SCIENCE CHINA
Technological Sciences

• Article •

January 2015 Vol.58 No.1: 174–180
doi: 10.1007/s11431-014-5709-8

Analysis of the ionospheric variability based on wavelet decomposition

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Received April 23, 2014; accepted July 15, 2014; published online December 17, 2014

In this work, the ionospheric variability is analyzed by applying the wavelet decomposition technique to the noontime foF2, F10.7, interplanetary magnetic field (IMF) Bz, Ap, and lower thermospheric temperature at pressure of 10^{-4} hPa in 2002. Results show that the variance of periodic oscillations in the ionosphere is largest in the 2–4-day period and declines with the increase of the period. The maximum variance of the periodic oscillations in solar irradiation is in the 16–32-day period. For geomagnetic activities, most of the variance is about equally distributed on intervals of periods shorter than 32 days. Variance distributions of IMF Bz and lower thermospheric temperature are similar to those of the ionosphere. They show the maximum in the 2–4-day period and decline with the increase of the period. By analyzing the distributions of the variances, the potential connections between the ionosphere and the external sources are discussed.

ionosphere, variability, foF2, Wavelet decomposition, 2–32-day period

Citation: Shi H, Zhang D H, Liu Y M, et al. Analysis of the ionospheric variability based on wavelet decomposition. Sci China Tech Sci, 2015, 58: 174−180, doi: 10.1007/s11431-014-5709-8

1 Introduction

The ionosphere exhibits variability because of complicated processes and changeable sources from above and below. A detailed classification of these sources probably responsible for ionospheric variability has been given by Rishbeth and Mendillo [1]. Briefly, these sources and processes can be classified into four broad categories, including solar ionizing radiation, solar wind and geomagnetic activity, neutral atmospheric condition, and electrodynamics. No doubt, the characteristic variations in the ionosphere due the sources should be manifested in some way. Nevertheless, although the connections between the ionospheric variation and the sources are physically clear, it is difficult to separate the contribution of these sources to ionospheric variability quantitatively for the given ionospheric observations.

The most powerful source of the ionospheric variability is the solar irradiation, which provides most of the ionizing energy. There are the 11-year solar cycles, quasi-27-day solar rotations and the day-to-day basis that lead to the corresponding periods in the ionospheric variations. Some other periodic variations in the ionosphere are also possibly related to the solar irradiation. Also, the ionospheric plasma densities could be changed because of the solar flux-induced variations in the neutral composition, neutral temperatures, winds, and conductivities [2,3]. The solar activity dependences of the ionospheric peak electron density (NmF2) have been analyzed by Liu et al. [4] that the observed change rate of NmF2 can be reproduced by a modulated solar activity factor. Also, the solar flares, active regions, and some other violent activities can all lead to changes in the state of the ionosphere [5,6].

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The interaction of interplanetary conditions with the earth's magnetosphere that include the interplanetary magnetic field (IMF) and the solar wind energetic particles, can bring in a series of modulations in the ionosphere [7–9]. Researches have shown that on magnetically quiet days, a large part of the day-to-day variability of the ionosphere seems to be attributed to the polarity changes of the IMF Z component (in GSM coordinates) Bz. The position of the main ionospheric trough may also change as an effect of the IMF sector structure and of the IMF Bz component turnings [10–13]. Bremer et al. [14] statistically studied the effects of the structure of the IMF on the ionospheric variability and found that negative Bz values can cause distinct negative ionospheric effects. The effects of the solar wind particle on high-latitude ionosphere have been studied thoroughly. Under some extreme conditions, for example, during coronal mass ejections (CMEs), these effects can be found even in the middle- and low-latitude ionosphere. Besides the extreme conditions, the routine effects of the normal solar wind, such as the 9- and 7-day periodic oscillations in the global mean total electron content (TEC) related to the solar wind streams, which is more often observed during the declining phase of the solar cycle and in the solar minimum, have also been found in the ionosphere [15,16].

