JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 107, NO. A10, 1281, doi:10.1029/2001JA005076, 2002

Spectral properties of the ionospheric Alfvén resonator observed at a low-latitude station (L = 1.3)

T. Bösinger,[1] C. Haldoupis,[2] P. P. Belyaev,[3] M. N. Yakunin,[3] N. V. Semenova,[4]
A. G. Demekhov,[5] and V. Angelopoulos[6]

Received 30 August 2001; revised 5 December 2001; accepted 10 January 2002; published 9 October 2002.

[1] Data of the first half year of operation of a sensitive search coil magnetometer at a remote site in the island of Crete, Greece (35.15°N, 25.20°E), was used to investigate properties of the spectral resonance structure (SRS) of the ionospheric Alfvén resonator (IAR) at $L = 1.3$. Most of the properties known from earlier reports and a recent paper (A. G. Yahnin et al., Morphology of the spectral resonance structure of the electromagnetic background noise in the range of 0.1–4 Hz at $L = 5.2$, submitted to *Annales Geophysicae*, 2002) (hereinafter referred to as paper CP) at mid and high latitude ($L = 2.65$ and $L = 5.2$) could be verified as being valid also at $L = 1.3$, but several new features were also found. In contrast to mid and high latitudes, SRS signatures were detected every night but not at all during daytime. The average frequency difference Δf between two adjacent harmonics is very small (0.2 Hz) and does not exhibit a local time dependence from evening to night hours. The seasonal dependence is very weak though distinct. A large variability of Δf from night to night was found which increases when proceeding from summer to winter. This variability could not be accounted for by standard IAR models employing an International Reference Ionosphere (IRI). Moreover, the modeled Δf values typically exhibited a systematic offset to higher values as compared to observed ones. It is expected that calibration of the IRI model by local f_oF_2 ionosonde measurements will improve the agreement between model and observation, but it cannot explain fully the variability of Δf and the systematic offset. Most likely the standard IAR model itself requires revision to be fully applicable in the low-latitude ionosphere. *INDEX TERMS:* 2443 Ionosphere: Midlatitude ionosphere; 6914 Radio Science: Electromagnetic noise and interference; *KEYWORDS:* ionosphere, Alfvén wave, resonance, low latitude

Citation: Bösinger, T., C. Haldoupis, P. P. Belyaev, M. N. Yakunin, N. V. Semenova, A. D. Demekhov, and V. Angelopoulos, Special properties of the ionospheric Alfvé resonator observed at a low-latitude station (L = 1.3), *J. Geophys. Res.*, *107*(A10), 1281, doi:10.1029/2001JA005076,2002.

1. Introduction

[2] The ionospheric Alfvén resonator (IAR) has become a well known phenomenon among the ULF/ELF research community, as documented in many publications (e.g., see reviews by *Belyaev et al.* [1990], *Lysak* [1993], *Pokhotelov et al.* [2001], and references therein), international workshops (e.g., http://space.sgo.fi/htmls/IARreport.html), research projects (e.g., http://spaceweb.oulu.fi/projects/INTAS_99-0335/), and in a special journal issue (*Journal of Atmospheric and Solar-Terrestrial Physics, 62*(4), 2000). IAR belongs to the class of magnetic field line resonances (FLR) and refers to a cavity for shear Alfvén waves in the F region ionosphere. Due to the relatively short part over the field line and the high Alfvén speed, the resonance frequencies are comparably high, typically between 0.5 to 7 Hz. Often many harmonics are simultaneously excited giving rise to the so-called spectral resonance structure (SRS).

[3] It is generally believed that the main excitation of IAR is due to electromagnetic emission stemming from global thunderstorm activity [*Belyaev et al.*, 1989a, 1989b]. Electromagnetic wave energy of the TM mode in the Earth-ionosphere cavity is leaking into the ionosphere by virtue of mode coupling to the shear Alfvén and magnetoacoustic wave mode in the bottom E region ionosphere. The shear Alfvén wave can get trapped in the F region ionosphere thereby exciting the IAR resonator. There is some leakage of shear Alfvén wave energy back to the Earth-ionosphere cavity by a similar wave mode coupling mechanism and SRS signatures observed on the ground by magnetometers are detected as a TME wave mode component. The IAR

---

[1] Department of Physical Sciences, University of Oulu, Oulu, Finland.
[2] Physics Department, University of Crete, Iraklion, Greece.
[3] Radiophysical Research Institute, Nizhny Novgorod, Russia.
[4] Polar Geophysical Institute Apatity, Murmansk, Russia.
[5] Institute of Applied Physics, Nizhny Novgorod, Russia.
[6] Space Science Laboratory, University of California, Berkeley, California, USA.

0148-0227/02/2001JA005076$09.00

properties are governed mainly by the *F* region ion mass loading of the magnetic field line and the top side *F* region vertical gradient of the ion density. The role of the *E* region is restricted (beside the mode coupling mentioned above) to damping and screening.

[4] SRS can be understood as a portrait of the local ionosphere [e.g., *Belyaev et al.*, 1989b; *Demekhov et al.*, 2000]; therefore it is desirable to think of a global monitoring network of SRS observatories, for large-scale diagnostic purposes and space weather assessments. Despite efforts for more measurements, still the exploration of IAR spectral properties at different latitudes remains a formidable task to be accomplished. The pioneering work on SRS was carried out at a mid latitude station (L = 2.65), but the largest amount of continuous SRS observations is available from a high-latitude station, at L = 5.2, in Sodankyla, Finland (A. G. Yahnin et al., Morphology of the spectral resonance structure of the electromagnetic background noise in the range of 0.1–4 Hz at L = 5.2, submitted to *Annales Geophysicae*, 2002; see also *Belyaev et al.* [1990, 1991]). The work by Yahnin et al. is considered a key paper and is referred to hereinafter as paper CP. To our knowledge, there are not yet SRS observations reported in the polar caps and lower latitudes or near the magnetic equator. The present paper is meant to, at least partially, fill the latitudinal gap in basic observational knowledge of SRS [*Belyaev et al.*, 1989a, 1989b], by presenting for first time, long-lasting, high-resolution measurements from a low-latitude station in Crete at L = 1.3.

