Terannual variation in the $F_2$ layer peak electron density ($N_mF_2$) at middle latitudes

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[1] Ionosonde data from 33 stations in three longitude sectors from 1969 to 1986 have been used to study the seasonal variations of ionospheric $F_2$ layer peak electron densities ($N_mF_2$). We found that there is a periodic oscillation in daytime $N_mF_2$ with a period of 4 months (terannual). Our analysis shows that there is a very good phase match between the annual and semiannual oscillations and the terannual oscillations. These three oscillations vary with solar activity in the same way: large amplitudes during solar maximum. The amplitude of the terannual oscillation is also correlated with the product of the amplitudes of annual and semiannual oscillations. These suggest that the terannual oscillation might be related to the nonlinear interaction between the annual and semiannual oscillations. In addition, the terannual oscillation is stronger in the midlatitude region in the Northern Hemisphere than in the Southern Hemisphere. Furthermore, there are large differences in the ionospheric seasonal variations between daytime and nighttime. No obvious terannual oscillation signature is seen in the nighttime $F_2$ layer.


1. Introduction

[2] The peak electron density of the ionospheric $F_2$ layer ($N_mF_2$) has large seasonal variations. These variations, which have been referred to as “anomalies,” depart significantly from the “normal” seasonal behavior that is predicted by the Chapman theory if the ionosphere is controlled mainly by the solar zenith angle. These anomalies include the winter anomaly in which $N_mF_2$ is greater in winter than in summer, the annual anomaly in which the global $N_mF_2$ is greater in December than in June, and the semiannual anomaly in which $N_mF_2$ is the greatest in equinox [e.g., Yonezawa, 1971; Torr and Torr, 1973; Zou et al., 2000; Rishbeth et al., 2000; Ma et al., 2003; Yu et al., 2004; Rishbeth and Muller-Wodarg, 2006]. The causes of these anomalies are still unknown and remain a hot topic of current ionospheric research [Zou et al., 2000; Rishbeth et al., 2000; Richards, 2001; Mendillo et al., 2002; Kawamura et al., 2002; Ma et al., 2003; Rishbeth, 2004; Rishbeth and Muller-Wodarg, 2006; Oliver et al., 2008; Ren et al., 2011; Mikhailov and Perrone, 2011]. The winter anomaly is a daytime phenomenon that occurs mostly at medium and high solar activity at middle latitudes and appears to be stronger in the Northern Hemisphere. It has been suggested that the thermospheric composition difference between summer and winter is the plausible process producing the winter anomaly. This summer-winter composition change is caused by the prevailing upwelling of molecular rich air in the summer hemisphere and the downwelling of atomic rich air in the winter hemisphere [e.g., Rishbeth and Setty, 1961; Zou et al., 2000; Rishbeth et al., 2000; Yu et al., 2004; Pavlov and Pavlova, 2005].

[3] The semiannual anomaly of $N_mF_2$ has been observed globally. Its strength appears to increase with solar activity. The maximum of the semiannual anomaly usually occurs in April and October and they are also much larger at noon than at night [e.g., Torr and Torr, 1973; Richards, 2001; Ma et al., 2003; Zhang et al., 2005; Rishbeth and Muller-Wodarg, 2006; Zhao et al., 2007; Liu et al., 2009]. The exact mechanisms of the semiannual anomaly have not been fully understood [e.g., Rishbeth, 1998, 2004]. Theoretical studies suggested that the semiannual anomaly at middle latitudes might be also caused by the variations of the neutral circulation in the thermosphere-ionosphere system which changes the ratio between atomic oxygen and molecular nitrogen concentrations [Zou et al., 2000; Rishbeth et al., 2000; Qian et al., 2009].