It is well known that the influence from the lower atmosphere is one of the primary origins of the ionospheric variability. Through some physical processes, waves in the lower atmosphere can propagate to the height of the ionosphere and bring in corresponding periodic oscillations in the ionosphere. The periods of these variations vary from minutes to tens of days and overlap some of the solar variations. Obviously, the identification of the ionospheric variations that originated from the lower atmosphere is worthy of attention. In recent years, studies on the ionospheric variability focus mainly on estimating the effects [17–19] such as planetary waves (PWs) and phenomena such as thunderstorms, typhoons, hurricanes, tornadoes, and even seismological events that are all potential origins of the ionospheric variability [20–22]. Although it has been widely recognized that this type of oscillations are generally related to the global scale PWs generated in the lower atmosphere, there are some other studies indicating that they are related to the solar wind. Using wavelet filter algorithms, Borries et al. [23] estimated that 38%–42% of the PW-type oscillations observed in TEC are related to the quasi-periodic variability of the EUV, solar wind speed, and geomagnetic disturbances. Focusing on the PW-type responses of the thermosphere/ionosphere system to the forcing from above and below during a major sudden stratospheric warming (SSW), Mukhtarov et al. [24] studied the periodic components of the ionospheric oscillation, and found that the observed global ionospheric oscillations with periods of ~9, ~14, and ~24–27 days are approved to be of solar origin and the ~18-day wave is allocated to a 18-day PW observed in the stratosphere/mesosphere/lower thermosphere region. Besides the oscillations with periods of days, the day-to-day variability is another major subject in the study of ionospheric variability. Forbes et al. [2] found that under quiet geomagnetic conditions, the variability of NmF2 because of the meteorological influences, is 25%–35% at periods of a few hours to 1–2 days and 15%–20% at periods of PWs (2–30 days). Also, considering the possible differences in the ionosphere between day and night, Rishbeth and Mendillo [1] also studied the ionospheric variability and found that for years of medium solar activity, the standard deviation of the NmF2 are 20% by day and 33% by night. It was concluded that the geomagnetic activity is a major cause of the ionospheric variability, though "meteorological" causes transmitted from lower levels may make a comparable contribution.

The spectrum of the ionospheric short-period variation is formed by various sources from above and below, external and internal. Most studies focus on certain origins and cover part of the periods with spectral analysis and band pass filters [25–27]. It should be noticed that the spectral peaks and band pass filtered signals are both limited by the width of the bands. To avoid the loss of information, the wavelet decomposition method is applied. The method, as well as the data set used in this study, will be introduced in Section 2. Considering the complicated relation between the ionosphere and those space environmental factors, the variance distributions of the periodic oscillations are calculated instead of the direct correlation between the original series or the filtered signals. In Section 3, for the period intervals of 2–64 days, the variance distribution of the critical frequency of the ionospheric F2-region (foF2) and its possible relation with F10.7 index, IMF Bz, Ap index, and lower thermospheric temperature will be analyzed.

2 Data and method

The noontime ionospheric foF2 in 2002, contemporaneous F10.7 index, IMF Bz, Ap index and the lower thermospheric temperature are used in this study. Considering the latitudinal difference of the ionospheric variability, two Chinese ionosonde stations at the mid- and low-latitudes, respectively, are selected. Their geographical locations and geomagnetic locations are given in Table 1. It can be seen that these two stations locate in the same longitude zone, and the magnetic latitude difference between them is over 15 degrees, covering from mid to low geomagnetic latitude. BP440 is a mid-latitude station. The ionosphere at this latitude is rarely disturbed by the equatorial fountain effect and the high-latitude auroral heating, which means that its status is relatively stable. GU421 is a low-latitude station under the northern crest of the equatorial anomaly. The ionospheric status at this latitude is strongly influenced by the equatorial fountain effect. The IMF Bz is observed by the ACE (advanced composition explorer). Based on the

Table 1 Station coordinates (degrees), both geographic and geomagnetic

Site ID	GeoLat	GeoLong	MagLat	MagLong
BP440	40.1	116.3	29.5	186.8
GU421	23.1	113.4	12.4	184.6

consideration of temporal resolution and the local time dependence in foF2, the 1-hour average of Bz at noontime of the local time of the two stations are used. The temperature is observed by SABER (sounding of the atmosphere using broadband emission radiometry) on the TIMED (thermosphere, ionosphere, mesosphere energetics and dynamics) satellite. The temperature at the pressure of 10^{-4} hPa (altitude about 100 km) is selected and the daily average is calculated within two areas (5°×25°) of the globe, corresponding to the locations of BP440 and GU421, respectively.