2. Measurements and Data

[5] The observations were made with a search coil pulsation magnetometer of the Finnish network [*Bösinger and Wedeken*, 1987] (see http://spaceweb.oulu.fi/projects/pulsations/) that was installed in May 1999 at a remote site in the island of Crete, Greece (35.15°N, 25.20°E, local time LT = UT + 1.5 hours). The sampling rate is 20 Hz and the Nyquist filter cuts off at 8 Hz. The three axis instrument is equipped with a GPS clock providing exact timing of data points close to the nearest second. The system is fully controlled and operated by a PC, with the 12 bit digital data stored on a DAT tape for further processing. Spectral analysis is (if not otherwise mentioned) done with raw data (not corrected for the frequency and phase response of the instrument) since raw data is of advantage in SRS analysis; this is because the increase of sensitivity with frequency counteracts with the decay of background noise amplitude. Quick look, daily dynamic spectra are produced and made available in the web on a routine basis ftp://spaceweb.oulu.fi/pub/pulsations/Crete/).

[6] This report includes data analysis for the first half a year of operation, from 16 May 1999 to 16 January 2000, with an unfortunate data gap from 19 October to 15 December 1999.

3. Observations

[7] Typical spectrograms obtained from one day of data is shown in Figure 1. Figure 1a displays the total power spectral density of the magnitude of the horizontal magnetic disturbance (noise) vector in a color-coded, arbitrary scale. As can be seen the noise power is rather uniformly distributed over frequency and time with a more-or-less steady increase of power from evening to night and a decrease from night to day hours.

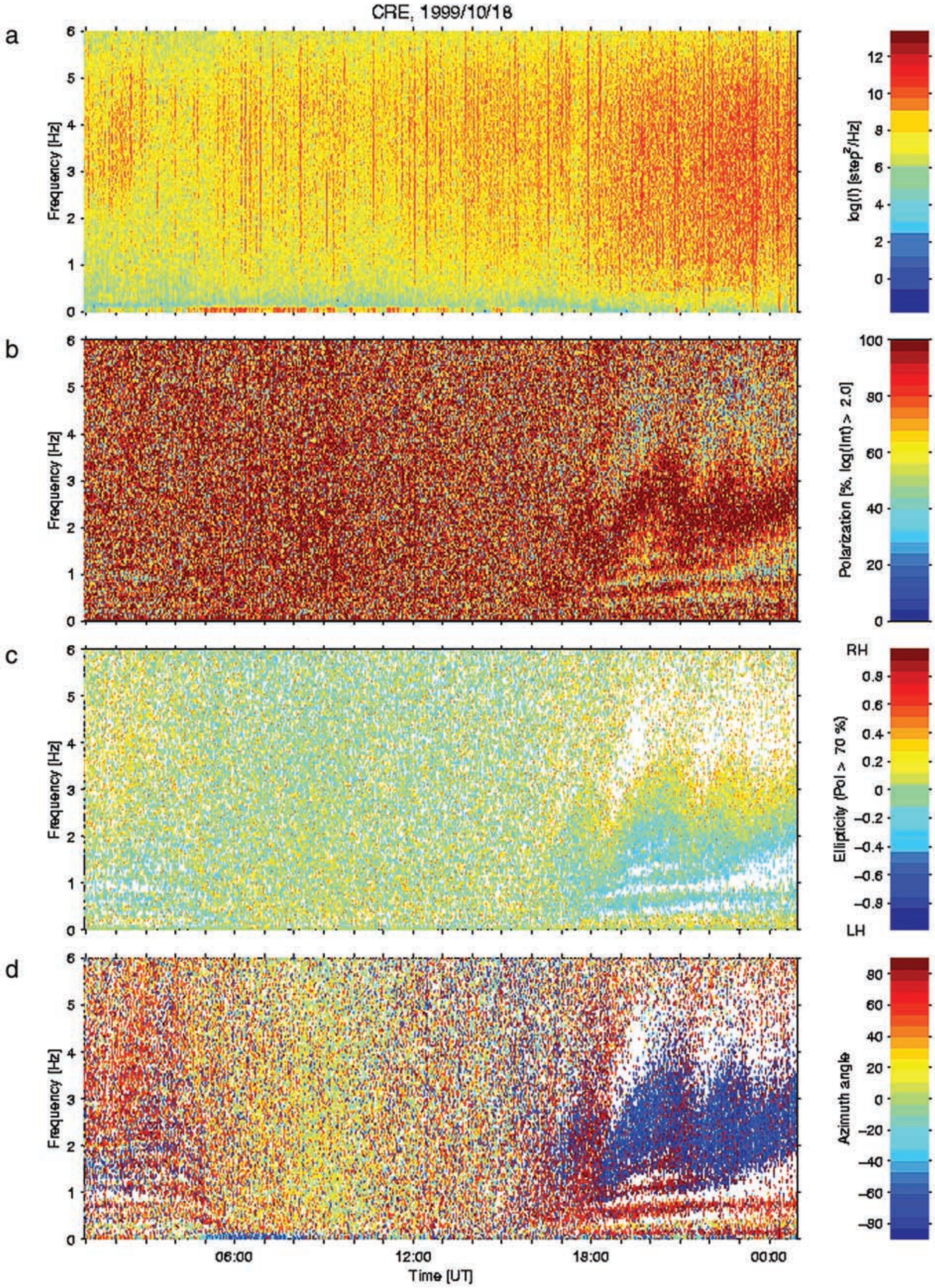
[8] Figure 1d shows the azimuth angle (with respect to the direction of magnetic east) of the major axis of the horizontal polarization ellipse. What draws first attention is the "blue," quasiperiodic (2 to 3 hours' period) dispersive, modulation pattern in the azimuth angle during evening to night hours. This feature, which relates entirely with large-scale variations in the dark ionosphere, will be dealt with in a future study. In this paper we focus our attention alone on the "red," slightly dispersive, equally spaced, rising structures in the display from early evening to night, which are also visible, but less distinct, during night to morning hours. These structures seen as slanting stripes between 0 and 2 to 3 Hz is what is here (and elsewhere) referred to as SRS. Such "fingerprints" of IAR show up in all polarization properties as, e.g., the azimuth angle (Figure 1d), degree of polarization (Figure 1b), and ellipticity (Figure 1c).

