Adaptation of IRI-2012 Model for Estimation of IAR Harmonic Structure

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Abstract— The ionospheric Alfvén resonator (IAR) can amplify and accumulate ultra-low frequency (ULF) wave energy in the upper ionosphere. Close connection of the IAR emission 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. In this paper we propose a new approach to analysis of emission of ionospheric Alfvén resonator (IAR). We apply the IRI-2012 version of International Reference Ionosphere model to calculate difference between frequencies of adjacent harmonics of IAR emission. The calculated values are compared with the frequency data obtained from the search-coil magnetometer observations made at two different stations, the mid-latitude observatory Mondy (Eastern Sayan, Russia) and the high-latitude Sodankylä Geophysical Observatory (Finland). The results showed a good correlation between the measured and calculated values both at medium and high latitude. The calculation results at Mondy have a systematic error of about 0.35 Hz. The reasons of this discrepancy are discussed.

1. INTRODUCTION

The ionospheric Alfvén resonator (IAR) is a structural formation in the ionosphere between two peaks of Alfvén speed in its altitude profile [1]. The IAR can amplify and accumulate ultra low frequency (ULF) wave energy in the upper ionosphere [2]. As a result of the IAR occurrence the multiband spectral resonance structure (SRS) appears in the ULF observations, both ground-based and satellite. Frequency of discrete spectral bands 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 [3]. Close connection of SRS 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 [4].

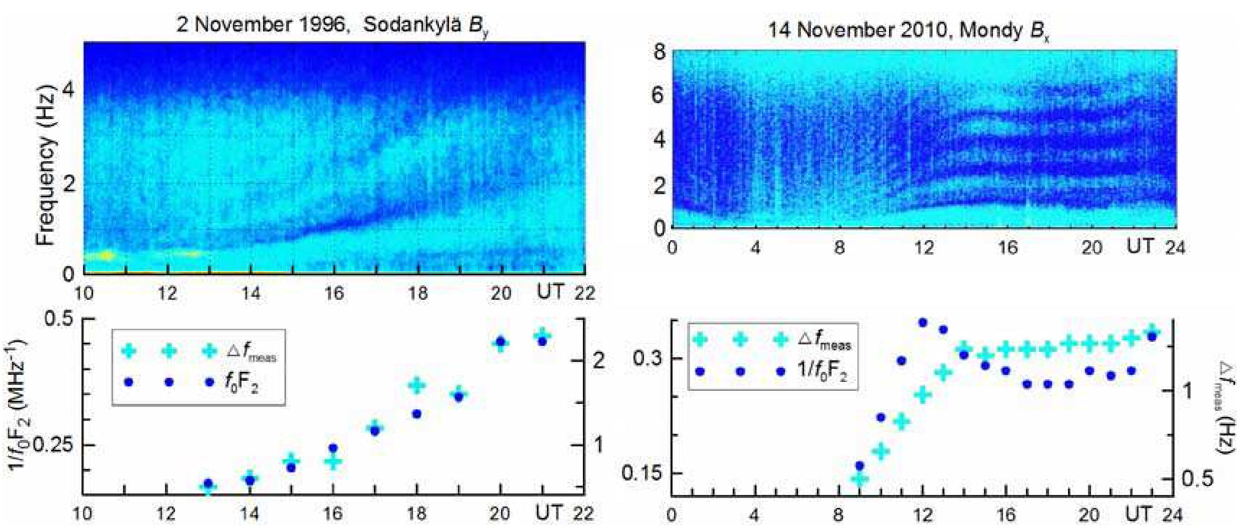
In this paper we propose a new approach to analysis of emission of ionospheric Alfvén resonator (IAR). We apply the IRI-2012 version of International Reference Ionosphere model to calculate difference between frequencies of adjacent harmonics (harmonic difference) of IAR emission. The calculated values are compared with the harmonic difference data obtained from search-coil magnetometer observations made at two different stations, the mid-latitude observatory Mondy (Eastern Sayan, Russia) and the high-latitude Sodankylä Geophysical Observatory (Finland). For measurements made at medium latitudes, it appears that to reach satisfactory results it is necessary to modify IRI-2012 model replacing the vertical profile of ionospheric parameters adopted in the standard model with the profile elongated along the magnetic field lines [3]. For polar latitudes, where the field lines deviate from the vertical insignificantly, such a procedure is not so important. On the other hand, irregular behavior of the polar ionosphere results in the diffusive character of the SRS. That is why the spectral bands of the SRS at SGO spectrograms are blurred which cumbers precise measurements of the frequency values.

