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Routine determination of the plasmapause based on COSMIC GPS total electron content observations of the midlatitude trough

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[1] Observations from the Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) GPS precise orbit determination (POD) antennae are used to create a database of vertical total electron content (VTEC) measurements between roughly 800 and 20,200 km. Owing to the correlation between the midlatitude trough and the plasmapause, the COSMIC GPS VTEC observations are used to determine the plasmapause location throughout 2008. The COSMIC observations of the plasmapause during 2008 are used to illustrate the variations with local time and geomagnetic activity as well as to reveal periodic behavior of the plasmapause. The plasmapause variation with geomagnetic activity obtained by the COSMIC observations is found to be consistent with previous results based on different observation methods. The similarity to prior results demonstrates the effectiveness of using the COSMIC POD observations for determining the plasmapause. The COSMIC observations further reveal that the plasmapause exhibits significant variability and is, on average, primarily invariant in local time. The plasmapause is also found to oscillate at periods of 9 and 13.5 days during 2008 in connection with recurrent geomagnetic activity due to high-speed solar wind streams. This is the first time that multiday oscillations have been observed in the plasmapause. The presence of a periodic modulation of the plasmapause further demonstrates the importance of periodic high-speed streams in the Earth's upper atmosphere and inner magnetosphere during the current solar minimum.

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1. Introduction

[2] The plasmasphere consists of relatively cold, high-density plasma that approximately corotates with the Earth. The outer boundary of the plasmasphere, known as the plasmapause, is highly dynamic and represents the boundary between plasma controlled by the Earth's corotation electric field and plasma influenced by magnetospheric electric fields [*Lemaire and Gringauz*, 1998]. Owing to its dynamic nature and importance for understanding mass and energy flow in the inner magnetosphere, determining the location of the plasmapause has attracted significant attention, and a variety of techniques have been implemented for this purpose. Early studies of plasmapause location utilized whistler observations along with limited satellite observations [*Carpenter*, 1966; *Carpenter et al.*, 1968; *Gringauz and Bezrukikh*, 1976]. In situ satellite observations of the sharp plasma density gradient found at the plasmapause have also been used, resulting in the development of several empirical relationships between geomagnetic activity level and plasmapause radius [*Carpenter and Anderson*, 1992; *Moldwin et al.*, 2002; *O'Brien and Moldwin*, 2003]. General features of the plasmapause, such as its inward movement with increasing geomagnetic activity, were revealed by these observations. More recently, the global views of the plasmasphere and plasmapause afforded by the EUV instrument on the Imager for Magnetopause-to-Aurora Global Exploration satellite provided new insight into the nature of the plasmasphere. Such global observations revealed that the structure of the plasmapause is significantly more complex than previously thought and also demonstrated the connection between the plasmapause and other regions, such as the outer radiation belts [*Baker et al.*, 2004; *Darrouzet et al.*, 2009; *Goldstein et al.*, 2003, 2004; *Spasojevic et al.*, 2003].

[3] In addition to direct observation of the plasmapause location, various ionospheric observations are correlated with the plasmapause and have thus been employed to determine its location. Observations have revealed the close relationship between the location of the midlatitude electron density trough and the plasmapause [*Grebowsky et al.*, 1976; *Yizengaw and Moldwin*, 2005; *Yizengaw et al.*, 2005]. Additionally, *Anderson et al.* [2008] demonstrated that the plasmapause location corresponds closely to the light ion trough in the topside ionosphere. Although unable to reveal some of the finer-scale structures as effectively as methods

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such as direct EUV imaging, the use of ionospheric observations to determine the plasmapause is advantageous because relatively continuous observations can be made in different local time sectors. Furthermore, this approach can help maintain the continuity of observations during periods when other satellite observations of the plasmapause are unavailable.

[4] The high sample rate along with the global distribution of receivers makes observations of the GPS total electron content (TEC) ideal for study of the ionosphere and plasmasphere. Ground-based observations of GPS TEC are primarily influenced by electron densities in the F region [*Klobuchar*, 1996]; consequently, GPS TEC observations used to study the disturbed and quiet time ionosphere predominantly reveal characteristics of the F-region ionosphere [*Afraimovich et al.*, 2008; *Coster and Komjathy*, 2008; *Mendillo*, 2006]. Ground-based GPS TEC measurements can, however, also reveal information concerning the structure of the plasmasphere [e.g., *Foster et al.*, 2002]. Observations of TEC from GPS receivers on board low-Earth-orbit (LEO) satellites allow for the separation of the TEC into different altitude regions, enabling a unique perspective on the structure and dynamics of electron densities in both the F-region ionosphere and the topside ionosphere and plasmasphere. Furthermore, compared to ground-based observations, satellite observations of GPS TEC are advantageous because of the more complete global coverage that they offer. As a result of these advantages, GPS TEC observations from LEO satellites have been applied to study several geomagnetic disturbances to gain new insight into the dynamics of the storm-time ionosphere as well as the underlying physical mechanisms [*Mannucci et al.*, 2005, 2008; *Pedatella et al.*, 2009; *Yizengaw et al.*, 2006].