[9] Although displays of the type shown in Figure 1 are highly informative, for our statistics based on a large number of spectrograms we use a less computer-time-consuming, grey-scaled spectrogram displaying only one polarization property, the ellipticity ϵ. By experience ϵ (see Figure 1 caption for its definition) turned out to be the best suited parameter for surveying SRS (see Figure 1). An example of typical dynamic spectra of ϵ displaying two weeks of data, one from summer and one from winter months, is given in Figure 2.

[10] We identify the resonances of IAR as the "rising tone" structures seen in the grey-scale coding, between 0 Hz and 2 to 3 Hz, starting typically at ~18 UT and ending typically at ~3 UT (the vertical stripes are the same as the 2–3 hour period undulations that were shown in Figure 1 and will be the topic of future work). There are usually several resonance bands (harmonics) exhibiting a frequency increase with time from evening to early morning hours [*Belyaev et al.*, 1990].

[11] In the present analysis, spectrograms of the type shown in Figure 2 were produced for the entire set of observations. Next, based on these spectra, a data base was built which tabulates the frequencies of the first five

Figure 1. (opposite) (a) The power spectral density (PSD) of the magnitude of the horizontal magnetic disturbance (noise) vector in a color-coded form of arbitrary scale (step or byte to the power of two per Hz). (b) The degree of polarization in percent for all PSD levels above 10^2 in Figure 1a. (c) The ellipticity $\epsilon = (L - R)/(L + R)$, where R and L represent the right- and left-handed circularly polarized components, in color-coded form with "red" for right-handed ($\epsilon = +1$) and "blue" for left-handed ($\epsilon = -1$) circular polarization for all PSD levels with a degree of polarization greater than 70% (see Figure 1b). (d) The angle of the major axis of the horizontal polarization ellipse with the direction of magnetic east in degrees; the angle is counted positively in the counterclockwise direction.


CRE, 1999/10/18
a
b
c
d
Frequency [Hz]
0
1
2
3
4
5
6
log(I) [step²/Hz]
0
2
4
6
8
10
12
Polarization [%, log(Int) > 2.0]
0
20
40
60
80
100
Ellipticity (Pol > 70 %)
RH
0.8
0.6
0.4
0.2
0
−0.2
−0.4
−0.6
−0.8
LH
Azimuth angle
80
60
40
20
0
−20
−40
−60
−80
06:00
12:00
18:00
00:00
Time [UT]