2. EQUIPMENT AND DATA PROCESSING

We used magnetic and ionospheric data from the Sodankylä Geophysical Observatory (SGO, geographic coordinates $\varphi = 67.37°$, $\lambda = 26.63°$; McIlwain parameter $L = 5.2$) for a period of January–March and November–December 1996 and for the same months of 1997. Both solar and magnetic activity indices were below their average levels: monthly a_p-index averaged over the above period was $a_p = 15.9$; the monthly sunspot number was $R = 8.8$. These values are typical for solar minimum. To compare the results with those obtained basing on a mid-latitude site, we used data from the Sayan Solar Observatory Mondy (MND, geographic coordinates $\varphi = 51.6°$, $\lambda = 100.9°$; $L = 2.1$) which is situated near the border between Russia and Mongolia. We processed the MND data for a period of March 2010–May 2011. Magnetic activity during this period was also low; monthly averaged a_p-index never exceeded 10.3 nT. The monthly sunspot number exceeded 30 only in the last three months of the period, never rising above 57. This is consistent with low solar activity.

In SGO, data samples taken from a search-coil magnetometer with 40 Hz sampling, were stored with GPS timing. In SSO, induction magnetometer LEMI-30 with sampling rate of 60 Hz measured signals within 0.001–30 Hz frequency range. To compare magnetic data with ionospheric data above MND and SGO, we used one-hour values of the critical frequency $f_0\text{F}_2$ from the DPS-4 digital ionosounder installed in Irkutsk, about 260 km from the MND, and the IS-14 ionsounder at Sodankylä, respectively.

Digital magnetic records in the range of 1–10 Hz were processed using specifically developed MATLAB code. 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. Fig. 1 shows typical examples of the IAR events at two observatories. Spectrograms obtained were analyzed visually. As a rule, we managed to make measurements of no more than 5–6 harmonics (bands), but more often three or four (two for SGO). We used these data for detailed comparison with changes in ionospheric parameters and to calculate the correlation coefficients and regression line between the harmonics and critical frequency variations of the ionosphere F2 layer.



(a) (b)

Figure 1: Two upper panels show dynamic spectra of the IAR emissions at (a) Sodankylä and (b) Mondy. Bottom panels show changes in the critical frequency $f_0\text{F}_2$ and the harmonic difference Δf_{meas} measured from the upper spectrograms.

3. THE SRS FREQUENCY AND THE IONOSPHERE CRITICAL FREQUENCY $f_0\text{F}_2$

Since the observed discrete spectral bands are formed by capturing low-frequency wave in the ionospheric Alfvén resonator being ionospheric structure, the behavior of the main characteristics of SRS should closely correlate to variations of the 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 $f_0\text{F}_2$, measured by ionosonde: $f_0\text{F}_2 = 8.98 * 10^{-3} N_e^{1/2}$, where the electron number density is measured in cm^{-3}, and the critical frequency in MHz.

Evidence for a connection between the measured harmonic difference Δf_{meas} and the critical frequency $f_0\text{F}_2$ can be seen at the bottom panels of Figure 1. In Figure 2 we compared values of the SRS frequency with the reverse value of $1/f_0\text{F}_2$ statistically for all events analyzed at the two observatories.