For analyzing the periodic variations, the wavelet "db6" is used to perform a multi-level one-dimensional wavelet decomposition. The component of the original data at any single level can be reconstructed after decomposition [28–30]. In this work, the period scales of the reconstructed levels are 2–4, 4–8, 8–16, 16–32 and 32–64 days. After excluding these "zero mean" periodic components from the original data, there is still a secular trend containing some periodic information with periods longer than 64 days. As an example, the original series and the decomposed components of F10.7 and daytime foF2 at BP440 during 2002 are presented in Figure 1. The top two panels are the original data of F10.7 and foF2. Downward from the second two panels are the levels of decomposition in the order of the period. The last row shows the long-period trends.

Comparing the decompositions of F10.7 and foF2, the most obvious difference is the contrast in the amplitudes of the first five periodic variations. For F10.7, the variation at the period of 16–32 days shows largest amplitude, although for foF2, the largest amplitude seems to be at the short periods of 2–4 or 4–8 days. The distribution of periodic oscillations provides significant information of the original data and could be used to represent the periodic characteristics. To quantitatively analyze the variations, a quantification method is needed. Based on the lossless decomposition and the mean zero feature of the wavelet decomposition results, the variance percentage of each level is calculated by the following formula to reveal the variability:

$$\text{Variance\%}_i = \frac{\text{Variance}_i}{\sum_{i=1}^{n} \text{Variance}_i} \times 100\%,$$

where Variance_i is the variance of the wavelet decomposition results at level i.

3 Results and discussion

Figure 2 shows the variance distribution of periodic oscillations in the ionospheric foF2 at two stations. The variance percentages at both stations declines with the increase of the period. More than 50% of the variance concentrates upon the 2–8 days short-period variations, whereas variations