[4] The ionospheric annual anomaly or asymmetry, occurs at both day and night, and at all levels of solar activity [e.g., Torr et al., 1980; Richards, 2001; Zhang et al., 2005; Rishbeth and Muller-Wodarg, 2006; Zhao et al., 2007; Zeng et al., 2008; Liu et al., 2009]. The cause of the annual asymmetry has been recently studied by Zeng et al. [2008] using the COSMIC satellite data and the thermosphere ionosphere electrodynamics general circulation model (TIEGCM). They carried out a series of TIEGCM numerical studies and concluded that the displacement of the geomagnetic poles from
Figure 1. Observed $N_mF_2$ at three stations (Wakkanai, Karaganda, and Point Arguello; black lines) and fitted $N_mF_2$ using equation (1) (red lines) are shown in the first row. Residuals between the observed and fitted $N_mF_2$ are shown in the second row. Observed $N_mF_2$ (black lines) and fitted $N_mF_2$ using equation (2) (red lines) are shown in the third row. Residuals between the observed and fitted $N_mF_2$ from the third row are shown in the fourth row.
The winter anomaly and annual anomaly are in phase in the Northern Hemisphere with maximum in December and minimum in June. In the Southern Hemisphere they are out of phase by 180°. Observations have shown that the winter anomaly effect is relatively weak in the Southern Hemisphere [Yu et al., 2004]. At most longitudes this effect is overwhelmed by the normal seasonal changes of \(NmF_2\) with the solar zenith angle (high electron densities in December southern summer) and the annual anomaly. Thus, in most places in the Southern Hemisphere \(NmF_2\) shows the same annual variations as those in the Northern Hemisphere with high densities occurring in December [e.g., Yu et al., 2004].

Up until now, in almost all the studies of the seasonal variations of \(NmF_2\), the ionospheric peak density has been expressed by three terms: the annual mean, and the annual and semiannual components [e.g., Rishbeth et al., 2000; Mendillo et al., 2002; Yu et al., 2004; Liu et al., 2009]

\[
NmF_2(d) = A_0 + A_1 \cos(\omega_0(d - d_1)) + A_2 \cos(2\omega_0(d - d_2)),
\]

(1)

where \(\omega_0 = \frac{2\pi}{365}\) is the angular frequency of Earth rotation, \(d\) is the day number, \(A_1\), and \(A_2\) are the amplitudes of annual and semiannual anomalies, and \(d_1\) and \(d_2\) are the phases of these two anomalies.

The first row in Figure 1 gives examples of this approach of fitting the seasonal variations of \(NmF_2\). The thick black lines show \(NmF_2\) observed at three Northern Hemisphere ionosonde stations in 1979, while the red lines are the fitted \(NmF_2\) using equation (1). The fitted \(NmF_2\) followed the general trend of the seasonal variations of the observed \(NmF_2\). This trend includes equinoctial peaks of \(F_2\) peak electron densities (semiannual anomaly) as well as higher peak densities in December than in June (annual anomaly).

The most striking feature in the first row, however, is the evident large deviations or residues (\(\Delta NmF_2\)) between the observed and the fitted \(NmF_2\) (second row). Thus, the annual and semiannual components cannot fully represent the actual seasonal variations of the ionosphere at these stations. An examination of the residuals reveals that they are not random noises but have a clear three-peak structure with relatively large amplitudes. This suggests that there might be a 4 month (terannual) periodic variation in \(NmF_2\).

When we include this terannual component into the fitting formula, equation (1) becomes:

\[
NmF_2(d) = A_0 + A_1 \cos(\omega_0(d - d_1)) + A_2 \cos(2\omega_0(d - d_2)) + A_3 \cos(3\omega_0(d - d_3)),
\]

(2)

### Table 1. Stations Whose Data Are Used in This Study

<table>
<thead>
<tr>
<th>Station</th>
<th>Code</th>
<th>Geographic Latitude</th>
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</table>

Stations Whose Data Are Used in This Study

The most striking feature in the first row, however, is the evident large deviations or residues (\(\Delta NmF_2\)) between the observed and the fitted \(NmF_2\) (second row). Thus, the annual and semiannual components cannot fully represent the actual seasonal variations of the ionosphere at these stations. An examination of the residuals reveals that they are not random noises but have a clear three-peak structure with relatively large amplitudes. This suggests that there might be a 4 month (terannual) periodic variation in \(NmF_2\). When we include this terannual component into the fitting formula, equation (1) becomes:

\[
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\]

(2)
where $A_3$ and $d_3$ are the amplitude and phase of the terannual oscillation. The third and fourth rows in Figure 1 show the fitted $N_m F_2$ and residuals using equation (2). In this case we obtain a much better fitting of $N_m F_2$ and the residuals become smaller and appear to be random on the seasonal or monthly scale (see the fourth row of Figure 1). The amplitudes of the terannual oscillations at these three stations are roughly the same as those of the semiannual

![Figure 2](image1.png)

**Figure 2.** Spectra of the 18 year daytime $N_m F_2$ (from 1968 to 1986) for (left) the Asian/Australian sector, (middle) the European/African sector, and (right) the America sector.