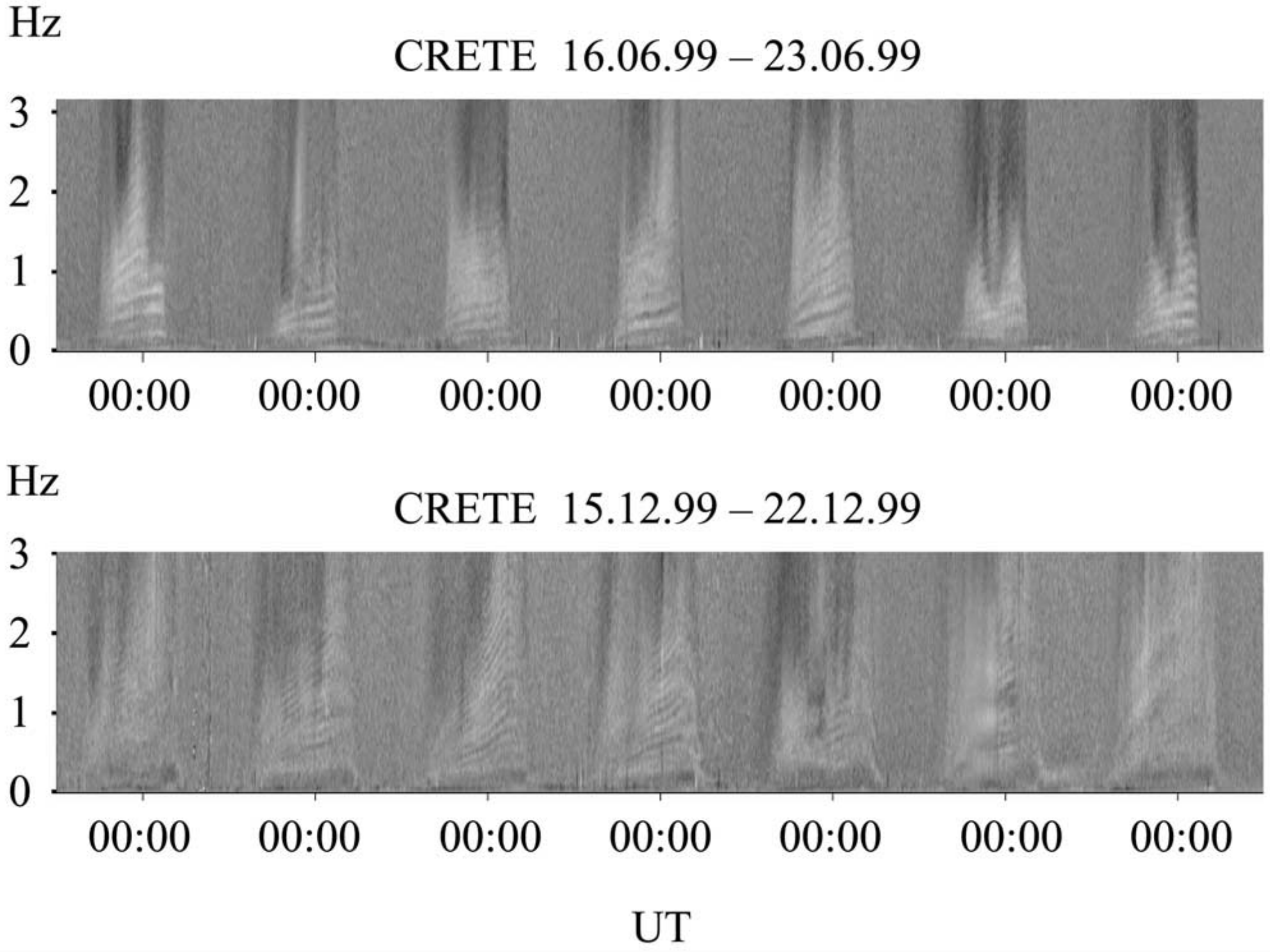


Figure 2. Dynamic spectra of the ellipticity ϵ of magnetic background noise observed at Crete over a week in (top) summer and (bottom) winter. Figure 2 shows the value of ϵ by means of a grey scale, with "white" corresponding to $\epsilon = +1$ and "black" to $\epsilon = -1$, as a function of time. For details see text and the Figure 1 caption.

resonance bands (maxima in the degree of greyness forming discrete ascending stripes/lines) as function of UT (1 hour bins) and date. What follows below is a presentation of the various statistical results obtained.

[12] It is found that SRS occur every single night but never during daylight between about 05 and 17 UT. This repeatability and strict nighttime occurrence is in contrast to SRS behavior at other latitudes/sites (e.g., paper CP; see also *Belyaev et al.* [1987] where distinct SRS observations belong to the exception rather than to the rule but daytime observations were reported as well. This low-latitude finding is quantified in Figure 3 (top panel) where the probability of SRS detection is shown as a function of UT. The probability approaches unity shortly after local midnight (23 UT) but is zero during daytime hours.

[13] In SRS studies, attention was usually paid not to the absolute value of the resonance frequencies but to the frequency difference between two adjacent resonance stripes, hereafter referred to as Δf [e.g., *Belyaev et al.*, 1990; *Demekhov et al.*, 2000]. This parameter is displayed in Figure 3 (bottom) as an average over the whole data set. As seen, there is a gradual increase of Δf from local midnight (2230 UT) to early morning (0330 UT) from about 0.23 to 0.32 Hz with an abrupt decrease to 0.15 Hz from 04 to 05 UT. On the other hand, Δf remains (on the average) fairly constant near 0.2 Hz in the premidnight hours. For comparison, corresponding values of Δf at higher latitudes (paper CP) are 0.55 Hz (23–02 LT) and 0.44 Hz (20–23 LT). This means that, on the average, Δf at $L = 1.3$ is about half of that observed at $L = 5.2$.

[14] To determine the quality and structure of the data, an overview over all data points for the frequency of the first harmonic, identified here with the first resonance line, is given for three representative LT sectors (UT bins) in Figure 4. As seen, the data points are scattered around a slightly positively inclined "line of mean value." This suggests a seasonal dependence of the resonance frequency: There is a general trend from lower to higher resonance frequencies when progressing from the summer to the winter season. This seasonal trend is well documented in paper CP and obviously holds also for the low-latitude station in Crete. Additionally, Figure 4 shows a considerable variance about the mean resonance frequency. This is also present in the higher harmonics (not shown here). This