[5] The use of GPS TEC observations from LEO satellites has focused primarily on the study of ionospheric storms; however, LEO satellite observations of GPS TEC are well suited for the study of climatological features of the electron densities in the topside ionosphere and plasmasphere and the structure and dynamics of the plasmapause. Additionally, the regular sampling in different local time sectors afforded by LEO satellites makes them advantageous for use in the study of the plasmapause. In the present study, we make use of GPS TEC observations from the six-satellite Constellation Observing System for Meteorology, Ionosphere and Climate (COSMIC) to determine the location of the plasmapause throughout 2008. On the basis of these observations, the variation with geomagnetic activity and local time is illustrated. The COSMIC observations of the plasmapause are also used to demonstrate the occurrence of periodic oscillations in the plasmapause location. This represents a new approach for routine determination of the plasmapause location and is an innovative use of GPS receivers that are flown on LEO satellites for the primary purpose of precise orbit determination.

2. Data Processing

2.1. COSMIC Vertical Total Electron Content Observations

[6] Launched in April 2006, COSMIC consists of six satellites in 72° inclination orbits. For the present study, we focus only on 2008 when all satellites (with the exception of COSMIC 3, which is not used) were at an orbital altitude of ~800 km. The six satellites are distributed evenly in longitude and precess at a rate of ~12 min per day. COSMIC thus provides observations at 12 different local times on any given day, making the constellation ideal for ionospheric and plasmaspheric studies. To study both the neutral atmosphere and the ionosphere, each satellite is equipped with multiple payloads, including two GPS antennae for GPS radio occultation, two GPS antennae for precise orbit determination (POD), a tiny ionospheric photometer, and a triband beacon [*Rocken et al.*, 2000; *Cheng et al.*, 2006].

[7] The two POD antennae support the primary science objectives by allowing for orbital position estimates at the accuracy and precision necessary to perform GPS radio occultation. However, the GPS POD observations also provide a signal of opportunity. For the present study the GPS POD observations are used to determine the TEC between the COSMIC satellites at ~800 km altitude and the GPS satellite altitude of ~20,200 km. To obtain the TEC from the COSMIC POD observations, the raw GPS observations are first preprocessed using the Jet Propulsion Laboratory GPS Inferred Positioning System software to determine the phase-connected arcs and identify and attempt to correct any cycle slips [*Lichten and Border*, 1987]. The line-of-sight relative TEC is then determined using the standard technique of leveling the ambiguous carrier-phase TEC to the absolute pseudorange TEC [e.g., *Klobuchar*, 1996; *Mannucci et al.*, 1998]. Given that the absolute levels of TEC vertically above 800 km are generally less than 10 TECu (1 TECu = 10^{16} electrons/m^2), small errors in the leveling bias are relatively significant. Therefore, accurate estimation of the leveling bias is of utmost importance. The COSMIC POD observations of pseudorange are often corrupted by a significant multipath, which can be on the order of 20 TECu and results in errors in the estimation of the leveling bias. The multipath is thought to arise due to the GPS signal reflecting off of the solar panels and also the use of patch GPS antennae that do not suppress the multipath as well as other antennae (e.g., choke-ring antennae). Given the magnitude of the multipath effect and the relatively small values of absolute TEC, it is necessary to mitigate the effects of the multipath to accurately estimate the leveling bias. In estimating the leveling bias, we thus weight the observations according to the observed multipath. This is done by weighting each observation point based on the absolute value of the difference between the pseudorange TEC and carrier-phase TEC after removal of the mean value.

[8] Determining the absolute line-of-sight TEC requires accounting for the receiver and satellite differential code biases (DCBs). The DCBs result from instrumental biases that are frequency-dependent and are different for each receiver and transmitter. A model-assisted method is used to estimate the COSMIC satellite DCBs using only high-latitude, nighttime observations [*Heise et al.*, 2002] and the Global Core Plasma Model [*Gallagher et al.*, 2000]. We use the GPS satellite biases estimated by the Center for Orbit Determination in Europe (CODE) [*Hugentobler et al.*, 2004]. The absolute line-of-sight TEC observations are converted to vertical TEC (VTEC) using a geometric mapping function [*Klobuchar*, 1996]. We limit our observations to data above 65° elevation angle to minimize the impact of errors due to mapping function and/or spatial gradients.

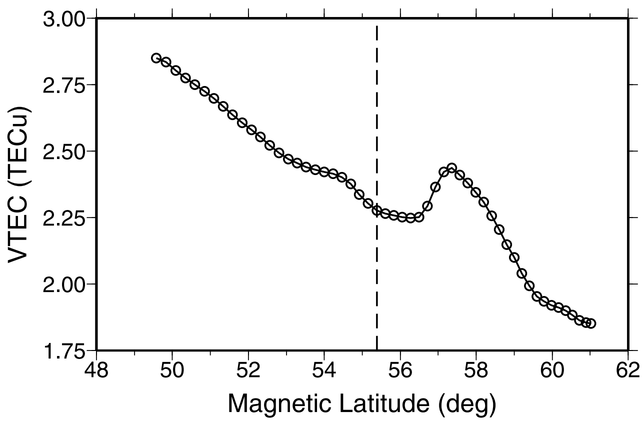

Figure 1. Vertical TEC observations for a single COSMIC pass. The estimate of the plasmapause location is indicated by the vertical dashed line. See text for details on determination of the plasmapause location.