![Figure 3](image2.png)

**Figure 3.** Same as Figure 2 but for the nighttime.
variations (cf. $A_2$ and $A_3$ in the third row). Thus, the terannual oscillation appears to be an important component of the seasonal variation of the ionosphere. Feichter and Leitinger [1997] also showed that there is a 4 month component of the annual variation of the $F_2$ peak electron density at two ionosonde stations of Lindau and Graz and that the amplitude of this component is comparable to those of the annual and semiannual components. However, no detailed studies on the terannual component have been done in the work of Feichter and Leitinger [1997] as well as in other investigations of the seasonal variations of the ionosphere.

The main purpose of this paper is first to show that the terannual variation is a ubiquitous phenomenon in the ionosphere and an important component of the seasonal variation of the ionospheric $F$ layer. We then present global morphology of the ionospheric terannual oscillation and give information of the location and timing of its occurrence, as well as its strength relative to those of the annual and semiannual oscillations. The paper is organized as follows. In section 2 we present the data set used in this work. In section 3 we analyze $N_mF_2$ spectra and carry out detailed studies of the terannual oscillation. Possible mechanisms for the terannual variations will be discussed in section 4.

2. Data Set

In this study, we used $N_mF_2$ observed by 33 ionosonde stations from 1969 to 1986 in three longitudinal sectors: the Asian/Australian sector, the European/African sector, and the American sector. The data covered low-, middle-, and high-latitude regions in the Southern and Northern Hemispheres. These ionosonde stations are listed in Table 1. The ionospheric data (CD-ROM of Ionospheric Digital Database) used in this paper are provided by the World Data Center (WDC-A and WDC-D). The geomagnetic indexes ($Dst$ and $Ap$) and the solar radio flux at the wavelength of 10.7 cm ($F_{10.7}$) are obtained from http://spidr.ngdc.noaa.gov/spidr/

In our analysis, $N_mF_2$ data for each day and at each station were separated into two local time (LT) bins: 10:00–
16:00 LT (daytime) and 22:00–04:00 LT (nighttime). For each bin averaged $N_m F_2$ values were used.

3. Terannual Oscillations of $N_m F_2$

[12] Figure 2 gives Fourier transform spectra of the 18 year data of daytime $N_m F_2$ for three longitudinal sectors: the Asian/Australian sector, the European/African sector, and the American sector. There were very strong annual spectral peaks (period around 365 days) at all stations, especially at middle latitudes in the Northern Hemisphere. These annual spectral peaks were weaker at higher latitudes in the Europe and American sectors. In addition, the annual spectral peak in the Northern Hemisphere was much stronger than that in the Southern Hemisphere.

[13] There were also obvious semiannual spectral peaks (period around 180 days) in daytime $N_m F_2$ at each station. The amplitudes of these semiannual spectral peaks were stronger in the lower-latitude region than in the high-latitude region. In the Asian/Australian sector, the semiannual spectral peaks in the Northern Hemisphere were stronger than those in the Southern Hemisphere, whereas in the European/African sector, the semiannual spectral peaks in the Southern Hemisphere were stronger than those in the Northern Hemisphere. In the American sector the semiannual peaks were strongest in the lower-latitude region, especially in the Northern Hemisphere. These features of annual and semiannual spectral peaks are consistent with previous results of the global structures of annual and semiannual anomalies [e.g., Torr and Torr, 1973; Richards, 2001; Ma et al., 2003; Zhang et al., 2005; Rishbeth and Muller-Wodarg, 2006; Zhao et al., 2007; Zeng et al., 2008; Liu et al., 2009].

[14] The most interesting feature in Figure 2 is that there were evident terannual (about 120 day) spectral peaks in the $N_m F_2$ spectra in the Northern Hemisphere. In the middle latitude region, the amplitudes of the terannual spectral peaks were almost the same as those of the semiannual spectral peaks at several stations, for instance, at Magadan (53.2° MLAT), Irkutsk (41.1° MLAT), Wakkanai (53.3° MLAT), Kokubunji (25.5° MLAT) and Yamagawa (20.4° MLAT) in the Asian sector, stations with magnetic latitudes higher than 30°N in the European and American sectors. In the Southern Hemisphere, however, the terannual spectral peaks were relatively weak.

[15] Figure 3 shows the Fourier transform spectra of nighttime $N_m F_2$. There were obvious annual spectral peaks at each station. The semiannual spectral peaks were very weak except near the equator in the Asian/Australian and American sectors. It is interesting to note that there were...
almost no terannual spectral peaks at almost all stations at night. Therefore, in the rest of the paper we will focus mainly on discussing terannual oscillations in the daytime $F_2$ layer at middle latitudes in the Northern Hemisphere.