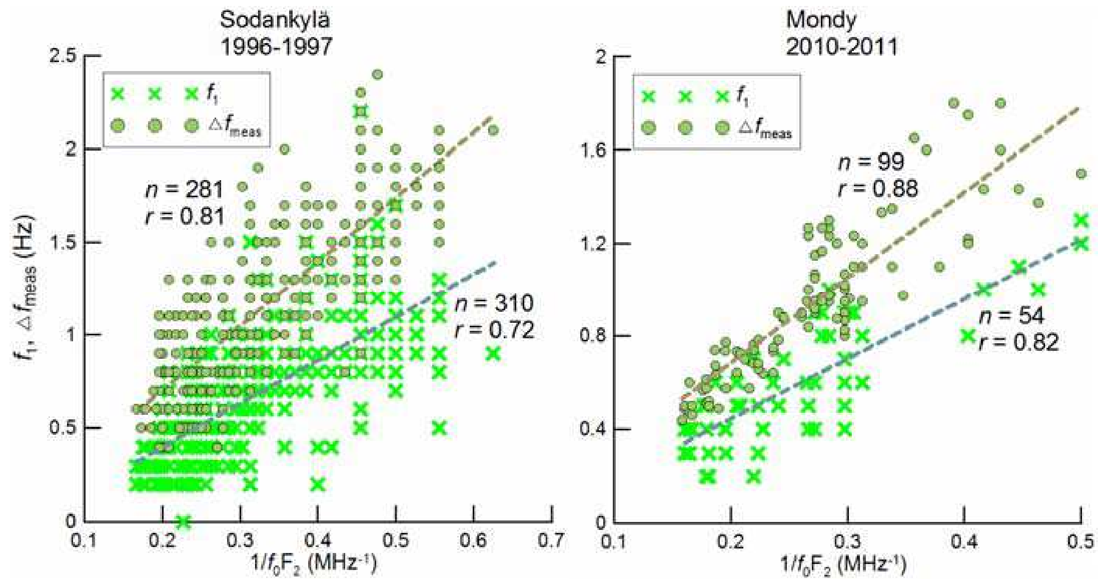


Figure 2: Scatter plots illustrating dependence of the SRS frequency structure versus the ionosphere critical frequency $f_0\mathrm{F}_2$ at the two observatories. Crosses show the frequency f_1 of the emission first harmonic; circles show the SRS frequency scale Δf_{meas} versus the reverse value of $1/f_0\mathrm{F}_2$. The observation numbers n and the correlation coefficients r are indicated for each pair of compared parameters separately.

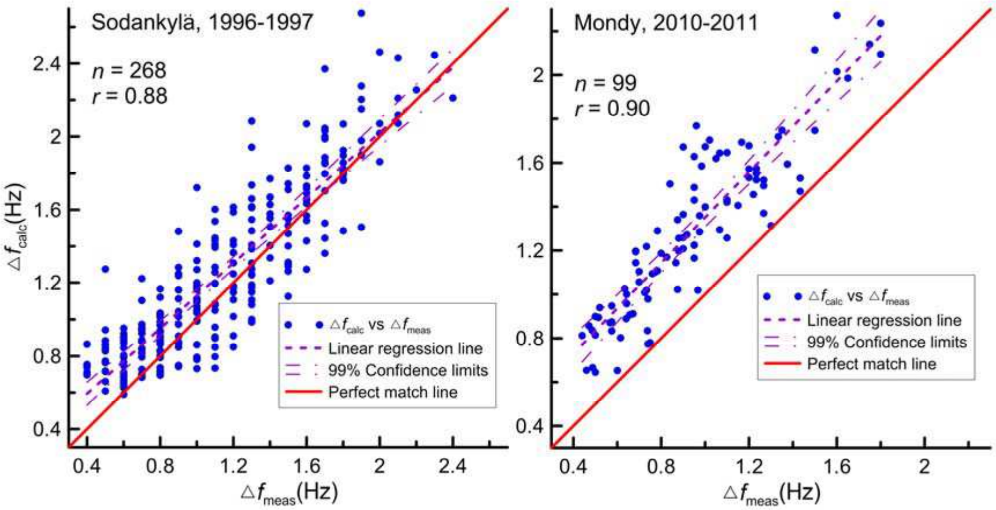
The results show a rather high correlation between the characteristics of SRS and the ionosphere critical frequency at both observatories. The Δf_{meas} relates to the $f_0\mathrm{F}_2$ closer than the f_1. The correlation coefficients are higher for Mondy observatory. One of the reasons of the latter result can be understood if we look at the upper panels of Figure 1: the spectral bands at SGO are much wider and more blurred than at MND, which hampers precise measurements of the frequency values. But it is only one reason. The other seems to be that often the high-latitude ionosphere structure is very intricate. Therefore the wave propagation is determined not only by the plasma density within the F_2 region, but also by overall plasma distribution in the ionosphere including its upper region.

4. MODEL OF THE IAR SPECTRUM FORMATION

The literature offers different versions of the model of the ionospheric Alfvén resonator [5–7]. The models are based on the resonance conditions of Alfvén wave reflection from the lower and upper ionosphere and capture analysis of the Alfvén waves in the cavity being formed along the magnetic field lines between the local maxima of the Alfvén speed ("walls" of the resonator) below the F_2 layer and at altitude of 2,000–4,000 km. All authors agree that for resonance of waves with the wave speed A in a uniform cavity of length L, the frequency f of harmonic number n is given by $f = (n+)/(2L/A)$. 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 the frequency f, but the harmonic difference $\Delta f = f_n - f_{n-1} = A/(2L)$. For non-uniform cavity, the latter relation can be rewritten as $\Delta f = 1/(2T_0)$, where

