

Frequency structure of IAR spectral bands and parameters of middle and upper ionosphere

A.S. Potapov¹, T.N. Polyushkina¹, B.V. Dovbnaya², B. Tsegmed^{1,3}, R.A. Rakhmatulin¹, and A.V. Podlesnyi^{*1}

¹Institute of Solar-Terrestrial Physics SB RAS, P.O.Box 291, Irkutsk 664033, Russia, e-mail: potapov@iszf.irk.ru

²Borok Geophysical Observatory of Institute of Physics of the Earth RAS, Borok, Yaroslavl region 152742, Russia, e-mail: dovbnaya@inbox.ru

³Research Center for Astronomy and Geophysics MAS, Ulaan-Baator, Mongolia, e-mail: tseg@iszf.irk.ru

Abstract

Continuous magnetic observations of IAR emission at the mid-latitude observatory Mondy performed by search-coil magnetometer LEMI-30 in the period from March 2010 to May 2011 are analyzed and compared with results of the simultaneous ionosphere sounding. We show good correlation of diurnal and seasonal IAR frequency variations with changes in the critical frequency f_0F_2 of the ionosphere. An attempt is made to model diurnal variation of IAR frequency calculating expected frequency scale of emission with use of IRI-2012 model. The results show good agreement with measurements, but contain systematic and random errors.

1. Introduction

Ionospheric Alfvén resonator (IAR) is an interesting subject of research. Its multiband electromagnetic emission in the frequency range between 0.5 and 10 Hz was first discovered in mid-eighties of the last century [1]. IAR emission is a manifestation of Alfvén waves captured between the lower part of ionosphere and a bend of plasma density in the region of transition from the ionosphere to magnetosphere at the height of about 3000 km [2]. Frequency of discrete spectral bands (DSP) and spacing between them are determined by the geometry of the resonator and the Alfvén speed in its cavity; the change in band frequency during the day with a minimum around noon and a maximum after midnight or in the early morning hours is due to diurnal variation of ionospheric parameters. Close connection of DSP mode and features with state of the ionosphere motivates many authors to study the details of this connection, and make suggestions about how to use observations of the spectral structure of the electromagnetic background in the range of 0.5-10 Hz for sounding ionospheric parameters and clarifying ionospheric models [3, 4].

In this paper, we analyze continuous magnetic observations made in the mid-latitude observatory Mondy using the induction magnetometer LEMI-30 in the period from March 2010 to May 2011. Low noise level at the observatory, high sensitivity of the magnetic sensors and the proximity of observation period to the minimum of solar activity have helped us to acquire a large enough sample of distinct DSP occurrences (350 events). Fig. 1 shows a typical example of winter event. The following sections describe briefly characteristics of the equipment used, processing technique, morphological features of the data acquired, including seasonal variation of DSP duration. We compare DSP variations with changes in f_0F_2 frequency measured simultaneously in Irkutsk. At last we try to model diurnal variation of DSP frequency calculating expected frequency scale of emission with use of IRI-2012 model. Results obtained are discussed in the last section of paper.

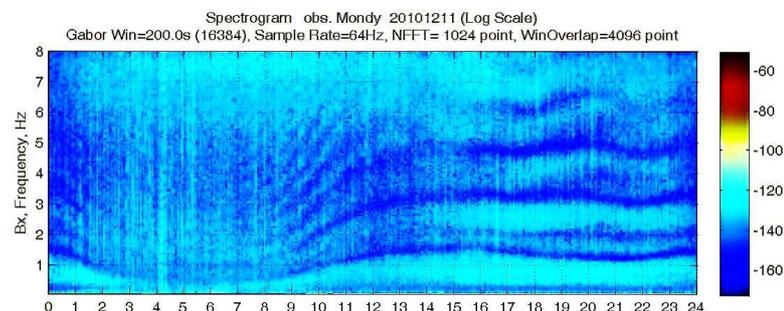


Fig. 1. An example of spectrogram with discrete spectral bands of IAR emission.