[16] We first investigate the temporal variations of the annual, semiannual, and terannual components of the seasonal variations of daytime ionospheric peak densities. The regression analysis method described in section 1 (i.e., least squares fitting; see equation (2)) has been employed to calculate the amplitudes and phases of these three components of $N_mF_2$ variations for each year from 1969 to 1986 for the three longitude sectors examined in this paper.

[17] The year-to-year variations of the amplitudes and phases of the annual, semiannual and terannual components in these three sectors are shown in Figures 4–6, respectively. The amplitudes of the annual (black), semiannual (red) and terannual (green) components are given in the first rows. The yearly averaged $F_{10.7}$ (red lines with squares) is also plotted in Figures 4–6 to show the level of solar activity. From Figures 4–6 we can see that the amplitudes of the annual, semiannual, and terannual components have pronounced solar cycle variations. During solar maximum years around 1980, all three components were strong. But at solar minimum near 1975, these components were relatively weak. In all three longitude sectors the annual component had the largest amplitude, followed by the semiannual and terannual components. At some stations, for instance, at Magadan (53.2°N) in the Asian sector, Leningrad (56.2°N) and Moscow (58.8°N) in the European sector, and Ottawa (56.8°N) in the American sector, the amplitudes of the terannual component were almost the same as those of the semiannual component.

[18] The average phases of the annual, semiannual and terannual components at each station (second rows in Figures 4–6) were calculated from the regression analyses. These three components had relatively constant phases that did not change with solar activity. For the annual component, the phase (black lines) was about 0 days thus the maximum magnitude of the annual oscillation occurred near the winter solstice of January/December. The phase of the semiannual oscillations was about 110 days and the maximums of the semiannual oscillation were near March/April and September/October, which were just shortly after the vernal/autumn equinoxes. For the terannual oscillations, the phase was about 70 days and so the maximums of the terannual oscillations occurred around February/March, June/July and October/November (cf. Figure 1).

[19] Figure 2 shows clearly that ionospheric daytime terannual oscillations occurred almost at all stations, were not limited to just one or two stations, although at some stations,
especially in the Southern Hemisphere, the amplitudes of terannual oscillations were relatively small. Terannual oscillations also had the same solar cycle variations as those of annual and semiannual oscillations. At middle latitudes in the Northern Hemisphere terannual oscillations were an important component of ionospheric seasonal variations, and their amplitudes were about the same as those of the semiannual oscillations.

4. Discussion

[20] Variations of ionospheric peak electron densities are caused by either changes in external drivers, such as solar EUV radiation and geomagnetic activity, or nonlinear dynamics within the thermosphere-ionosphere system. In section 4 we examine possible mechanisms for producing the observed terannual oscillation in the ionosphere.

[21] First, we examine whether external drivers, solar radiation and geomagnetic activities, are the cause of terannual oscillation in the ionosphere. Figure 7 gives Fourier spectra of $F_{10.7}$ (a proxy for solar EUV radiation) and geomagnetic activity indexes $Ap$ and $Dst$. There are clearly no noticeable terannual components (~120 days) in both solar radiation ($F_{10.7}$) and geomagnetic activity, although there is a strong semiannual oscillation (~180 days) in geomagnetic indexes. Thus, the terannual oscillation is unlikely caused direct by changes in solar and geomagnetic activities.

[22] It is well known that the processes that determine the plasma density of the ionosphere are nonlinear. The nonlinear interaction of periodic variations of the ionospheric electron density, such as annual and semiannual oscillations, can result in different modes of the variations of ionospheric electron densities. Here we explore the possibility that ionospheric terannual oscillation is related to the nonlinear interaction between the annual and semiannual oscillations in the ionosphere.

[23] Assume that there is a nonlinear interaction between annual and semiannual oscillations. Then the phase of the resultant oscillation must satisfy the following equations:

$$\omega_0 d_1 + 2 \omega_0 d_2 = 3 \omega_0 d_3, \quad (3a)$$

or

$$d_3 = \frac{d_1 + 2d_2}{3}, \quad (3b)$$

where $d_1$, $d_2$, and $d_3$ are the phases of the annual, semiannual oscillations and their child/resultant oscillation, respectively. In Figures 4–6 we present the phases calculated by the above formula in the second rows (blue triangle lines in the second row) for each station. It is evident that the calculated phases using equations (3a) and (3b) matched those directly obtained from the observations (green lines in the third row) very well at all stations in the three longitude sectors. This means that these three oscillations satisfy the phase relationship (equations (3a) and (3b)) of nonlinear interaction.