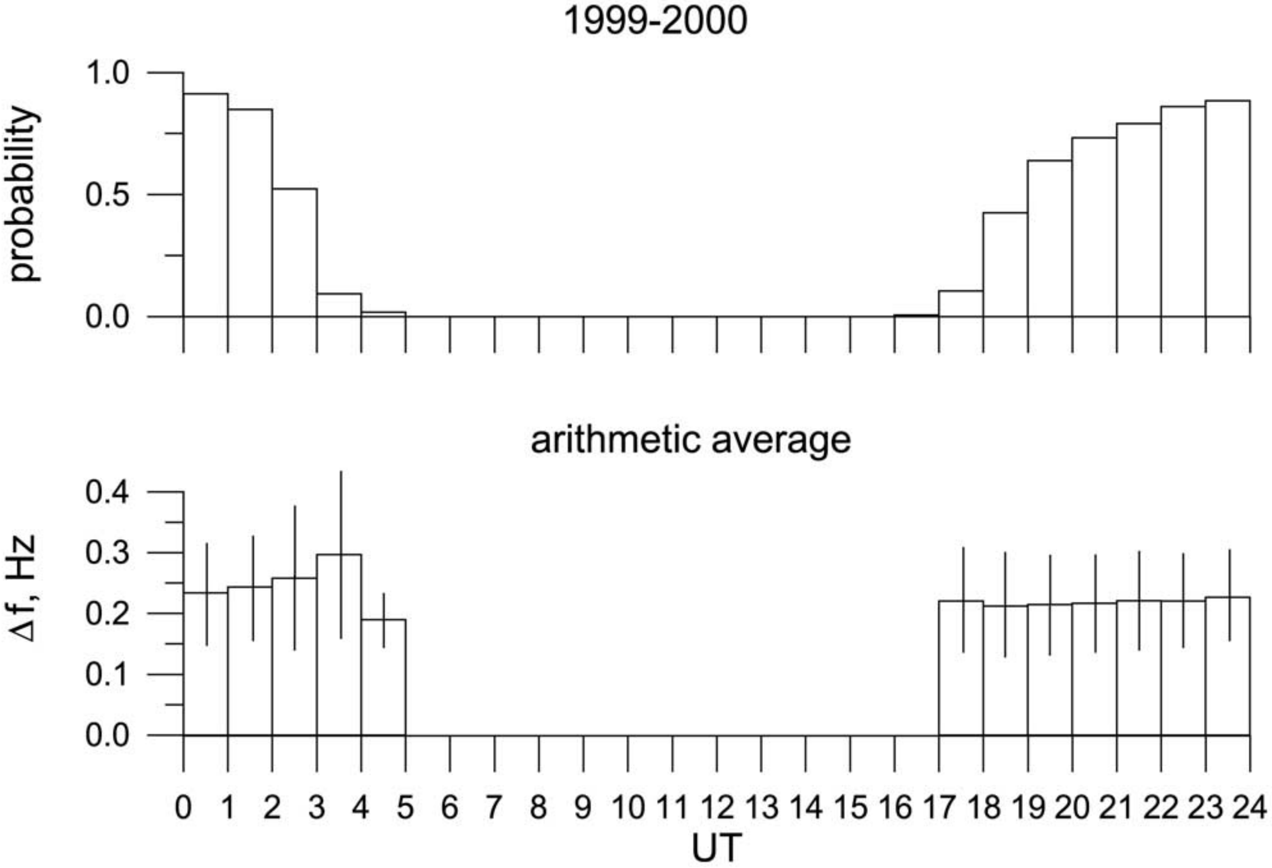


Figure 3. (top) The probability from May 1999 to January 2000 to detect SRS as a function of UT. (bottom) The average Δf over this period as a function of UT (LT = UT + 1.5 hours).

variance also increases with time (i.e., from summer to winter).

[15] Some more details of the experimental findings are summarized as follows: (1) In the midnight to early morning sector from 23 to 03 UT, the summer months (day 140 to 220) are characterized by a regular behavior with small variability. The mean value of Δf is practically the same (= 0.22 Hz) for each UT sector, and very little seasonal increase of Δf is noticed. Deviations from the mean value start to become more frequent in autumn (day 240 to 290) and even more frequent in winter (day 350 to 380), when Δf values may differ from day to day by 0.6 Hz. Note that Figure 3 presents an average over all data, whereas in sector 1 above and also in sector 2 below we distinguish between summer, autumn, and winter. Note also the error bars in Figure 3. (2) In the evening to midnight sector from 17 to 22 UT, between 18 and 19 UT, Δf starts with very small values (<0.2 Hz) and increases in accordance with the seasonal trend. All other statements made above for the midnight to the early morning time period hold also here, especially about the large deviations from mean Δf at wintertime.

4. Modeling

[16] The physics and mathematics of the SRS modeling will not be repeated here since they have been described extensively in a number of papers [*Polyakov and Rapoport*, 1981; *Lysak*, 1993; *Belyaev et al.*, 1990; *Demekhov et al.*, 2000]. For the sake of convenience a simple formula for the resonance frequencies f_A is repeated below (e.g., see *Hickey et al.* [1996], whereas an elementary description of its physics can be found at, e.g., http://dsentman.gi.alaska.edu/iarbands.htm):

$$f_A = \frac{c(k + \frac{1}{4})}{2n_A(h_F + l_F)}, k = 0, 1, 2, \ldots \tag{1}$$

[17] Here c represents the speed of light, n_A the refractive index of shear Alfvén waves at the $F2$ layer peak, h_F the thickness of the F layer maximum and l_F the spatial scale of the decrease of n_A above the $F2$ layer peak.

[18] In brief, the estimation of the resonance/eigenfrequencies of IAR reduces approximately to the determination of the maximum of the topside ionosphere reflection coefficient for shear Alfvén waves. In the present paper we applied both, the formula given by *Polyakov and Rapoport* [1981] and the algorithm of the full-wave approach by *Ostapenko and Polyakov* [1990] and obtained nearly identical results. Since minima and maxima of the topside ionosphere reflection coefficient determine equally well the scale (spacing) between the resonance frequencies, the numerical calculation of Δf was carried out by an automatic algorithm that searches for the minima (instead of maxima) of the reflection coefficient (see Figure 5).

[19] As shown in several publications, the overall features of SRS can be reasonably well reproduced by the IAR theory and an up-to-date ionosphere model, such as the