2. Equipment and Processing Technique

Sayan Solar Observatory Mondy (geographic coordinates $\varphi = 51.6^\circ$, $\lambda = 100.9^\circ$; McIlwain parameter $L = 2.1$) is situated near the border between Russia and Mongolia. Search-coil magnetometer LEMI-30 of Lviv Center of Ukrainian

Institute of Space Research measures magnetic signals within 0.001–30 Hz frequency range. Noise level does not exceed 0.2 pT/Hz^{1/2} at 1 Hz and 0.2 pT/Hz^{1/2} at 10 Hz frequency. ADC has 24 digits. Sampling rate is 60 Hz.

Since Sayan Solar Observatory does not have any ionosounding equipment, we used data from DPS-4 digital ionosounder installed in Irkutsk, about 260 km from the observatory. Latitude difference between the two points is less than 0.6°, Irkutsk is located north. As main ionospheric data we used 15-min values of critical frequency f_0F_2 .

Digital magnetic records in the range of 1-10 Hz were processed using computer code specifically developed for the study purposes in MATLAB language. The program calculates dynamic spectrum of the signal in two components and builds daily spectrogram in coordinates "frequency-time". The intensity of the signal at a given frequency in a given time is displayed in color. Spectrograms obtained were analyzed visually. Usually we managed to make measurements of 5-6 harmonics (bands), but more often three or four. These data we used for detailed comparison with changes in ionospheric parameters and to calculate the correlation coefficients and regression line between harmonics and critical frequency variations of the ionosphere F_2 layer.

3. Morphology of DSP

Intensity of IAR emission is rather weak and usually it is difficult to find it against noisy background. But in our case, a set of favorable conditions for ULF measurements stipulated high quality of observations. Experience of visual processing of spectrograms obtained showed that the most suitable for digitizing is the second harmonic frequency of the signal; the first harmonic is often noisy owing to lower-frequency irregular emission, and the higher harmonics are not always distinct due to the natural decay of the IAR signal amplitude with frequency.

The observation period (March 2010 – May 2011) coincides in time with beginning of ascending branch of solar cycle 24 and is characterized by low solar and magnetic activity. Mean occurrence rate of DSP was almost 90% that is much higher comparing with occurrence of these structures reported in earlier papers [4, 5]. We found that duration of DSP observation within a day strongly depends on season. Fig. 2 is a comparison between time interval of IAR emission and duration of nighttime. It is clear from the figure that the emission is a nighttime event; DSP are mainly observed during shadowing of the lower ionosphere.

4. DSP Frequency and f_0F_2

Since the observed discrete spectral bands are formed by capturing low-frequency emission in the ionospheric Alfvén resonator being ionospheric structure, the behavior of the main characteristics of DSP should closely correlate to variations of ionospheric parameters, primarily to changes in the electron concentration. In turn, the electron number density in the F_2 layer is uniquely linked to the critical frequency f_0F_2 , measured by ionosonde: $f_0F_2 = 8.98 \cdot 10^{-3} N_e^{1/2}$, where number density is measured in cm⁻³, and critical frequency in MHz.

We compared behavior of DSP frequency and f_0F_2 depending on the season. To do that, we calculated a reverse value of $1/f_0F_2$ for 15 monthly median values of critical frequency and plotted them in Fig. 3 along with mean values of frequency scale Δf_{IAR} , that is, the spacing between neighbor bands of the IAR emission. Overall progress of the averaged monthly ionospheric characteristics and DSP matches well, although there is a discrepancy at the transition from summer to autumn months of 2010.