[24] Another interesting fact that may also suggest that the terannual variation is related to the nonlinear interaction of the annual and semiannual variations is that the terannual oscillations were noticeable only when the annual and semiannual oscillations were both strong at the same time. For example, Figures 4–6 show that during solar maximum
near 1980, all three oscillations were strong. However, during solar minimum near 1975, all three oscillations were weak simultaneously. Figure 2 also shows that at lower latitudes, the semiannual oscillation was very strong, but the annual oscillation was weak, and the terannual oscillation was very weak too. In Figures 4–6 we give scatterplots of $A_3$ and $\sqrt{A_1A_2}$ in the third rows, where $A_1$, $A_2$, and $A_3$ are the amplitudes of annual, semiannual and terannual oscillations obtained from the regression analysis, respectively. From these plots, we can see that the amplitudes of the terannual oscillation increased monotonically with the product of the amplitudes of annual and semiannual oscillations. Thus, the amplitude of the terannual oscillation seems to be related to the product of the amplitudes of annual and semiannual variations. The terannual oscillation occurs when both the annual and semiannual oscillation are large. This happens at middle latitudes in the Northern Hemisphere. The lack of terannual oscillation at night is probably related to the fact that semiannual oscillations were relatively weak at that time. All these features suggest that the terannual variation in $N_mF_2$ is probably related to the nonlinear interaction between the annual and semiannual oscillations. Further studies using a combination of modeling and global observations are needed to fully uncover the cause of this terannual variation. The terannual component has an obvious modulation on the seasonal variation of the ionosphere, especially in the middle latitude in the Northern Hemisphere. It thus should be further studied for its production mechanisms and its role in the overall picture of the seasonal variations of the ionosphere, and should be included in empirical modeling of the ionosphere.

[25] In addition to annual, semiannual, and terannual oscillations, there are also other high-order harmonic oscillations in the ionosphere, such as 3 month (1/4 year), and 1/5 year oscillations, although they are much weaker. Figure 8 gives two examples of these harmonic oscillations at Yamagawa (20.4N) and Kokubunji (25.5N) in the Asian/Australian sector. From Figure 8 we can see clearly oscillations with periods of 1 year, 1/2 year and 1/3 year, as well as very weak but noticeable harmonic oscillations with periods of 1/4 and 1/5 year. The 3 month (1/4 year) oscillation is probably produced by the nonlinear interactions between the annual and terannual and between the semiannual oscillations themselves. The nonlinear interaction between the semiannual and terannual oscillations can generate the oscillation with the period of 1/5 year. These high-order oscillations are secondary oscillations and thus usually weaker than their parent annual and semiannual oscillations. The mechanisms of producing these harmonic components clearly need further observations and modeling studies.

5. Summary

[26] In this paper, 18 year (1969–1986) data of ionospheric $F_2$ peak densities observed by ionosondes at 33 stations located in the Asian/Australian sector, the European/African sector, and the American sector were used to analyze the seasonal variations of the ionospheric $F_2$ layer peak density. These data cover low, middle, and high latitudes in both the Southern and Northern Hemispheres.

[27] We have shown that the terannual oscillation of the ionospheric peak electron densities is a common component of the seasonal variation of the ionosphere. It occurs almost globally and primarily during daytime. The strongest terannual (4 months) oscillation happens in the daytime $F_2$ layer at middle latitudes in the Northern Hemisphere. This terannual oscillation has a close correlation with ionospheric annual and semiannual oscillations. Our results show that during solar max, these three oscillations were strong simultaneously, and during solar minimum, they were all weak at the same time. In addition, the terannual oscillation in the Northern Hemisphere was stronger than that in the Southern Hemisphere. There was not obvious terannual oscillation in the $F_2$ layer at the nighttime.

[28] There are no terannual components in either solar radiation or geomagnetic activity, thus they are unlikely the direct source of this terannual oscillation. However, the close correlation between the annual and semiannual oscillations...
and the terannual oscillations, including their phases and amplitudes, suggests that the terannual oscillation in the ionosphere is probably related to the nonlinear interaction of the annual and semiannual oscillations. There is also a possibility that lower/middle atmospheric oscillation may introduce or affect the terannual oscillation through dynamic and electrodynamic coupling with the thermosphere and ionosphere system. Further global observations and physics based modeling are needed to fully uncover the characteristics and mechanisms of the seasonal variations of the ionospheric $F_2$ layer density, including the 4 month variation that is presented in this paper.

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References


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