

Unusually high frequency natural VLF radio emissions observed during daytime in Northern Finland

This content has been downloaded from IOPscience. Please scroll down to see the full text.

2016 Environ. Res. Lett. 11 124006

(<http://iopscience.iop.org/1748-9326/11/12/124006>)

View [the table of contents for this issue](#), or go to the [journal homepage](#) for more

Download details:

IP Address: 210.77.64.106

This content was downloaded on 11/04/2017 at 04:45

Please note that [terms and conditions apply](#).

You may also be interested in:

VERY-LOW-FREQUENCY RADIO EMISSION OF THE UPPER ATMOSPHERE AND ITS RELATIONSHIP TO GEOPHYSICAL PHENOMENA

B N Gershman and V Yu Trakhtengerts

Progress in planetary lightning

S J Desch, W J Borucki, C T Russell et al.

First VIKING results: high frequency waves

A Bahnsen, M Jespersen, E Ungstrup et al.

A review of selected topics in magnetospheric physics

G E Morfill

Laboratory simulation of magnetospheric chorus wave generation

B Van Compernelle, X An, J Bortnik et al.

A generation mechanism of chorus emissions using BWO theory

Ashutosh K Singh, R P Patel, R Singh et al.

VLF Wave Propagation and its Interaction with the Magnetoplasma

P K Shukla and R N Singh

Investigation of Io's auroral hiss emissions due to its motion in Jupiter's magnetosphere

Mohsen H. Moghimi

MICROWAVE BURSTS WITH FINE STRUCTURES IN THE DECAY PHASE OF A SOLAR FLARE

Jing Huang and Baolin Tan

Environmental Research Letters



LETTER

Unusually high frequency natural VLF radio emissions observed during daytime in Northern Finland

OPEN ACCESS

RECEIVED
8 June 2016REVISED
5 November 2016ACCEPTED FOR PUBLICATION
11 November 2016PUBLISHED
24 November 2016

Original content from this work may be used under the terms of the [Creative Commons Attribution 3.0 licence](#).

Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.

Jyrki Manninen^{1,6}, Tauno Turunen¹, Natalia Kleimenova², Michael Rycroft³, Liudmila Gromova⁴ and Iina Sirviö^{1,5}¹ Sodankylä Geophysical Observatory, Sodankylä, Finland² Schmidt Institute of the Earth Physics of RAS, Moscow, Russia³ CAESAR Consultancy, Cambridge, UK⁴ Pushkov Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation of RAS, Moscow, Russia⁵ University of Jyväskylä, Department of Physics, Jyväskylä, Finland⁶ Author to whom any correspondence should be addressed.E-mail: jyrki.manninen@sgo.fi**Keywords:** VLF radio emissions, unusual high-frequency emissions, recently revealed emissions, sferics filtering**Abstract**

Geomagnetic field variations and electromagnetic waves of different frequencies are ever present in the Earth's environment in which the Earth's fauna and flora have evolved and live. These waves are a very useful tool for studying and exploring the physics of plasma processes occurring in the magnetosphere and ionosphere. Here we present ground-based observations of natural electromagnetic emissions of magnetospheric origin at very low frequency (VLF, 3–30 kHz), which are neither heard nor seen in their spectrograms because they are hidden by strong impulsive signals (sferics) originating in lightning discharges. After filtering out the sferics, peculiar emissions are revealed in these digital recordings, made in Northern Finland, at unusually high frequencies in the VLF band. These recently revealed emissions, which are observed for several hours almost every day in winter, contain short (~1–3 min) burst-like structures at frequencies above 4–6 kHz, even up to 15 kHz; fine structure on the 1 s time scale is also prevalent. It seems that these whistler mode emissions are generated deep inside the magnetosphere, but the detailed nature, generation region and propagation behaviour of these newly discovered high latitude VLF emissions remain unknown; however, further research on them may shed new light on wave-particle interactions occurring in the Earth's radiation belts.

1. Introduction

It is generally accepted that the Earth's magnetic field (MF) is one of the necessary conditions for the existence of the biosphere and for human life to emerge and develop on Earth. The invisible magnetic shell which protects the Earth from harmful cosmic rays is the magnetopause, the outer boundary of the magnetosphere, and many other geomagnetic flux tubes. Changes of solar and geomagnetic activity can influence different processes operating in the Earth's atmosphere, including the climate, the biosphere (e.g., Adey 1993, Chibisov *et al* 1995), and even human health (e.g., Watanabe *et al* 1994, Breus *et al* 1995, Gurfinkel *et al* 1995, Palmer *et al* 2006, Kleimenova

et al 2007, Babayev *et al* 2012 and many others). Thus, the geomagnetic field, with its essential feature of variations having different time scales and waves occurring over a wide range of frequencies, is an important factor in determining the environment of the Earth. These waves act as a specific interface between the interplanetary medium and the magnetosphere, transferring the energy input from the solar wind and the varying Interplanetary MF into the magnetosphere. Moreover, these waves are a very effective remote sensing tool for studying the physics of plasma processes operating in the Earth's magnetosphere and ionosphere.