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

Here l_{bottom} and l_{top} are positions of the lower and upper walls of the resonator, respectively; Alfvén speed $A(l) = B(l)/\sqrt{4\pi m_{\mathit{eff}}(l)N_e(l)}$, 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 all hourly events. D layer height of 100 km was taken as a lower wall of the resonator. The height of the maximum Alfvén speed above the F_2 layer was taken as an upper wall. Altitude profile of the magnetic field $B(l)$ was calculated by DGRF/IGRF model. Altitude profiles of the electron density $N_e(l)$, the effective mass m_{eff}, and the Alfven speed $A(l)$ were calculated to the height $l* = 2{,}000$ km



(a) (b)

Figure 3: Calculated Δf_{calc} versus measured Δf_{meas} values of the IAR frequency scale for the (a) Sodankylä and (b) Mondy observatories. Calculations were performed using the IRI-2012 model. Dashed lines are the linear regression lines; dashed-dot lines are the 99% confidence limits; thick red line is the line of perfect match $\Delta f_{\mathrm{calc}} = \Delta f_{\mathrm{meas}}$.

based on the International Reference Ionosphere model IRI-2012, and above 2,000 km based on an extrapolation formula similar to that used in [8].

In total, for 13(55) selected days of observations at Mondy (Sodankylä), we have performed 99(268) calculations of the frequency scale Δf_{calc} and compared them with the measured Δf_{meas} values. A greater number of Sodankylä events included into the analysis aimed to provide better statistics for the high-latitude station. The result depicted in Fig. 3 shows that the correlation between the calculated and measured values is quite high, but at Mondy the regression line does not pass through zero, although it has the slope of nearly 45 degrees. Calculated harmonic differenceΔf_{calc} exceeds measured value Δf_{meas} on average by 0.35 Hz. This means that for this station there is some systematic error in the determination of Δf_{calc}. On the contrary, at Sodankylä the regression line almost coincides with the perfect match line.

We see two possible reasons of this distinction. First, we calculated the frequency scale using the standard IRI-2012 model that gives ionospheric parameters along the vertical profile. However, the resonator cavity captures Alfven waves along the magnetic field line. The inclination angle at the Mondy latitude is about 70 degrees, whereas at Sodankylä the field line is much closer to the vertical, the inclination here is about 77 degrees. 70-degree inclination extends the wave travel time by 6.5%, reducing equally the frequency. At Sodankylä the 77-degree inclination corresponds to only 2.5% travel time extension. Second, calculating Δf_{calc} for Mondy we used $f_0\mathrm{F}_2$ values of Irkutsk as input data because we had not available digisonde data closer to Mondy. This might introduce errors in the calculated values. At Sodankylä we used digisonde data installed directly at the observatory.

5. DISCUSSION AND CONCLUSION

In this paper we compared the SRS characteristics observed at two observatories, high-latitude SGO and mid-latitude MND. We found clearer IAR emission structure at Mondy as compared to Sodankylä. Correlation coefficients between the frequency features of SRS (harmonic difference Δf and first harmonic frequency f_1) and the local ionosphere critical frequency $f_0\mathrm{F}_2$ are a bit higher at Mondy with Δfvs $f_0\mathrm{F}_2$ correlation being closer than f_1 vs $f_0\mathrm{F}_2$ at both stations. The upper limit of Δf at Sodankylä (2.7 Hz) is higher than the Δf upper limit at Mondy (2.3 Hz) in accordance with the lower limit of $f_0\mathrm{F}_2$ at Sodankylä (1.6 MHz) as compared to $f_0\mathrm{F}_2$ at Mondy (2 MHz).

We also calculated values of the harmonic difference Δf at both stations within the framework of a simple time-of-travel model of the resonator. The results showed a good correlation between the measured Δf_{meas} and calculated Δf_{calc} values both at medium and high latitude. The calculation results at Mondy have a systematic error of about 0.35 Hz. The reasons of it are discussed.

In conclusion, we would like to note that studies of the IAR regularities and their dependence on various factors can result in future development of a new method for monitoring the ionosphere. In particular, it is important for the high-latitude ionosphere that is very unstable and often non-measurable using common radio sounding. Comparing results for Sodankylä presented in Figures 2 and 3 we see sufficiently higher correlation between Δf_{meas} and Δf_{calc} than between Δf_{meas} and calculated $f_0\mathrm{F}_2$. This fact means that Δf is determined not only by plasma density in the F_2 region, but also by plasma distribution above this region. So Δf_{meas} contains information about the upper ionosphere. We plan to find the ways to reveal this information from the analysis of SRS data in our next papers.

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