[9] Owing to the significant level of multipath effect present in the COSMIC POD observations, it is important to assess the errors that this introduces into the VTEC observations and how effectively we are able to mitigate these effects. Although it is not possible to determine the absolute accuracy of the individual VTEC observations, an estimate of the precision can be obtained by comparing simultaneous observations using different GPS satellites. If no errors are present and there are no spatial gradients, simultaneous observations of VTEC should be identical. On the basis of 1 month of observations, the average absolute difference between simultaneous observations is found to be 1.89 TECu when the observations are weighted as detailed earlier compared to 2.42 TECu without implementing a weighting scheme to reduce the multipath effect. Thus, we may conclude that our weighting method is an effective means for mitigating the effect of multipath on estimating the absolute TEC. Minimizing this effect is desired to obtain a high-quality set of observations suitable for application to scientific studies. Furthermore, sufficiently minimizing the multipath effect allows for combining multiple data arcs, which improves the continuity of observations while the COSMIC satellites pass through the trough region. The ability to combine data arcs is useful in the event of carrier phase cycle slips and, in the present study, we combine VTEC observations for multiple GPS satellites if they are separated by less than 30 min in local time. Combining observations for multiple satellites may introduce some error due to structures in local time; however, this is done to increase the number of available plasmapause observations.

2.2. Determination of Plasmapause

[10] On the basis of the methods detailed earlier, we obtained a high-quality set of VTEC observations from the COSMIC satellites during 2008 that can be used to determine the location of the plasmapause. As previously demonstrated by *Yizengaw et al.* [2005], GPS TEC observations of the ionospheric midlatitude trough are correlated with the position of the plasmapause. In the present study, the COSMIC VTEC observations are used to determine the equatorward edge of the midlatitude trough and we define the plasmapause to be located at this point. The equatorward edge is defined as the location equatorward of the trough minimum where the gradient exceeds 0.10 TECu/degree. Each COSMIC satellite passes through the trough region four times per orbit. The trough is known to exhibit hemispheric asymmetry due to the larger offset between the geomagnetic and geographic poles in the Southern Hemisphere [e.g., *Sojka et al.*, 1985]. Therefore, in the present study, we only used Northern Hemisphere observations to ensure that any hemispheric differences do not influence the results. As an illustration of our method, the VTEC for a single pass is shown in Figure 1 along with the estimated location of the plasmapause. As can be seen in Figure 1, the COSMIC VTEC observations are capable of identifying the trough region and subsequently determining the location of the plasmapause.

[11] Although the observations shown in Figure 1 reveal a distinct midlatitude trough and allow for estimation of the plasmapause location, it should be noted that this is not always the case for a number of reasons. First, because only data above a 65° elevation angle are used, data gaps are prevalent. The presence of data gaps makes it impossible to unambiguously determine the plasmapause for many passes, and any data with gaps greater than 1 min are not analyzed. Furthermore, there are occasional "jumps" in the data that may result from changes in the GPS satellites used to compute the VTEC or cycle slips in the carrier-phase observations. Such jumps in the data may lead to inaccurate determination of the plasmapause location, and we thus do not use arcs that contain a greater than 0.3 TECu change in the VTEC from one epoch to the next. The aforementioned restrictions result in the elimination of a large number of passes and based on 1 year of COSMIC observations the location of the plasmapause has been determined for about 1800 passes, which represents ~19% of the possible crossings. Clearly, there are some drawbacks to the present method; however, the good spatial resolution and local time coverage of the COSMIC observations represent significant advantages and, thus, these observations provide a valuable new technique for studying the plasmapause.

3. Results and Discussion

3.1. Variation With K_p

[12] The location of the plasmapause is well known to vary with geomagnetic activity and generally moves inward (outward) with increasing (decreasing) activity levels [*Carpenter and Anderson*, 1992; *Moldwin et al.*, 2002; *O'Brien and Moldwin*, 2003]. Therefore, we illustrate the variation with geomagnetic activity to demonstrate the effectiveness of applying the COSMIC observations for determination of the plasmapause during 2008. The plasmapause position for all local times as a function of the maximum K_p in the previous 24 h is shown in Figure 2. It should be noted that the plasmapause observations during 2008 are biased toward a low geomagnetic activity level due to the relative absence of significant geomagnetic activity during this time period. Nonetheless, the reduction in plasmaspheric radius with increasing levels of geomagnetic activity is evident. The best-fit line to the COSMIC observations is also shown in Figure 2, along with the best-fit line to CRRES observations previously obtained by *Moldwin et al.* [2002]. The linear