Here we pay especial attention to natural electromagnetic waves in the audio frequency range, which

are termed very low frequency (VLF, 3–30 kHz) waves (Helliwell 1965). A particular type of these waves called atmospherics (sferics) originate in lightning discharges (Volland 1995) and propagate thousands of km in the Earth-ionosphere waveguide. Other types of wave, such as broadband unstructured auroral hiss (Gurnett 1966) and discrete rising frequency signals known as chorus, originate as plasma instabilities within the ionospheric or magnetospheric plasma itself. These whistler mode emissions are guided to the Earth's surface by geomagnetic flux tubes; they are common wave phenomena in the Earth's environment. These waves may be observed on the ground or aboard satellites in the ionosphere or magnetosphere (for example, see Tsurutani *et al* 2012).

Chorus is generated via a cyclotron resonance of the energetic electrons travelling in the opposite direction to the wave through the inner magnetosphere (Trakhtengerts and Rycroft 2008). These electromagnetic waves play a controlling role in the dynamics of Earth's radiation belts, known as the van Allen belts (e.g., Trakhtengerts 1963, Kennel and Petschek 1966, Rycroft 1991, Meredith *et al* 2001, Thorne *et al* 2013). It is also important to mention that in the last two decades some authors (e.g., Hayakawa *et al* 1996, Molchanov and Hayakawa 1998, Němec *et al* 2009, Rozhnoi *et al* 2009, Boudjada *et al* 2010, Pisa *et al* 2013) have used VLF observations to study precursor effects of earthquakes, an active field of research today.

Although more than 50 years have passed since the classical work by Helliwell (1965), and despite significant successes of many different ground-based and satellite observations, the full nature and behaviour of different VLF waves is still not fully understood. Many naturally occurring VLF waves at higher frequencies (above 4–6 kHz) could not be studied because strong atmospherics (sferics) hide all such waves. To study these waves, we have to apply special digital programmes which filter out the strong impulsive sferics. That process uncovers completely new types of high frequency daytime VLF emissions with various unusual spectral structures that have never been seen before. The aim of this paper is to present, and briefly discuss, the spectral characteristics of some of these new natural electromagnetic emissions of magnetospheric origin having frequencies higher than 4 kHz.

2. Data

Our results are based on the VLF observations made in Northern Finland at Kannuslehto, with the geographic coordinates (67.74°N, 26.27°E), and $L \sim 5.5$, where L is the distance measured in Earth radii ($1R_E = 6378$ km) from the centre of the planet to the equatorial crossing of the geomagnetic field line through the site. Several wintertime VLF campaigns (2006–2016) have been carried out at this remote, low

noise field site some 35 km North of the Sodankylä Geophysical Observatory, in the auroral zone. The VLF emissions were recorded digitally in the frequency band of 0.2–39 kHz by two orthogonal magnetic loop antennas oriented in the north–south and east–west directions. The threshold of the receiver sensitivity is about 0.1 fT, (i.e. $\sim 10^{-14}$ nT² Hz⁻¹). As a result of these very sensitive observations, some interesting new emissions typical of this high geomagnetic latitude, at frequencies below 3–4 kHz, have been recently reported (Manninen *et al* 2012, 2013, 2014, 2015).

3. Results

Figures 1 and 2 demonstrate examples on different days of the 1 h total power spectrograms (frequency–time dynamic spectra) of such previously unknown daytime VLF emissions. The left panels show unfiltered data, including strong narrowband communication transmitter signals at frequencies above 11 kHz, and the right panels present the spectrograms after filtering. The three strong white high-frequency lines in the right panels are the removed radio transmitter traces; the bottom red band at frequencies <0.5 kHz is due to the local power line harmonic radiation (PLHR). Many very strong sferics hide—like a curtain—all signals with frequencies above ~ 5 kHz.

The right panels show the same events after digital filtering out of the sferics, the narrowband transmitter signals and the PLHRs. Strong sferics are removed by a broadband digital filter (from 0.6 to 16 kHz), with properly rounded edges so as not to cause deleterious effects on the dynamic spectral analysis. Over successive intervals of 20 ms (the duration of the filter) the signal is reduced to zero, and corrections are applied to the remaining power estimate for the power loss occurring during these 20 ms intervals. The signals from several strong VLF transmitters at frequencies >10 kHz are removed by several narrow band digital Fourier transform filters tuned to the known transmitter frequencies. Similarly, the strongest PLHR occurring at, or near, multiple harmonics of the 50 Hz electrical grid system in Finland are removed by a number of digital notch filters tuned to the interfering frequencies (up to several kHz) which are measured over successive 5 s samples of the signal. A correction is then applied for the small power loss of the dynamic spectral signal at each of these frequencies which are filtered out. Typically, these filters are set to from 950 to 4050 Hz at every odd harmonic.