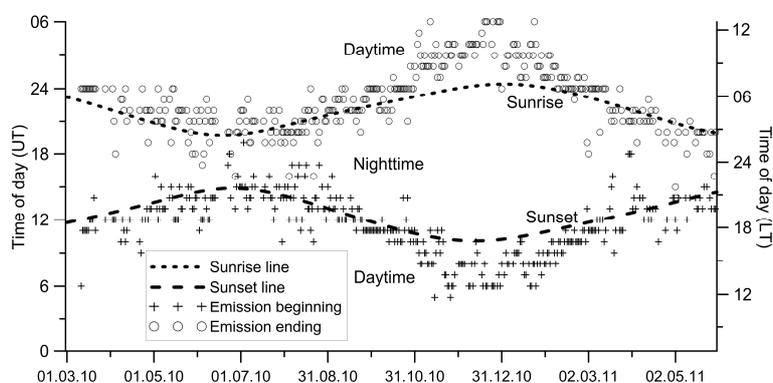


Fig. 2. Time of beginning (crosses) and ending (circles) of DSP in different seasons. Dashed lines show time of sunrise and sunset.

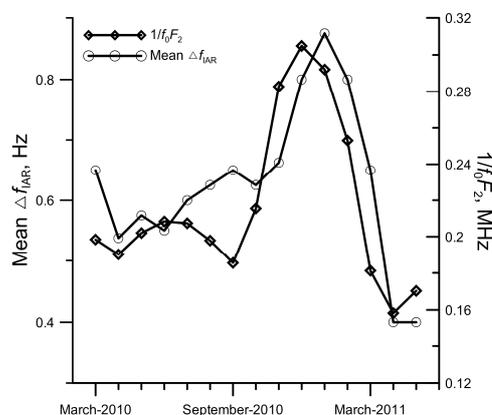


Fig. 3. Comparison between seasonal dependence of $1/f_0F_2$ and variations in DSP frequency gap Δf_{IAR} .

5. Model of the IAR spectrum formation

The literature offers different versions of the model of the ionospheric Alfvén resonator [6, 3, 7]. The models are based on the resonance conditions of Alfvén wave reflection from the lower and upper ionosphere and capture analysis of Alfvén waves in the cavity being formed along the magnetic field lines between the local maxima of the Alfvén speed ("walls" of the resonator) in the F₂ layer and at altitude of 2,000-6,000 km. All authors agree that for resonance of waves with wave speed A in a uniform cavity of length L , the frequency f of harmonic number n is given by $f = (n + \Phi)/(2L/A)$. In reality, the cavity is not uniform, and the phase factor Φ is complicated function of conditions on the walls of the resonator. To exclude phase factor Φ we can measure not frequency f , but frequency scale $\Delta f = f_n - f_{n-1} = A/(2L)$. For non-uniform cavity, the latter relation can be rewritten as $\Delta f = 1/(2T_0)$, where

$$T_0 = \frac{1}{2} \int_{l_{\text{bottom}}}^{l_{\text{top}}} \frac{dl}{A(l)}. \quad (1)$$

Here l_{bottom} and l_{top} are positions of the lower and upper walls of the resonator, respectively; Alfvén speed $A(l) = B(l)/\sqrt{4\pi m_{\text{eff}}(l)N_e(l)}$, magnetic field B , electron number density N_e , and effective ion mass m_{eff} , all vary with l .

Using formula (1) we calculated transit time T_0 for some hours of 13 events, taking one event per month. D layer height of 100 km was taken as a lower wall of the resonator. The height of maximal Alfvén speed above the F₂ layer was taken as the upper wall. Altitude profile of the magnetic field $B(l)$ was calculated by DGRF/IGRF model (available from http://omniweb.gsfc.nasa.gov/vitmo/igrf_vitmo.html). Altitude profiles of the electron density $N_e(l)$, the effective mass $m_{\text{eff}}(l)$ and the Alfvén speed $A(l)$ were calculated to the height $l^* = 2,000$ km based on the model IRI-2012 (http://omniweb.gsfc.nasa.gov/vitmo/iri2012_vitmo.html), and above 2,000 km based on extrapolation formula similar to that used in [8].