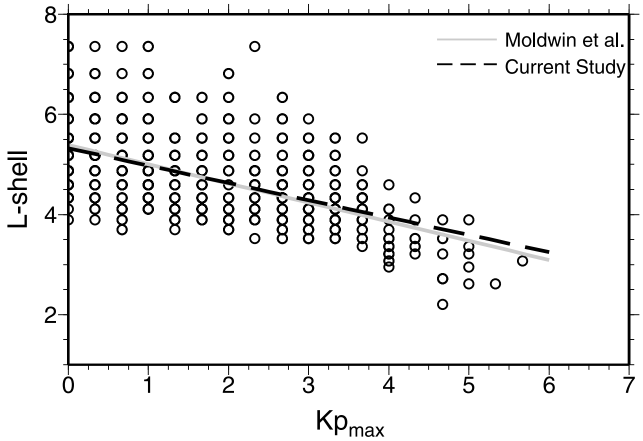

Figure 2. COSMIC observations of the plasmapause location during 2008 as a function of the maximum K_p in the previous 24 h for all local times. The linear best fit based on COSMIC observations is shown along with the relationship determined by *Moldwin et al.* [2002] from CRRES observations. Coefficients for both fits are provided in the text.

best fit is found to be $L_{pp} = 5.322 \pm 0.040 - (0.346 \pm 0.019) K_{p_{max}}$, compared to the *Moldwin et al.* [2002] result of $L_{pp} = 5.390 \pm 0.072 - (0.382 \pm 0.019)K_{p_{max}}$. The good agreement between the COSMIC results and previous observations indicates that VTEC observations from GPS receivers on board LEO satellites, such as the COSMIC, represent a useful means for routine determination of the plasmapause.

3.2. Local Time Variation

[13] The local time variation of the plasmapause location for different levels of geomagnetic activity during 2008 is shown in Figure 3. Both the raw observations and the mean plasmapause location within 2 h magnetic local time bins are presented. As expected, the COSMIC observations reveal a general decrease in plasmapause radius as the geomagnetic activity level increases. It is also clearly evident that there is significant variability in the plasmapause location about the mean value, with standard deviations on the order of 0.5–1.0 L. The variability is most pronounced at low levels of geomagnetic activity. Unfortunately, as noted previously, there are considerably fewer observations during periods of high geomagnetic activity compared to low levels of activity due to only using COSMIC observations during 2008. Therefore, the results for K_p greater than 4 may not be an accurate representation of the average plasmapause for high levels of geomagnetic activity.

[14] Previous studies of the plasmapause location as a function of local time have revealed both noon-midnight and dawn-dusk asymmetries [*Gringauz and Bezrukikh*, 1976; *Moldwin et al.*, 2002; *O'Brien and Moldwin*, 2003]. Although there is a slight asymmetry of ~0.25 L, the COSMIC observations in Figure 3 reveal a plasmapause that is generally invariant in local time and exhibits significant variability. There are several reasons why the COSMIC observations of the plasmapause may be more symmetric in comparison to previous observations. First, the local time variation presented in Figure 3 is representative of average conditions and does not reveal the instantaneous shape of the plasmapause. During periods of quiet geomagnetic activity, the plasmapause is known to exhibit significant structure in local time; however, the location of the bulge region is highly variable even over relatively short time scales [*Moldwin et al.*, 1994]. Such variations in the local time structure of the plasmapause may result in the observed plasmapause being circular in an average sense even though the instantaneous plasmapause exhibits significant structure. Additionally, the location of the trough minimum exhibits a local time dependency that is different than that of the plasmapause [e.g., *Werner and Prolss*, 1997] and, furthermore, *Yizengaw et al.* [2005] observed that the separation between the equatorward edge of the trough and the plasmapause tends to be larger during the daytime. As the present study assumes that the plasmapause is collocated with the equatorward edge of the trough, the local time structure of the trough combined with any local time difference in the relationship between the plasmapause and the equatorward edge of the trough may potentially result in the observed symmetry in local time. In addition to these shortcomings in the present method, the discrepancy with prior observations may be related in part to biases in other methods which may produce a more asymmetrical plasmapause. For example, CRRES observations used by *Moldwin et al.* [2002] and *O'Brien and Moldwin* [2003] suffer from insufficient sampling at high L during the daytime, which may result in greater local time asymmetry.

3.3. Periodicities During 2008

[15] During the declining phase of solar cycle 23, oscillations at periods of 7, 9, and 13.5 days have been observed in thermosphere neutral composition and density as well as in the ionosphere [*Crowley et al.*, 2008; *Lei et al.*, 2008a, 2008b]. Similar periodicities were also observed during 2008 in auroral electron power, electron fluxes in the outer radiation belt, and solar wind velocity [*Gibson et al.*, 2009]. These periodic oscillations in Earth's upper atmosphere are the result of recurrent geomagnetic activity due to periodic high-speed solar wind streams associated with coronal hole distributions on the Sun. Because the plasmapause location is correlated with the level of geomagnetic activity, one may surmise that the plasmapause should exhibit periodic oscillations during 2008 as well. Lomb-Scargle [*Lomb*, 1976; *Scargle*, 1982] periodogram analyses of the daytime (0700–1800 LT) and nighttime (2000–0500 LT) plasmapause locations during 2008 along with K_p are presented in Figure 4. Not surprisingly, 9 day periodicities are observed in K_p as well as the daytime and nighttime plasmapause. Weaker 13.5 day oscillations are also observed, although the 13.5 day period is not above the 95% significance level for the nighttime plasmapause. It is unknown why the 13.5 day oscillation is not significant in the nighttime plasmapause, but this may be related to a weaker dependence on geomagnetic activity and larger variability in the plasmapause during these local times [e.g., *Moldwin et al.*, 2002].

