, it localizes exclusively at the longitudes of the western hemisphere, where the geomagnetic field is weak. In the morning, the RIT is observed at all longitudes, including in the eastern hemisphere.

In the evening, an extremely specific region of the ionosphere forms at the longitudes of America. First, in addition to the RIT, a special structure is often formed here (and partly over the Atlantic): a weak minimum of electron density is observed at the base of the poleward wall of the MIT, and a deep minimum is formed equatorward. This equatorward minimum is located at a much lower latitude than the statistical minimum of MIT. This seems to be associated with the decay of the electron density beyond the polar circle. This minimum masks the minimum of MIT, and with careless data processing, the true position of MIT can be greatly underestimated. Second, the poleward wall of MIT, probably driven by a horizontal drift, sometimes shifts to the equator, and then the entire structure of the high-latitude ionosphere is located much more equatorward than usual (see Figure 4). In this case, the amplitude of the longitudinal variations in the trough position can reach an incredible 18°. Third, the poleward wall of MIT at the longitudes of America is very low. Moreover, the electron density often monotonically falls to high latitudes without showing a noticeable minimum. As a result, the trough does not form at all at these longitudes.

6. Conclusions

The main result of the study is an almost unambiguous solution to the problem of separating different ionization troughs in the morning and evening ionosphere. The problem of the MIT and HLT separating is more complicated in the eastern hemisphere, the problem of the MIT and RIT separating is more complicated in the western hemisphere. Considering the results of [16], it can be argued that the problem of separation and classification of troughs in the nighttime ionosphere of the southern hemisphere is solved. This led to a decrease in the data scatter in the MIT position, the standard deviations are 1.8° in the evening, 1.85° at midnight, and 2.1° in the morning, which are less than in other statistical studies (see, for example, [10,30,31]). This is important for creating an accurate MIT model.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/rs14164072/s1. Figure S1: Model of auroral particle precipitation: diffuse auroral zone I equatorward of aurora (blue), structured auroral oval precipitation (auroral lights region or aurora, green), and soft diffuse precipitation zone II (orange) poleward of aurora. Figure S2: Longitudinal variations in the averaged auroral precipitation energy flux at 21–03 MLT under Kp = 2 for the June solstice (Jun.) in southern hemisphere [18].

Funding: This research received no external funding. The author would like to thank sponsors and operators of the CHAMP mission; Deutsches GeoForschungsZentrum (GFZ) Potsdam and German Aerospace Center (DLR).

Data Availability Statement: The CHAMP data are available on the website: http://op.gfz-potsdam.de/champ (accessed on 12 January 2015).

Conflicts of Interest: The author declares no conflict of interest.