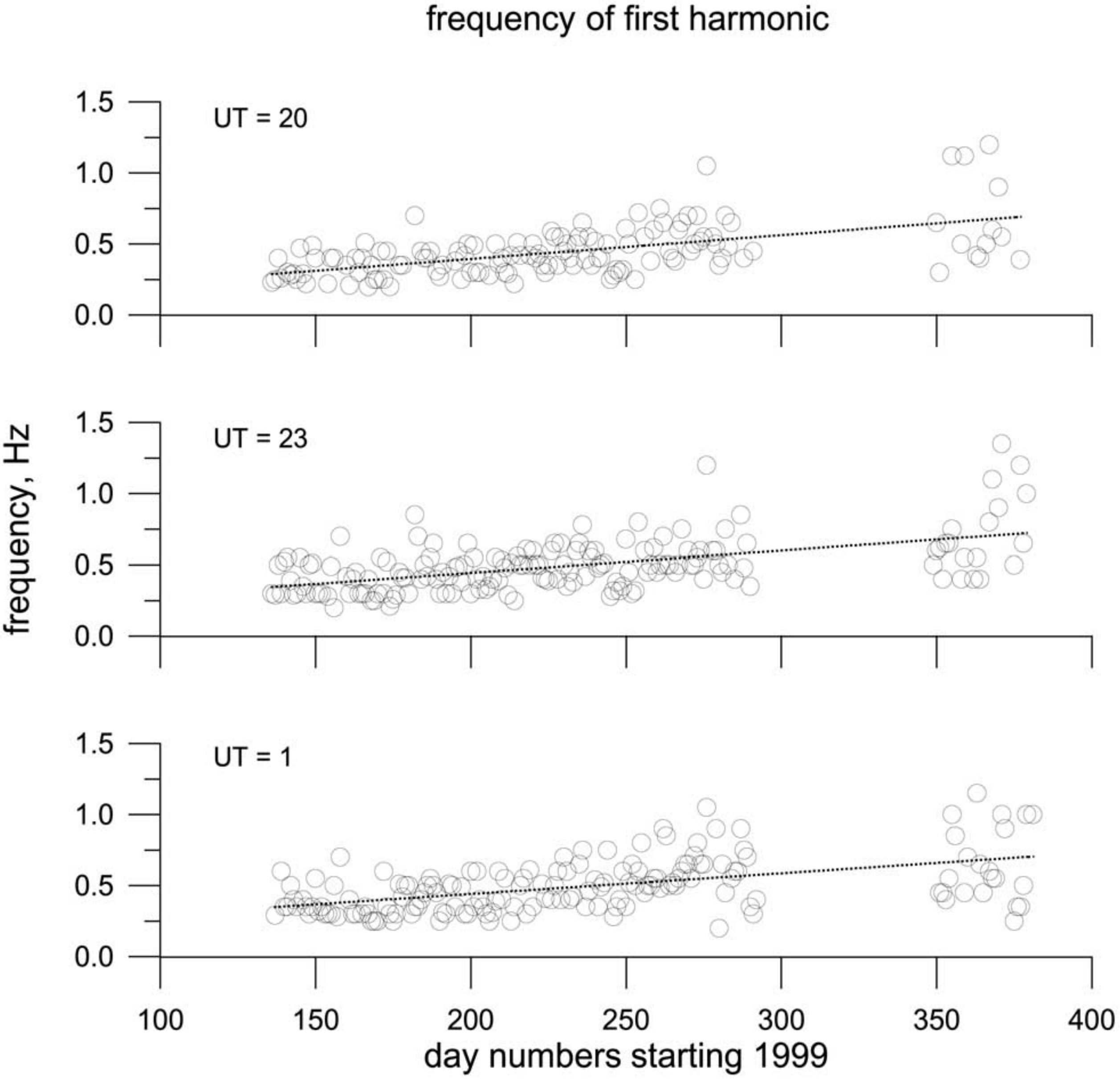


Figure 4. The fundamental frequency of IAR as a function of day number (numbering starts at 1 January 1999) for three selected UT sectors (LT = UT + 1.5 hours).

International Reference Ionosphere (IRI). This is nicely demonstrated in paper CP for high latitudes, by *Belyaev et al.* [1999] and *Demekhov et al.* [2000] for high and mid latitudes and by *Belyaev et al.* [1990] for mid latitudes. This agreement, however, turns out to be only partially true for low-latitude observations presented here.

[20] Figure 5 shows typical comparisons between the model results for the minima of the topside ionospheric reflection coefficient and the values observed for the first few resonance frequencies (harmonics). For a good agreement the modeled reflection coefficient minima should be in between the observed resonance frequencies (denoted here by stars/crosses/boxes). As seen, the observation during evening/night hours of 18 October 1999 (bottom) follow nicely the model "minima" traces, thus exhibiting a good agreement between observation and theory besides a systematic offset: Instead of lying in between the minima traces, the stars (representing observed "maxima") are almost on top of the "minima." Next, when comparing the model traces of 17 October 1999 (top) with the one of the following day (bottom), it can be noticed that the model does not produce any significant difference in the traces of both days. For the model these days are almost identical. This is quite in contrast to the actual observations. On 17 October 1999 (top) the spacing between adjacent "maxima" (that is Δf) is about only half of the spacing between corresponding "minima" traces. Thus there is no good agreement for the evening/night hours of 17 October 1999 (top). The agreement is somewhat better for the morning hours of 18 October (bottom) but not as good as for the evening/night hours of this day (bottom).

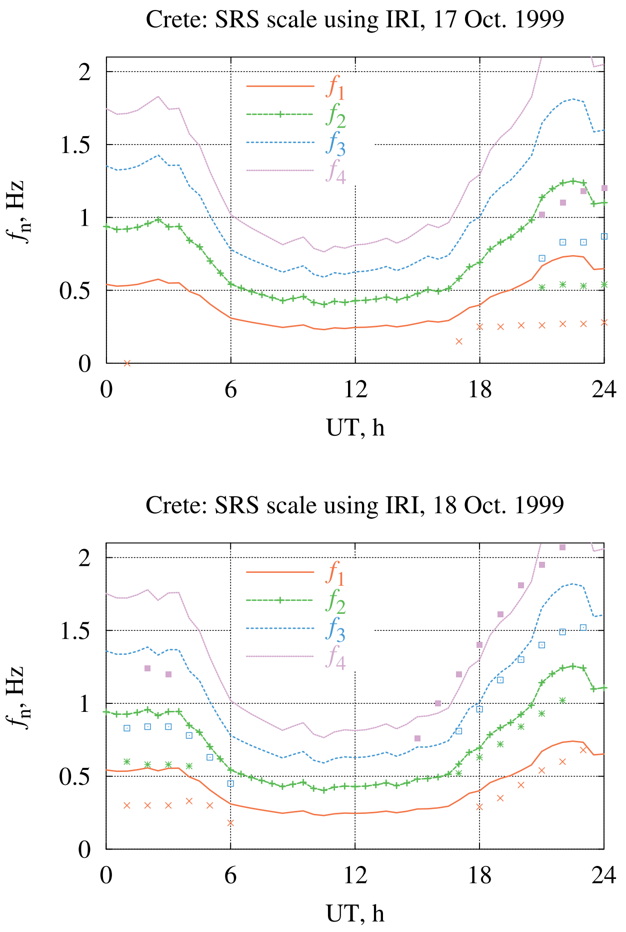


Figure 5. The frequencies of the modeled minima of the topside ionosphere reflection coefficient (full line) and the observed resonance frequencies of IAR (stars/crosses/boxes) as a function of UT. The resonance frequencies should lie in between the full lines (minima) for a good matching between theory and observation. Two successive days are displayed: (top) 17 October and (bottom) 18 October 1999.

[21] With regard to the seasonal dependence of Δf the model estimates undergo a qualitatively similar trend, as the observations, but the observed day-to-day variability of Δf is by no means reproduced by our model. Moreover, for most of the time the model results exhibit a systematic offset in Δf compared to our observations. The modeled Δf is larger by a factor of up to 2, with this offset being on the average smallest in the evening and largest in early morning time sectors. We suspect that a severe drawback in our present analysis might be the lack of ionosonde data over Crete (and Greece) in 1999/2000. This did not allow for the applied IRI model to be calibrated by a locally measured f_0F_2 value over time, which is expected to have provided more realistic resonance frequency estimates.