[16] Combined with the numerous previous studies on periodic oscillations in Earth's upper atmosphere, the identification of periodic oscillations in the plasmapause demonstrates that the entirety of near-Earth geospace is likely to be influenced by periodic high-speed solar wind streams. Given the importance of the plasmapause for controlling the flow of mass and energy in the inner magnetosphere,

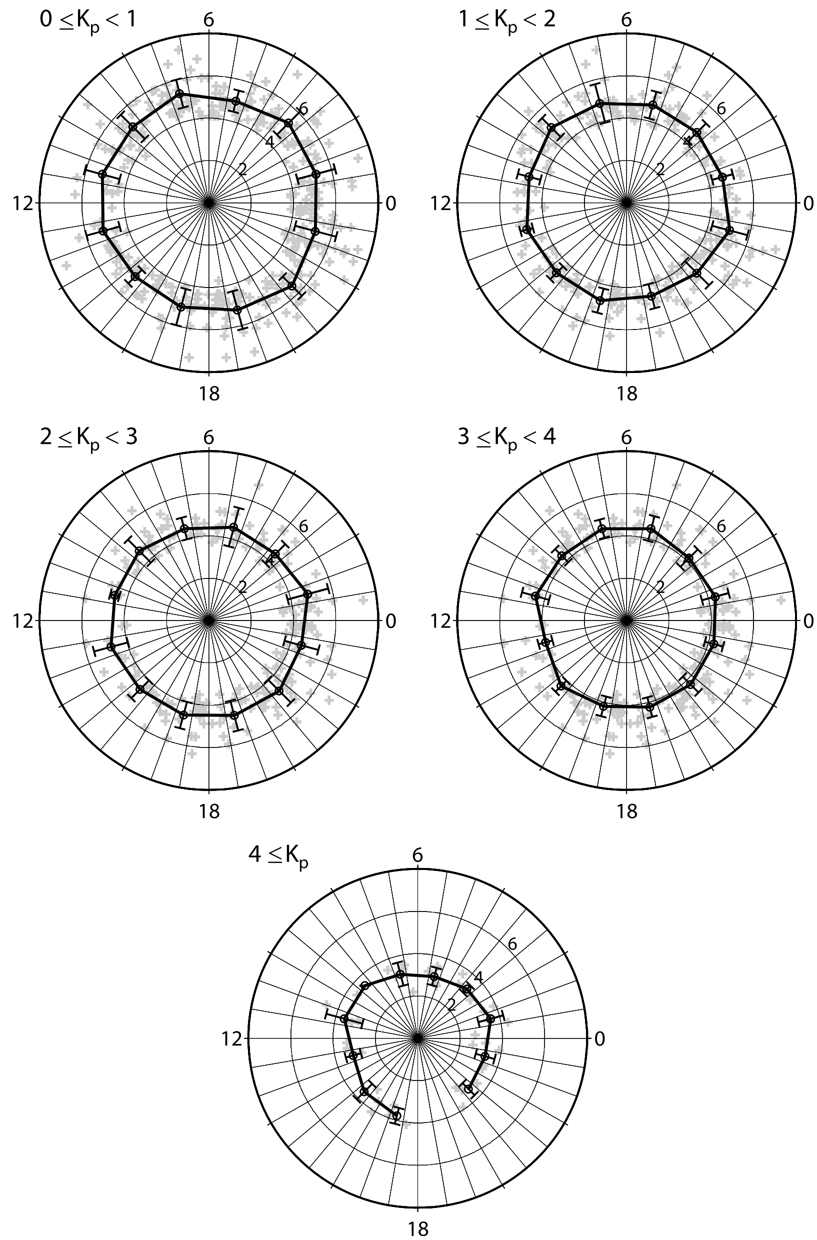

Figure 3. COSMIC observations of the plasmapause during 2008 as a function of magnetic local time for different levels of geomagnetic activity. Individual observations are indicated by the gray plus symbol. The solid black line indicates the mean and standard deviation within 2 h local time bins.

the presence of periodic oscillations in the plasmapause has significant implications for this region. Furthermore, observations have demonstrated that the inner edge of the outer radiation belt is closely tied to the plasmapause location [*Baker et al.*, 2004], and our results indicate that the location of the inner edge of the outer radiation belt region may also exhibit oscillations during the current solar minimum.