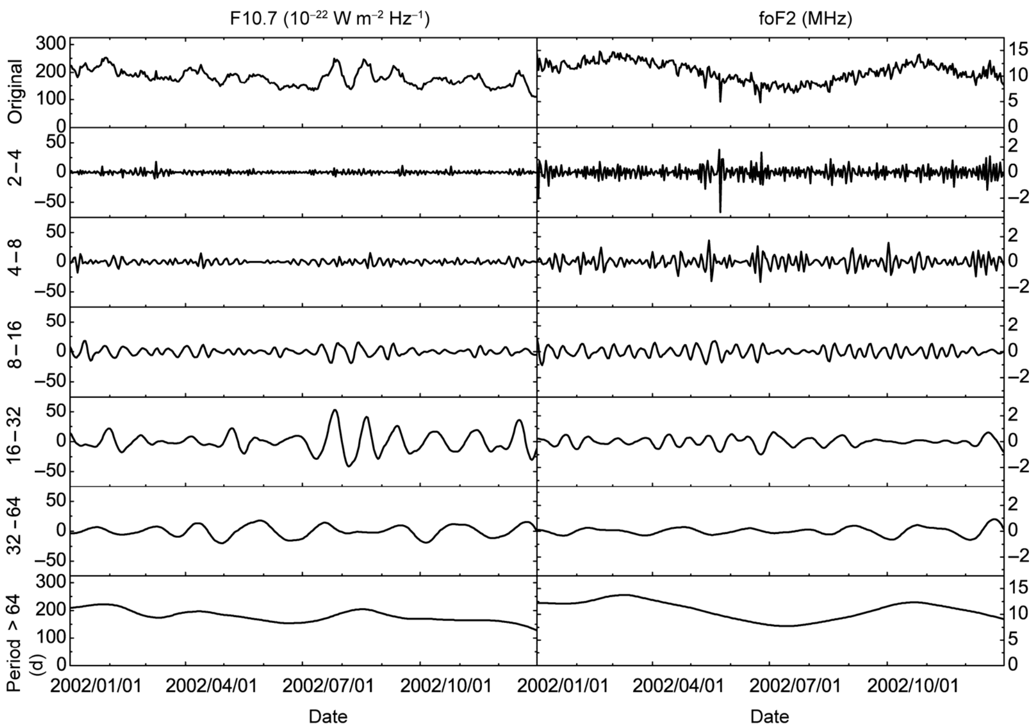

Figure 1 Original data and wavelet decompositions of F10.7 and noontime foF2 at BP440 during 2002. From top to bottom are the original data, the 2–4, 4–8, 8–16, 16–32, 32–64-day periodic variations and the long period trends.

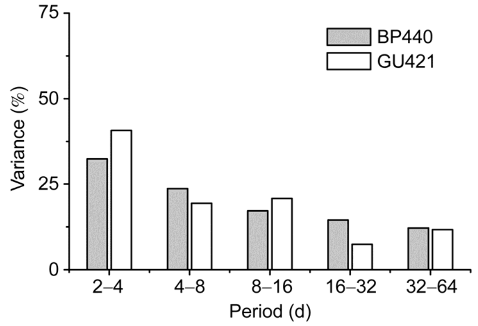

Figure 2 The variance percentages in the ionospheric foF2 at two stations in East-China. The grey columns stand for the BP440 station and the white ones for the GU421 station. The horizontal ordinates correspond to the period in the form of logarithm and the vertical ordinates correspond to the variance percentage.

with periods longer than 8 days take less than half of the variances. This indicates that the periodic oscillations in the ionosphere are more concentrated on short periods. Still there are some differences between the two stations. Compared with the mid-latitude station BP440, the variance percentages at the low-latitude station GU421 are higher at periods of 2–4 and 8–16 days, lower at periods of 4–8 and 16–32 days, and approximately the same at 32–64 days.

To study the origins of ionospheric variability, the variance percentages of the periodic oscillations in F10.7, IMF Bz, Ap, and lower thermospheric temperature are calculated and their distributions are shown in Figure 3. Panel (a) is the distribution of the variances of the periodic oscillations in F10.7. The significant maximum is at the 16–32-day period, which covers the quasi-27-day solar rotation cycle. This 16–32 days variation takes over 60% out of the solar variance and dominates the 2–64 days interval. For the other periods, the percentage of variance is lowest at the period of 2–4 days and increase along with the period. Using band-pass filter and some other methods, it has been found that there are also some quasi-27-day variations in the ionosphere and they are correlated with those in the solar radiation [31]. However, the variance percentages of the 16–32-day periodic oscillations in foF2 at two stations are both lower than 20%, which are far less than that of the corresponding period of F10.7. This may suggest that the solar rotation effect in the ionosphere is not as much as the effects from other sources. On the other hand, it could be noticed that the 2–4 days variance of F10.7 takes the smallest part in the 2–64 days interval, whereas the variance of foF2 at this band is the maximum of all periods. This has already been reported by some studies that changes in the NmF2 due to the day-to-day solar photon flux variation are relatively small [2]. Comparing the variance distributions of F10.7 and foF2, it is suggested that the solar originated quasi-27-day variations take a minor part in all the variations of the ionosphere. Meanwhile, the 2–4 days component in the solar irradiation is not the main source of the ionospheric 2–4 days variations.