5. Discussion

[22] In the light of previous experimental and theoretical studies [e.g., *Belyaev et al.*, 1989a, 1989b, 1990, 1999; *Lysak*, 1993; *Hickey et al.*, 1996; *Demekhov et al.*, 2000] the occurrence characteristics of SRS at this low-latitude station are well anticipated. Within our present IAR understanding it is easy to explain (1) why low-latitude SRS is strictly a nighttime phenomenon, (2) why SRS occurs every night at lower latitudes in contrast with its sporadic appearance at higher latitudes, and (3) why Δf is almost constant over local time for evening/night hours.

[23] With respect to point 1 this is because of the strong E region presence during sunlit hours and its virtual disappearance during dark hours due to rapid recombination of molecular ions. High ionospheric conductance is known to be associated with a low modulation depth in the ionospheric reflection coefficient and consequently with a low Q value of the resonator [*Trakhtengerts et al.*, 2000]. With respect to point 2 this is because a low-latitude station is closer to the SRS source or excitor which is known statistically to be in the tropics. As a result, the "quiet" background magnetic noise level measured in Crete is on the average higher by a factor of 5 to 10 than at the high-latitude stations of the Finnish pulsation magnetometer network (L = 3.3 to 6.6). Moreover, at high (auroral) latitudes SRS is disabled, or masked, by particle precipitation that could lead to dramatic E region enhancements. With respect to 3 the low-latitude F region ion/electron density profiles differ little between daytime and nighttime, so the scale, l_F, (see equation (1)) of the F region topside density decay does not change very much. The change in resonance frequency is thus mainly determined by a change in the absolute value of the ion/electron density at the F layer peak and the frequencies of the harmonics remain nearly equidistant.

[24] We have no clear explanation as to why the SRS model estimates do not agree with the observed large variability in Δf and why there is an offset between calculated and observed resonance frequencies. The possibility exists that this offset can be accounted for, at least partly, by using proper calibration of the IRI profiles applied in the computations. Still, however, the systematic shift to larger Δf values casts some doubts about resolving the differences by IRI calibration only. Therefore it is possible that the SRS model itself may be in error; this requires extensive and careful consideration which, however, is beyond the scope of this paper.

[25] Although its definite demonstration would require a larger database than presently available, we have noticed that the majority of points (resonance frequencies) is clustered inside a frequency band between 0.3 and 0.7–0.8 Hz, whereas the minority of points is loosely scattered into a frequency band above 0.8 Hz reaching occasionally even 1.6 Hz (see Figure 4). Each population exhibits the same seasonal trend, so the extreme points appear preferentially (but not always) in the autumn to winter months (in every UT sector). It is interesting that adjacent days irrespective of season could exhibit SRS belonging to the "regular" type at one day and to the (widely spaced) "irregular" type at the next day or vice versa (see Figure 2). This makes it somehow suspicious that the agreement between model and observation is fairly good for the "irregular" type of data points.

[26] Most intriguing are the Δf values observed during winter months (see Figure 4). All experiences so far made at higher latitudes showed the largest Δf values to occur in December/January. In fact, this is also true for Crete (Δf up to 0.7 Hz), but often very small Δf values are also observed as well, so that on the average Δf in December attains a small mean value but has a large variance. This suggests that at low latitudes, besides the shear Alfvén wave mode, an additional mode might also be contributing. For example, the fact that the magnetic dip is near 50° brings up the possibility that the magnetoacoustic wave mode may also play a role here, an option that perhaps needs to be taken into consideration [cf. *Pokhotelov et al.*, 2001].

[27] Finally, in order to test likely contributions from variations in different geophysical parameters, four periods of a large Δf neighboring on each side with days of small Δf were chosen in order to investigate concurrent changes in solar radiation (10.6 cm), *Kp*, *Dst*, and *Ne*, the latter deduced from IRI f_oF_2 values. None of these parameters, however, was found to have undergone considerable change over the same time period when the pronounced variations in Δf took place.

6. Summary and Conclusions

[28] The main characteristics of SRS at L = 1.3 can be summarized as follows (note that when a reference is made to high latitude (L = 5.2), then a correspondence should be made to paper CP):

1. SRS is observed every single day of the year.
2. SRS is a nighttime phenomenon; it is never seen during daylight hours.
3. The probability of observing SRS is greatest at 23–24 UT (0030–0130 LT).
4. The resonance frequencies (RF) are on the average smaller by a factor of 2 to 3 than those at high latitude (0.4 Hz versus 1.0 Hz in case of the fundamental frequency).
5. The difference Δf between adjacent RF is on average only half of the Δf at high latitudes.
6. There is a systematic increase of RF from May 1999 to January 2000, but this is smaller than at high latitude. This is also true for Δf.

[29] All these properties are basically consistent with the existing SRS model using IRI, the latter providing only a statistical average on the state and composition of the low-latitude ionosphere. The SRS properties exhibit, nevertheless, a high degree of variability, which is reasonably small in summer but it increases toward winter and can reach variation amplitudes up to about a factor of 3. Thus it appears as the variability of SRS rather than SRS itself is the quantity which deserves the attribute of a seasonal dependence.

[30] The variability in SRS properties was investigated specifically for two consecutive days (17 and 18 October 1999) when SRS from "normal" patterns, it suddenly turned over to an "irregular" situation. Concurrent indices for magnetic and solar activity did not correlate with the, at least, short-term variability in Δf. Due to the limited amount of data nothing yet can be said about the solar activity dependence. As pointed out by the study of *Belyaev et al.* [2000], observations of SRS should become very rare during years of solar maximum. Our observations, however, show that even in 1999, a year of solar activity maximum, SRS were observed every night. It remains to be clarified whether these different findings are due to the difference in latitude (mid versus low) or due to some other mechanisms. The high-latitude study by in paper CP, at least, revealed a similar trend in the dependence of the occurrence frequency of SRS from solar activity as found by *Belyaev et al.* [2000].