References

1. Muldrew, D.B. F layer ionization troughs deduced from Alouette data. *J. Geophys. Res.* **1964**, *70*, 2635–2650. [CrossRef]
2. Ahmed, M.; Sagalyn, R.C.; Wildman, P.J.L.; Burke, W.J. Topside ionospheric trough morphology: Occurrence frequency and diurnal, seasonal and altitude variations. *J. Geophys. Res.* **1979**, *84*, 489–498. [CrossRef]
3. Moffett, R.J.; Quegan, S. The mid-latitude trough in the electron concentration of the ionospheric F-layer: A review of observations and modeling. *J. Atmos. Terr. Phys.* **1983**, *45*, 315–343. [CrossRef]
4. Rodger, A.S.; Moffett RJQuegan, S. The role of ion drift in the formation of ionisation troughs in the mid-and high-latitude ionosphere–a review. *J. Atmos. Terr. Phys.* **1992**, *54*, 1–30. [CrossRef]
5. Karpachev, A.T. Dependence of the MIT shape on longitude, altitude, season, local time, solar and magnetic activity. *Geomagn. Aeron.* **2003**, *43*, 256–269.
6. Grebowsky, J.M.; Tailor, H.A.; Lindsay, J.M. Location and source of ionospheric high latitude troughs. *Planet. Space Sci.* **1983**, *31*, 99–105. [CrossRef]
7. Karpachev, A.T. The characteristics of the ring ionospheric trough. *Geomagn. Aeron.* **2001**, *41*, 57–66. (In Russian)
8. Karpachev, A.T. Dynamics of main and ring ionospheric troughs at the recovery phase of storms/substorms. *J. Geophys. Res.* **2021**, *126*, e2020JA028079. [CrossRef]
9. Karpachev, A.T. Statistical analysis of ring ionospheric trough characteristics. *J. Geophys. Res.* **2021**, *126*, e2021JA029613. [CrossRef]
10. Werner, S.; Prolss, G.W. The position of the ionospheric trough as a function of local time and magnetic activity. *Adv. Space Res.* **1997**, *20*, 1717–1722. [CrossRef]
11. Karpachev, A.T.; Deminov, M.G.; Afonin, V.V. Two branches of day-time winter ionospheric trough according to the Kosmos-900 data at F2-layer heights. *Adv. Space Res.* **1998**, *22*, 877–882. [CrossRef]
12. Karpachev, A.T. Variations in the winter troughs' position with local time, longitude, and solar activity in the Northern and Southern hemispheres. *J. Geophys. Res.* **2019**, *124*, 8039–8055. [CrossRef]
13. Liu, Y.; Xiong, C. Morphology evolution of the mid-latitude ionospheric trough in nighttime under geomagnetic quiet conditions. *J. Geophys. Res.* **2020**, *125*, e2019JA027361. [CrossRef]
14. Prolss, G.W. The equatorward wall of the subauroral trough in the afternoon/evening sector. *Ann. Geophys.* **2007**, *25*, 645–659. [CrossRef]
15. Rodger, A.S.; Brace, L.H.; Hoegy, W.R.; Winningham, J.D. The poleward edge of the mid-latitude trough–its formation, orientation and dynamics. *J. Atmos. Terr. Phys.* **1986**, *48*, 715–728. [CrossRef]
16. Karpachev, A. Advanced separation and classification of ionospheric troughs in midnight conditions. *Sci. Rep.* **2022**, *12*, 13434. [CrossRef]
17. Vorobjev, V.G.; Yagodkina, O.I. Effect of magnetic activity on the global distribution of auroral precipitation zones. *Geomagn. Aeron.* **2005**, *45*, 467–473.
18. Luan, X.; Wang, W.; Burns, A.; Solomon, S.; Zhang YPaxton, L.J.; Xu, J. Longitudinal variations of nighttime electron auroral precipitation in both the Northern and Southern hemispheres from the TIMED global ultraviolet imager. *J. Geophys. Res.* **2011**, *116*, A03302. [CrossRef]
19. Williams, P.J.S.; Jain, A.R. Observations of the high latitude trough using EISCAT. *J. Atmos. Terr. Phys.* **1986**, *48*, 423–434. [CrossRef]
20. Karpachev, A.T.; Deminov, M.G.; Afonin, V.V. Model of the mid-latitude ionospheric trough on the base of Cosmos-900 and Intercosmos-19 satellites data. *Adv. Space Res.* **1996**, *18*, 221–230. [CrossRef]
21. Rother, M.; Michaelis, I. CH-ME-2-PLPT-CHAMP electron density and temperature time series in low time resolution (Level 2). *GFZ Data Serv.* **2019**. [CrossRef]

22. Deminov, M.G.; Shubin, V.N. Empirical model of the location of the main ionospheric trough. *Geomagn. Aeron.* **2018**, *36*, 45–52. [CrossRef]
23. Hardy, D.A.; Gussenhoven, M.S.; Holeman, E. A statistical model of auroral electron precipitation. *J. Geophys. Res.* **1985**, *90*, 4229–4248. [CrossRef]
24. Spiro, R.W.; Reiff, P.H.; Maher, L.J. Precipitating electron energy flux and auroral zone conductance–an empirical model. *J. Geophys. Res.* **1982**, *87*, 8215–8222. [CrossRef]
25. Sotirelis, T.; Newell, P.T. Boundary-oriented electron precipitation model. *J. Geophys. Res.* **2000**, *105*, 18655–18673. [CrossRef]
26. Khalipov, V.L.; Galperin, I.I.; Lisakov, I.V.; Krane, Z.; Nikolaenko, L.M.; Sinitsyn, V.M.; Sovo, Z.A. Diffuse auroral zone. II. Formation and dynamics of the poleward border of the subauroral ionospheric trough in the evening sector. *Space Res.* **1977**, *1*, 708–725. (In Russian)
27. Foster, J.C.; Burke, W.J. SAPS: A New Categorization for Sub-Auroral Electric Fields. *EOS* **2002**, *83*, 393–394. [CrossRef]
28. Karpachev, A.T. Sub-auroral, mid-latitude, and low-latitude troughs during severe geomagnetic storms. *Remote Sens.* **2021**, *13*, 534. [CrossRef]
29. Fejer, B.G.; Scherliess, L. Mid- and low-latitude prompt penetration ionospheric zonal plasma drifts. *Geophys. Res. Lett.* **1998**, *25*, 3071–3074. [CrossRef]
30. Kohnlein, W.; Raitt, W.J. Position of the mid-latitude trough in the topside ionosphere as deduced from ESRO-4 observations. *Planet. Space Sci.* **1977**, *25*, 600–602. [CrossRef]
31. Aa, E.; Zou, S.; Erickson, P.; Zhang, S.-R.; Liu, S. Statistical analysis of the main ionospheric trough using Swarm in situ measurements. *J. Geophys. Res.* **2020**, *125*, e2019JA027583. [CrossRef]