Figure 3(b) is the distribution of variances of the periodic oscillations in Bz. It shows that the variance percentage declines with the increase of the period. The 2–4 days oscillations of Bz take over 50% of the variance and variations at the second period of 4–8 days take more than 25% out of the whole. This distribution is quite similar to those of foF2, but there are still some differences between them. At both 2–4 and 4–8-day periods, the variance percentages of Bz are always higher than those of foF2. This means that the

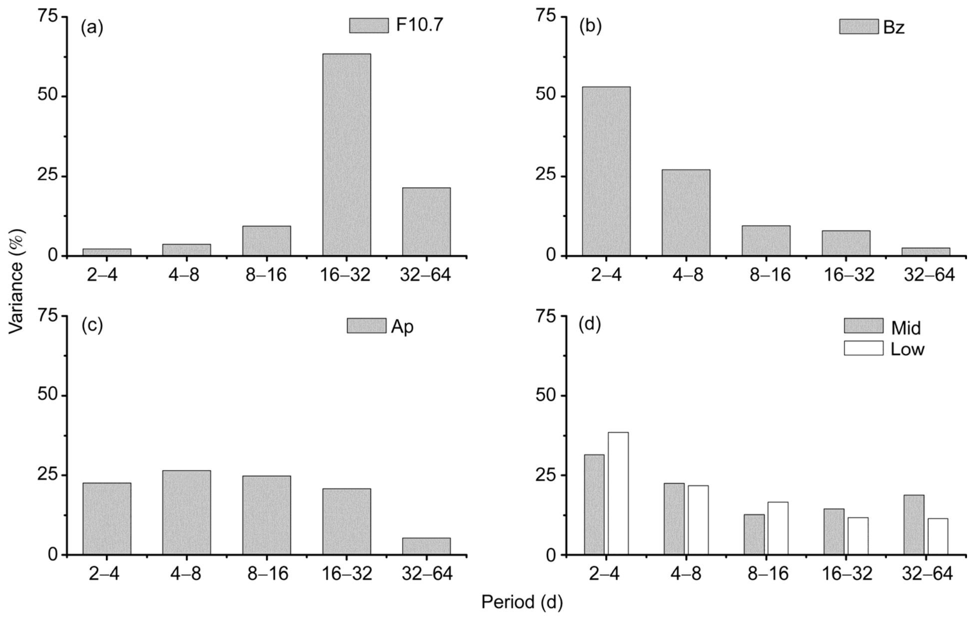

Figure 3 The variance percentages of different period variations in F10.7, Bz, Ap, and lower thermospheric temperature. In panel (d), the grey columns stand for the mid-latitude and the white ones for the low-latitude. The horizontal and vertical ordinates are both the same with those in Figure 2.

periodic variations of the IMF Bz are more concentrated on the shorter periods in the 2–64 days interval than those of the foF2. It should be noted that the 1-hour-average Bz in noontime is used to study the variance of the periodic oscillations. Actually, according to the researches, the short-period parts of the variation in IMF Bz, in most cases, the polarity changes, provide its main contribution to the changes in the state of the ionosphere [10–13]. Temporal scales of polarity changes because of the IMF sector boundary crossings are about several days. On the other hand, temporal scales of the ΔBz-changes in the IMF are about a few hours [14]. In this study, the daily noontime Bz provides general information of the periodic variation in the IMF Bz, which might not be able to reveal the ΔBz-changes. But the IMF sector boundary crossings, as well as the periodic variations in the IMF without polarity changes, are kept in the course of the wavelet decomposition. Based on the factor of most variances of periodic oscillations in the IMF Bz concentrating on short periods of 2–8 days, it could probably be suggested that it is the short-period variations in the IMF Bz providing the main contribution of the IMF Bz polarity turnings and periodic variations to the changes in the ionosphere. However, as the interaction between the IMF and the ionosphere is complicated and there are time delays for some processes, it is still difficult to determine the contribution from the IMF to the ionosphere.