Fig. 4 shows the altitude profiles of N_e , m_{eff} , B , and A for one of the runs (1300UT January 15, 2011). Time $2T_0$ in this case was found to be 0.57 sec, which corresponds to the frequency scale $\Delta f = 1.75$ Hz. This exceeds spacing between the harmonics measured on the spectrogram by 0.25 Hz. In total, for 13 selected days of observations we have performed 99 calculations of the frequency scale Δf_{calc} and compared them with the measured values Δf_{meas} . The result is shown in Fig. 5, which shows that the correlation between the calculated and measured values is quite high (correlation coefficient $r = 0.9$), but the regression line does not pass through zero, although it has the slope of nearly 45 degrees. Calculated frequency scale Δf_{calc} exceeds measured value Δf_{meas} on average by 0.35 Hz. This means that there is some systematic error in the determination of Δf_{calc} .

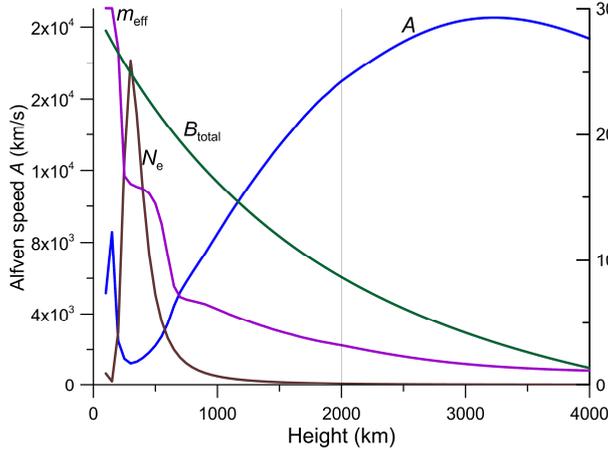


Fig. 4. Altitude profiles of N_e , m_{eff} , B , and A for one of the runs (1300 UT January 15, 2011).

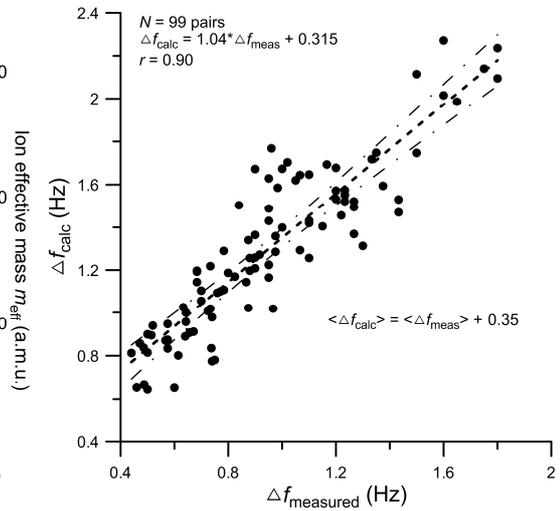


Fig. 5. Correlation between the calculated and measured values of Δf .

6. Discussion and Conclusions

Both systematic and random errors in modeling frequency structure of IAR can be explained by different reasons. One of them is that we considered vertical alignment of resonance cavity, not along the geomagnetic field line. Other causes may be a mismatch of DSP measurement place with the point of ionospheric sounding, inaccurate reflection of ionospheric conditions model IRI-2012, etc. Search for possible ways of a method refinement is a task for future work.

Nevertheless, we can conclude that, as far as we know, this is the first attempt to directly compare the measurements of variations in IAR emission frequency with more or less realistic description of the resonance structure

on the basis of the available models of the ionospheric plasma and magnetic field. It seems to us, in the future this way can be utilized to develop methods for verifying ionospheric models and diagnostic parameters of the upper ionosphere on the basis of magnetic measurements in the ultralow-frequency range.

7. Acknowledgments

The work was performed under Program 22 of the Presidium of RAS and supported in part by RFBR grants 13-05-00529 and 13-05-00066.

8. References

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