4. Conclusions

[17] A new approach for minimizing the impact of multipath errors on the retrieval of absolute GPS TEC was applied to measurements from the COSMIC satellite GPS POD antennae to obtain a high-quality data set of TEC observations during 2008. The observations are desirable for the study of electron densities in the topside ionosphere and plasmasphere due to the near-global coverage and even distribution in local time afforded by COSMIC. In the present study, the COSMIC VTEC observations are used to determine the plasmapause position throughout 2008. The variation of the COSMIC plasmapause observations with the level of geomagnetic activity is similar to the variation obtained by previous studies using different observation methods, indicating the effectiveness of using the COSMIC VTEC observations to routinely observe the location of the

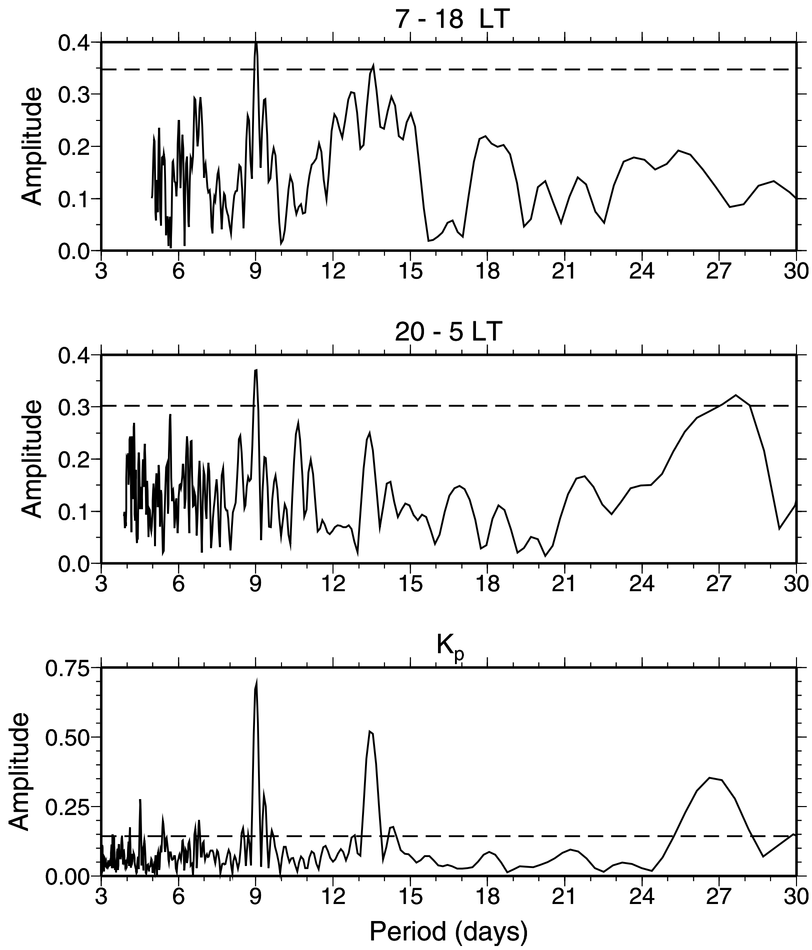

Figure 4. Lomb-Scargle periodograms of the COSMIC plasmapause location during 2008 for the (top) daytime and (middle) nighttime as well as (bottom) K_p. The 95% significance level is indicated by the horizontal dashed lines.

plasmapause. It is also observed that, in an average sense, the plasmapause is roughly symmetric in local time. However, there is significant variability and the plasmapause at any given time will exhibit significant structure in local time. Finally, the plasmapause is found to oscillate at periods of 9 and 13.5 days during 2008 due to recurrent geomagnetic activity associated with high-speed solar wind streams. Such oscillations further demonstrate the significant influence that high-speed solar wind streams have on the Earth's upper atmosphere and inner magnetosphere during the current solar minimum.

[18] The present study is the first to demonstrate the use of GPS TEC observations from LEO satellites for routinely determining the plasmapause. Although we focused solely on the COSMIC satellites for this purpose, the methods are applicable to any high-inclination satellite with a dual-frequency (nonocculting) GPS receiver that records both carrier-phase and pseudorange observations. A number of current satellites (e.g., CHAMP, Gravity Recovery and Climate Experiment, and Jason-2) satisfy this criterion and it is anticipated that many future satellites will as well. The results of the present study demonstrate that the GPS TEC observations from these satellites provide a valuable resource for future study of the plasmapause during both quiet and disturbed time periods.

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References

Afraimovich, E. L., E. I. Astafyeva, A. V. Oinats, Y. V. Yasukevich, and I. V. Zhivetiev (2008), Global electron content: A new conception to track solar activity, *Ann. Geophys.*, *26*, 335–344.

Anderson, P. C., W. R. Johnston, and J. Goldstein (2008), Observations of the ionospheric projection of the plasmapause, *Geophys. Res. Lett.*, *35*, L15110, doi:10.1029/2008GL033978.