The variance percentages of Ap are shown in Figure 3(c). At the first four period intervals, the variance percentages are all around 25%, leaving less than 10% to the longest period of 32–64 days. This indicates that for periods shorter than 64 days, most part of the periodic variations in the geomagnetic field activity distribute averagely on periods shorter than 32 days. However, this average is approximate. It could be noticed that despite the period of 2–4 days, variance percentages of the other three periods show a slightly decreasing trend with the period. Rishbeth and Mendillo [1] have calculated the geomagnetic component of the ionospheric variability at low-level fluctuations of activity. The estimated contribution is about 13% to the total daytime variability of the ionosphere. Also, Xiong et al. [32] showed that the geomagnetic oscillations are the most important drivers for the PW-type oscillations in the ionosphere with dominant periods of 5, 10, and 13.5 days, whereas the PWs in the mesosphere/lower thermosphere winds are the main drivers for the quasi-2-day oscillations in the ionosphere. They evaluated all of the possible events in 2002 and 2003 driven by geomagnetic oscillations and found that more than 70% of the events have a relationship with the geomagnetic oscillations with 5- and 10-day periods. Our results indicate that the variance percentages of Ap at periods of 4–8 and 8–16 days add up to more than 50% of the whole. The geomagnetic field is affected by the interplanetary conditions such as the IMF and solar wind. And these two factors both contain the 27-day period component which is a result of the solar rotation. Thus, the geomagnetic activity index Ap does show considerable variance in the period interval of 16–32 days, covering the 27-day period. However, in the IMF and solar wind, there are shorter periods such as 9 days [15,16] and day-to-day variations [10–14] which may lead to corresponding oscillations in the geomagnetic field. According to our results, their contributions to the geomagnetic activity are as much as the part from solar 27-day rotation. And it is the combination of effects from multiple sources that lead to the averagely distributed variances of periodic variations with periods lower than 32 days. The variations of the geomagnetic field at these periods may probably provide their main contributions to the ionospheric variability on an average. But an accurate estimation still needs some deeper research.

For studying the atmosphere-ionosphere coupling, the variance percentages of the temperature at a pressure of 10^{-4} hPa are calculated. The temperature is measured by SABER using remote sensing technology and the altitude at this pressure level is about 100 km. The results are presented in Figure 3(d). For both the areas, the maximum variance percentage is at the 2–4-day period. The minimum variance percentage is at the 8–16-day period for the mid-latitude area and at the 32–64-day period for the low-latitude area. The sum of the variance percentages at the 2–8-day period takes more than 50% out of the whole. Most of the variations in the temperature lie in the short period bands. This feature is similar to that of foF2. Some more agreements could be found by comparing the variance distributions between those of foF2 and temperature at the periods of 2–32 days. One agreement is that the variance distributions for both parameters are more concentrated on the 2–4 days short period band. The other one lies in the latitudinal differences. As mentioned earlier, there are some latitudinal differences in the variance distribution of foF2. For the period of 2–32 days, these differences also exist in the variance distribution of temperature. Compared with the mid-latitude area, the variance percentages at the low-latitude area are higher at periods of 2–4 and 8–16 days and lower at periods of 4–8 and 16–32 days. The similarities between the variance distribution of the temperature and foF2 provide some evidence of the atmosphere-ionosphere coupling. In fact, the atmospheric effects on the ionosphere come from both above and below [24]. On one hand, according to studies on the PWs, the PW-type oscillations in the ionosphere are apparently connected with the upward penetration of PWs and meteorological influences [21,26,27,33]. It should be noticed that although some of the waves in the lower atmosphere cannot propagate upward to the height of the F region, they can still affect the ionospheric F region by modulating the wind system in the dynamo region and composition [34]. The resultant electrodynamics associated with the waves is also important in the ionospheric variability. In recent years, the effects on the ionosphere from below are being paid more and more attention to [17–27]. The lower atmosphere is realized to be one of the major sources of the ionospheric variability [1,2]. On the other hand, recent studies by Xu et al. [35,36] have shown that heating of the magnetospheric origin in the auroral region is most likely the cause of the variations in the daily mean thermospheric mass density and neutral temperature. Using satellite observations, they found that under quiet geomagnetic conditions, there are strong longitude variations in the daily mean thermospheric mass density. The positive density peaks are always located near the magnetic poles and the high-density regions extend toward the lower latitudes and even into the opposite hemisphere. Strong longitudinal variations have also been found in temperature in the high-latitude lower thermosphere that persist over all seasons and are confirmed by the comparison of two model runs with and without auroral heating. In short, the upward and downward processes in the atmosphere-ionosphere coupling are both very important. As the variations from above and below are mixed in the ionosphere, it is hard to distinguish their contributions to the variances. But the similarities between foF2 and temperature still provide positive evidence for confirming the paradigm of atmosphere-ionosphere coupling.