[31] In summary, SRS observations at L = 1.3 exhibit most of the properties known from middle and high-latitude studies, but there are also very distinct differences which to our knowledge makes the observations at low latitude unique. This suggests the need for more research.

[32] **Acknowledgments.** The authors P.P.B. and A.G.D. acknowledge travel support by the NATO Collaborative Research Grant CRG.CRG 973834. The contributions of most authors were facilitated and accelerated by the INTAS99-0335 grant. The following grants of the Russian Basic Research Foundation are greatly appreciated: 01-02-16742, 015.-01.01.069, E008-0.8-44, 01-05-64437, and 02-05-06228. Support was also provided by the European Office of Aerospace Research and Development (EOARD). Our thanks go to Erkki Laukkanen, whose technical and electronic skill were essential for the installation and maintenance of the pulsation magnetometer. We wish to express our gratitude to the Right Reverend Bishop of Petra Nektarios for his enthusiastic support and for allowing the housing of the pulsation magnetometer in the grounds of the Kallerghi, Hagios Ioannis Monastery. Also we are grateful to Ioannis Karavalakis and Ioannis Katzagiannakis, friends and supporters of the Kalerghi Monastery, for their extremely valuable help for the unobstructed operation of our experiment.

[33] Michel Blanc thanks both referees for their assistance in evaluating this paper.

References

Belyaev, P. P., S. V. Polyakov, V. O. Rapoport, and V. Y. Trakhtengerts, Dynamic frequency spectrum formation of the Pc-1 pulsations, *Geomagn. Aeron.*, *27*, 652–656, 1987.

Belyaev, P. P., S. V. Polyakov, V. O. Rapoport, and V. Y. Trakhtengerts, Experimental studies of the spectral resonance structure of the atmospheric electromagnetic noise background within the range of short-period geomagnetic pulsations, *Radiofizika*, *32*, 663–672, 1989a.

Belyaev, P. P., S. V. Polyakov, V. O. Rapoport, and V. Y. Trakhtengerts, Theory of the formation of resonance structure of the atmospheric electromagnetic background noise in the range of short-period geomagnetic pulsations, *Radiofizika*, *32*, 802–810, 1989b.

Belyaev, P. P., S. V. Polyakov, V. O. Rapoport, and V. Y. Trakhtengerts, The ionospheric Alfvén resonator, *J. Atmos. Terr. Phys.*, *52*, 781–787, 1990.

Belyaev, P. P., T. Bösinger, S. V. Isaev, and J. Kangas, First evidence at high latitudes for the ionosphereic Alfvén resonator, *J. Geophys. Res.*, *104*, 4305–4317, 1999.

Belyaev, P. P., S. V. Polyakov, E. N. Ermakova, and S. V. Isaev, Solar cycle variations in the ionospheric Alfvén resonator 1985–1995, *J. Atmos. Sol. Terr. Phys.*, *62*, 239–248, 2000.

Bösinger, T., and U. Wedeken, Pi1B type magnetic pulsations observed simultaneously at mid and high latitudes, *J. Atmos. Terr. Phys.*, *49*, 573–598, 1987.

Demekhov, A. G., P. P. Belyaev, S. V. Isaev, J. Manninen, T. Turunen, and J. Kangas, Modelling the diurnal evolution of the resonance spectral structure of the atmospheric noise background in the Pc 1 frequency range, *J. Atmos. Sol. Terr. Phys.*, *62*, 257–265, 2000.

Hickey, K., D. D. Sentman, and M. J. Heavner, Ground-based observations of ionospheric Alfvén resonator bands, *Eos Trans. AGU*, *77*(46), Fall Meet. Suppl., F92, 1996.

Lysak, R. L., Generalized model of the ionospheric Alfvén resonator, in *Auroral Plasma Dynamics, Geophys. Monogr. Ser.*, vol. 80, edited by R. L. Lysak, pp. 121–128, AGU, Washington, D.C., 1993.

Ostapenko, A. A., and S. V. Polyakov, The dynamics of the reflection coefficient of Alfvén waves in the Pc1 range from ionosphere under variation of electron concentration of the lower ionosphere, *Geomagn. Aeron.*, *30*, 50–56, 1990.

Pokhotelov, O. A., V. Khruschev, M. Parrot, S. Senchenkov, and V. P. Pavlenko, Ionospheric Alfvén resonator revisited: Feedback instability, *J. Geophys. Res.*, *106*, 25813–25824, 2001.

Polyakov, S. V., and V. O. Rapoport, Ionospheric Alfvén resonator, *Geomagn. Aeron.*, *21*, 610–614, 1981.

Trakhtengerts, V. Y., A. G. Demekhov, P. P. Bellyaev, S. V. Polyakov, E. N. Ermakova, and S. V. Isaev, A mechanism of anti-correlation in the occurrence of ULF electromagnetic noise resonance structure and Pc1 magnetic pulsations through the solar activity cycle, *J. Atmos. Sol. Terr. Phys.*, *62*, 253–256, 2000.

V. Angelopoulos, University of California, Space Science Laboratory, Berkeley, CA 94720-7450, USA. (vassilis@ssl.berkeley.edu)

P. P. Belyaev and M. N. Yakunin, Radiophysical Research Institute, B. Pecherskaya 25, 603950 Nizhny Novgorod, Russia. (belyaev@nirfi.sci-nnov.ru; yakunin@nirfi.sci-nnov.ru)

T. Bösinger, Department of Physical Sciences, P.O. Box 3000, FIN-90014, University of Oulu, Finland. (tilmann.bosinger@oulu.fi)

A. G. Demekhov, Institute of Applied Physics, 46, Ulyanov Str., 603950 Nizhny Novgorod, Russia. (andrei@appl.sci-nnov.ru)

C. Haldoupis, Physics Department, University of Crete, Iraklion, Crete, 71003 Greece. (chald@physics.uoc.gr)

N. V. Semenova, Polar Geophysical Institute Apatity, Murmansk region 184200, Russia. (yahnin@pgi.kolasc.net.ru)