Baker, D. N., S. G. Kanekal, X. Li, S. P. Monk, J. Goldstein, and J. L. Burch (2004), An extreme distortion of the Van Allen belt arising from the 'Halloween' solar storm in 2003, *Nature*, *432*, 878, doi:10.1038/nature03116.

Carpenter, D. L. (1966), Whistler studies of the plasmapause in the magnetosphere: 1. Temporal variations in the position of the knee and some

evidence on plasma motions near the knee, *J. Geophys. Res.*, *71*(3), 693–709.
Carpenter, D. L., and R. R. Anderson (1992), An ISEE/Whistler model of equatorial electron density in the magnetosphere, *J. Geophys. Res.*, *97*(A2), 1097–1108.
Carpenter, D. L., F. Walter, R. E. Barrington, and D. J. McEwen (1968), Alouette 1 and 2 observations of abrupt changes in whistler rate and of VLF noise variations at the plasmapause: A satellite-ground study, *J. Geophys. Res.*, *73*(9), 2929–2940.
Cheng, C.-Z. F., Y.-H. Kuo, R. A. Anthes, and L. Wu (2006), Satellite constellation monitors global and space weather, *EOS Trans. AGU*, *87*(17), 166.
Coster, A., and A. Komjathy (2008), Space weather and the global positioning system, *Space Weather*, *6*, S06D04, doi:10.1029/2008SW000400.
Crowley, G., A. Reynolds, J. P. Thayer, J. Lei, L. J. Paxton, A. B. Christensen, Y. Zhang, R. R. Meier, and D. J. Strickland (2008), Periodic modulations in thermospheric composition by solar wind high speed streams, *Geophys. Res. Lett.*, *35*, L21106, doi:10.1029/2008GL035745.
Darrouzet, F., et al. (2009), Plasmaspheric density structures and dynamics: Properties observed by the CLUSTER and IMAGE missions, *Space Sci. Rev.*, *145*(1–2), 55.
Foster, J. C., P. J. Erickson, A. J. Coster, J. Goldstein, and F. J. Rich (2002), Ionospheric signatures of plasmaspheric tails, *Geophys. Res. Lett.*, *29*(13), 1623, doi:10.1029/2002GL015067.
Gallagher, D. L., P. D. Craven, and R. H. Comfort (2000), Global core plasma model, *J. Geophys. Res.*, *105*(A8), 18,819–18,833.
Gibson, S. E., J. U. Kozyra, G. de Toma, B. A. Emery, T. Onsager, and B. J. Thompson (2009), If the Sun is so quiet, why is the Earth ringing? A comparison of two solar minimum intervals, *J. Geophys. Res.*, *114*, A09105, doi:10.1029/2009JA014342.
Goldstein, J., M. Spasojevic, P. H. Reiff, B. R. Sandel, W. T. Forrester, D. L. Gallagher, and B. W. Reinisch (2003), Identifying the plasmapause in IMAGE EUV data using IMAGE RPI in situ steep density gradients, *J. Geophys. Res.*, *108*(A4), 1147, doi:10.1029/2002JA009475.
Goldstein, J., B. R. Sandel, M. R. Hairston, and S. B. Mende (2004), Plasmapause undulation of 17 April 2002, *Geophys. Res. Lett.*, *31*, L15801, doi:10.1029/2004GL019959.
Grebowsky, J. M., N. C. Maynard, Y. K. Tulunay, and L. J. Lanzerotti (1976), Coincident observations of ionosphere trough and the equatorial plasmapause, *Planet. Space Sci.*, *24*, 1177–1185.
Gringauz, K. I., and V. V. Bezrukikh (1976), Asymmetry of the Earth's plasmasphere in the direction noon-midnight from Prognoz and Prognoz 2 data, *J. Atmos. Terr. Phys.*, *38*, 1071.
Heise, S., C. Stolle, S. Schluter, and N. Jakowski (2002), Differential code bias of GPS receivers in low earth orbit: An assessment for CHAMP and SAC-C, in *Earth Observation with CHAMP*, edited by C. Reigber, H. Luhr, P. Schwintzer, and J. Wicker, Springer, Berlin, doi:10.1007/b138105.
Hugentobler, U., et al. (2004), CODE IGS analysis center technical report 2002, in *IGS 2001–2002 Technical Reports*, edited by K. Gowey, R. Neilan, and A. Moore, Int. Global Navig. Satell. Syst. Serv. Cent. Bur., Jet Propul. Lab., Pasadena, Calif.
Klobuchar, J. A. (1996), Ionospheric effects on GPS, in *Global Positioning System: Theory and Applications*, vol. I, edited by B. W. Parkinson and J. J. Spilker, pp. 485–515, Am. Inst. Aeronaut. Astronaut., New York.
Lei, J., J. P. Thayer, J. M. Forbes, Q. Wu, C. She, W. Wan, and W. Wang (2008a), Ionosphere response to solar wind high-speed streams, *Geophys. Res. Lett.*, *35*, L19105, doi:10.1029/2008GL035208.