The variance distributions of periodic oscillations in foF2 and space environmental parameters are analyzed and compared. Although the similarities or differences of the variance distributions cannot directly identify the effects on the ionosphere, they are still useful for analyzing the potential contributions of various factors based on the known physical processes of the interactions between the ionosphere and the origins of its variability. It is known that the thermosphere-ionosphere system responds to external forcing from various sources differently. As the source of the ionization of the ionosphere, variations of the solar irradiation directly lead to changes in the electron density [4–6]. The IMF sector structure and Bz turnings can also cause disturbances in the ionosphere [7–14]. The geomagnetic activity effects on the ionosphere are more complicated and there are often time delays between the geomagnetic activity events and disturbances in the ionosphere [37–39]. And for the atmosphere-ionosphere coupling, the influences can be both upward and downward. Various waves and oscillations in the neutral atmosphere with wide bands of periods are able to affect the ionosphere directly or indirectly [21,26,27,33]. The auroral heating can also change the thermospheric mass density and neutral temperature [35,36]. In most cases, the periodic oscillations in the origins lead to ionospheric variations at the corresponding bands of periods. Based on this premise, it is feasible for us to deduce possible connections between factors from the in variance distributions of periodic variations. However, the interactions between the sources and the ionosphere are more complicated than linear correlation. Some disturbances in the ionosphere because of specific causes do show the disagreement with their sources in the amplitudes and periods. Because of the limit of the dataset and the analyzing method in this study, it is hard for us to identify these kinds of events. More detailed classification of the periodic oscillations in the ionosphere and their causes will be studied in future analyses.

4 Summary

The variance distributions of the periodic variations of noontime foF2, F10.7, IMF Bz, Ap, and neutral atmosphere temperature in 2002 are analyzed using the wavelet decomposition method. Results show that the variance in the ionosphere is the largest at the 2–4-day period and decline with the increase of the period. The maximum variance of the periodic oscillations in solar irradiation is on the 16–32-day period. For geomagnetic activities, most of the variance is about averagely distributed on periods shorter than 32 days. The variance distributions of IMF Bz and lower thermospheric temperature are similar to those of the ionosphere. Their variances of periodic oscillations show the maximum at the 2–4-day period and decline with the increase of the period. It is known that the state of the ionosphere is influenced by sources from above and below, external and internal, and in most cases, the periodic oscillations in the origins can lead to corresponding periodic variations in the ionosphere. Based on comparing the variance distributions of periodic variations, contributions of the solar irradiation, IMF Bz, geomagnetic field and lower thermosphere are qualitatively estimated. It is suggested that the solar originated quasi-27-day variations take a minor part in all the variations of the ionosphere. Most variances of the periodic oscillations in the IMF Bz concentrate on short periods of 2–8 days, providing the main contribution of IMF Bz polarity turnings and periodic variations to the changes in the ionosphere. The variations of the geomagnetic field at periods of 2–32 days may probably provide their main contributions to the ionospheric variability averagely. The distributions of the variances of periodic oscillations of lower thermospheric temperature, for both latitudes, show agreement with those of foF2. This may provide a positive evidence for confirming the paradigm of atmosphere-ionosphere coupling. Because of the complex interactions between the ionosphere and the origins, the connections between them still need further investigation. It is recommended that some more factors and improvements in the research techniques should be considered in future studies on the ionospheric variability.

This work was supported by the National Natural Science Foundation of China (Grant Nos. 41174134 and 41274156), and the National Basic Research Program of China ("973" Project) (Grant No. 2011CB811405). The ionosonde data is from the National Key Laboratory of Electromagnetic Environment, China Research Institute of Radio wave Propagation.

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