Lei, J., J. P. Thayer, J. M. Forbes, E. K. Sutton, and R. S. Nerem (2008b), Rotating solar coronal holes and periodic modulation of the upper atmosphere, *Geophys. Res. Lett.*, *35*, L10109, doi:10.1029/2008GL033875.
Lemaire, J. F., and K. I. Gringauz (1998), *The Earth's Plasmasphere*, Cambridge Univ. Press, New York.
Lichten, S. M., and J. S. Border (1987), Strategies for high-precision Global Positioning System orbit determination, *J. Geophys. Res.*, *92*, 12,751–12,762.
Lomb, N. R. (1976), Least-squares frequency analysis of unequally spaced data, *Astrophys. Space Sci.*, *39*, 447–462.
Mannucci, A. J., B. D. Wilson, D. N. Yuan, C. H. Ho, U. J. Lindqwister, and T. F. Runge (1998), A global mapping technique for GPS-derived ionospheric total electron content measurements, *Radio Sci.*, *33*(3), 565–582.
Mannucci, A. J., B. T. Tsurutani, B. A. Iijima, A. Komjathy, A. Saito, W. D. Gonzalez, F. L. Guarnieri, J. U. Kozyra, and R. Skoug (2005), Dayside global ionospheric response to the major interplanetary events of October 29–30, 2003 "Halloween Storms," *Geophys. Res. Lett.*, *32*, L12S02, doi:10.1029/2004GL021467.
Mannucci, A. J., B. T. Tsurutani, M. A. Abdu, W. D. Gonzalez, A. Komjathy, E. Echer, B. A. Iijima, G. Crowley, and D. Anderson (2008), Superposed epoch analysis of the dayside ionospheric response to four intense geomagnetic storms, *J. Geophys. Res.*, *113*, A00A02, doi:10.1029/2007JA012732.
Mendillo, M. (2006), Storms in the ionosphere: Patterns and processes for total electron content, *Rev. Geophys.*, *44*, RG4001, doi:10.1029/2005RG000193.
Moldwin, M. B., M. F. Thomsen, S. J. Barne, D. J. McComas, and K. R. Moore (1994), An examination of the structure and dynamics of the outer plasmasphere using multiple geosynchronous satellites, *J. Geophys. Res.*, *99*(A6), 11,475–11,481.
Moldwin, M. B., L. Downward, H. K. Rassoul, R. Amin, and R. R. Anderson (2002), A new model of the location of the plasmapause: CRRES results, *J. Geophys. Res.*, *107*(A11), 1339, doi:10.1029/2001JA009211.
O'Brien, T. P., and M. B. Moldwin (2003), Empirical plasmapause models from magnetic indices, *Geophys. Res. Lett.*, *30*(4), 1152, doi:10.1029/2002GL016007.
Pedatella, N. M., J. Lei, K. M. Larson, and J. M. Forbes (2009), Observations of the ionospheric response to the 15 December 2006 geomagnetic storm: Long-duration positive storm effect, *J. Geophys. Res.*, *114*, A12313, doi:10.1029/2009JA014568.
Rocken, C., Y.-H. Kuo, W. Schreiner, D. Hunt, S. Sokolovskiy, and C. McCormick (2000), COSMIC system description, *Terr. Atmos. Ocean Sci.*, *11*, 21–52.
Scargle, J. D. (1982), Studies in astronomical time series analysis. II. Statistical aspects of spectral analysis of unevenly spaced data, *Astrophys. J.*, *263*, 835–853.
Sojka, J. J., W. J. Raitt, R. W. Schunk, L. Parish, and F. J. Rich (1985), Diurnal variation of the dayside, ionospheric, mid-latitude trough in the Southern Hemisphere at 800 km: Model and measurement comparison, *Planet. Space Sci.*, *33*(12), 1375–1382.
Spasojevic, M., J. Goldstein, D. L. Carpenter, U. S. Inan, B. R. Sandel, M. B. Moldwin, and B. W. Reinisch (2003), Global response of the plasmasphere to a geomagnetic disturbance, *J. Geophys. Res.*, *108*(A9), 1340, doi:10.1029/2003JA009987.
Werner, S., and G. W. Prolss (1997), The position of the ionospheric trough as a function of local time and magnetic activity, *Adv. Space Res.*, *20*(9), 1717–1722.
Yizengaw, E., and M. B. Moldwin (2005), The altitude extension of the mid-latitude trough and its correlation with plasmapause position, *Geophys. Res. Lett.*, *32*, L09105, doi:10.1029/2005GL022854.
Yizengaw, E., H. Wei, M. B. Moldwin, D. Galvan, L. Mandrake, A. Mannucci, and X. Pi (2005), The correlation between mid-latitude trough and the plasmapause, *Geophys. Res. Lett.*, *32*, L10102, doi:10.1029/2005GL022954.
Yizengaw, E., M. B. Moldwin, A. Komjathy, and A. J. Mannucci (2006), Unusual topside ionospheric density response to the November 2003 superstorm, *J. Geophys. Res.*, *111*, A02308, doi:10.1029/2005JA011433.

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