Different kinds of atypical high frequency VLF emissions are noted. Figure 1(a) shows 10–15 min long bursts of banded hiss-like emissions in the frequency range of ~ 7 –9 kHz with a sharp low frequency cut-off, looking rather like a bullet in the frequency–time plane. Figure 1(b) presents a narrow (5–6 kHz) band of very closely repeated risers about 1 min apart,

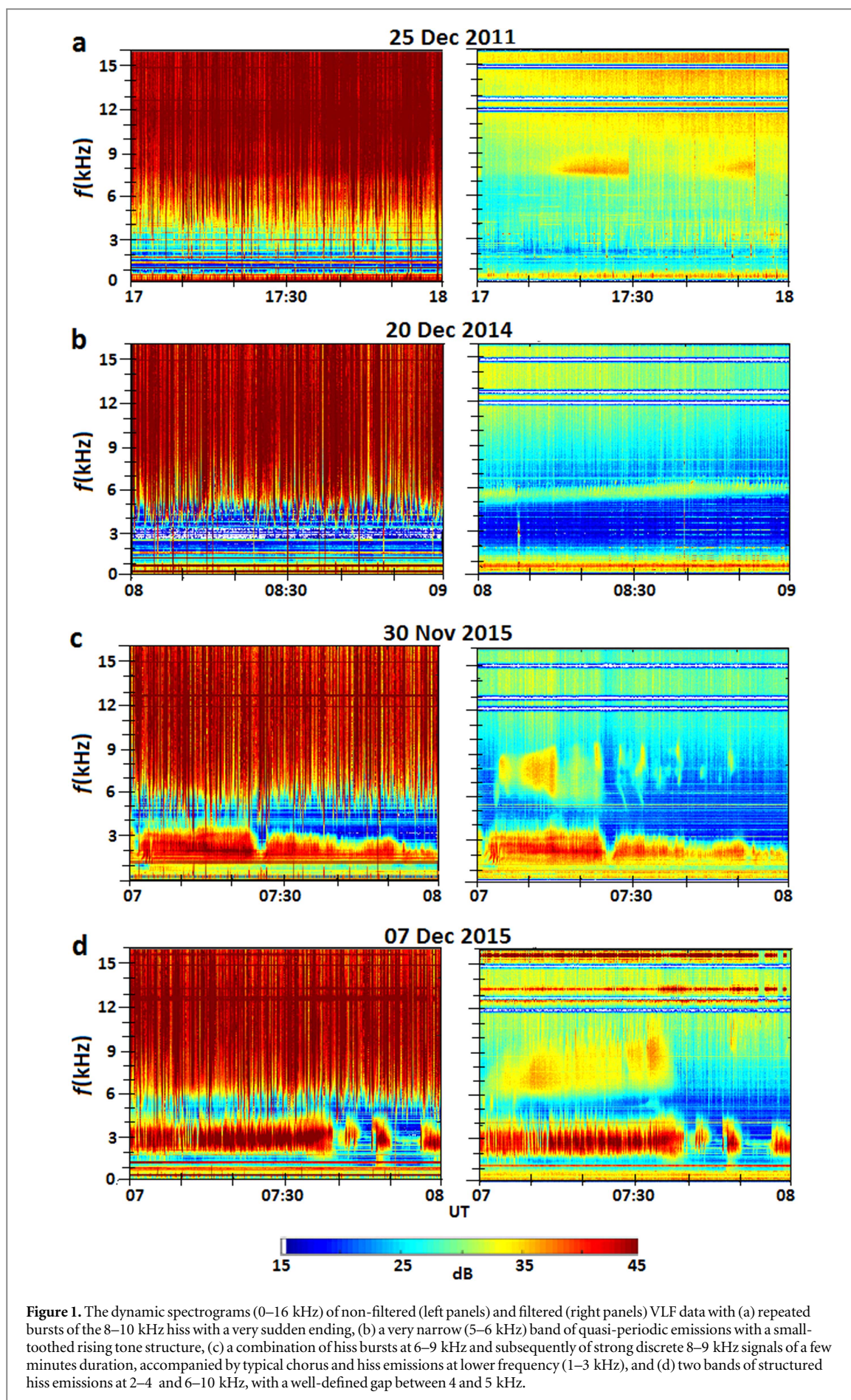
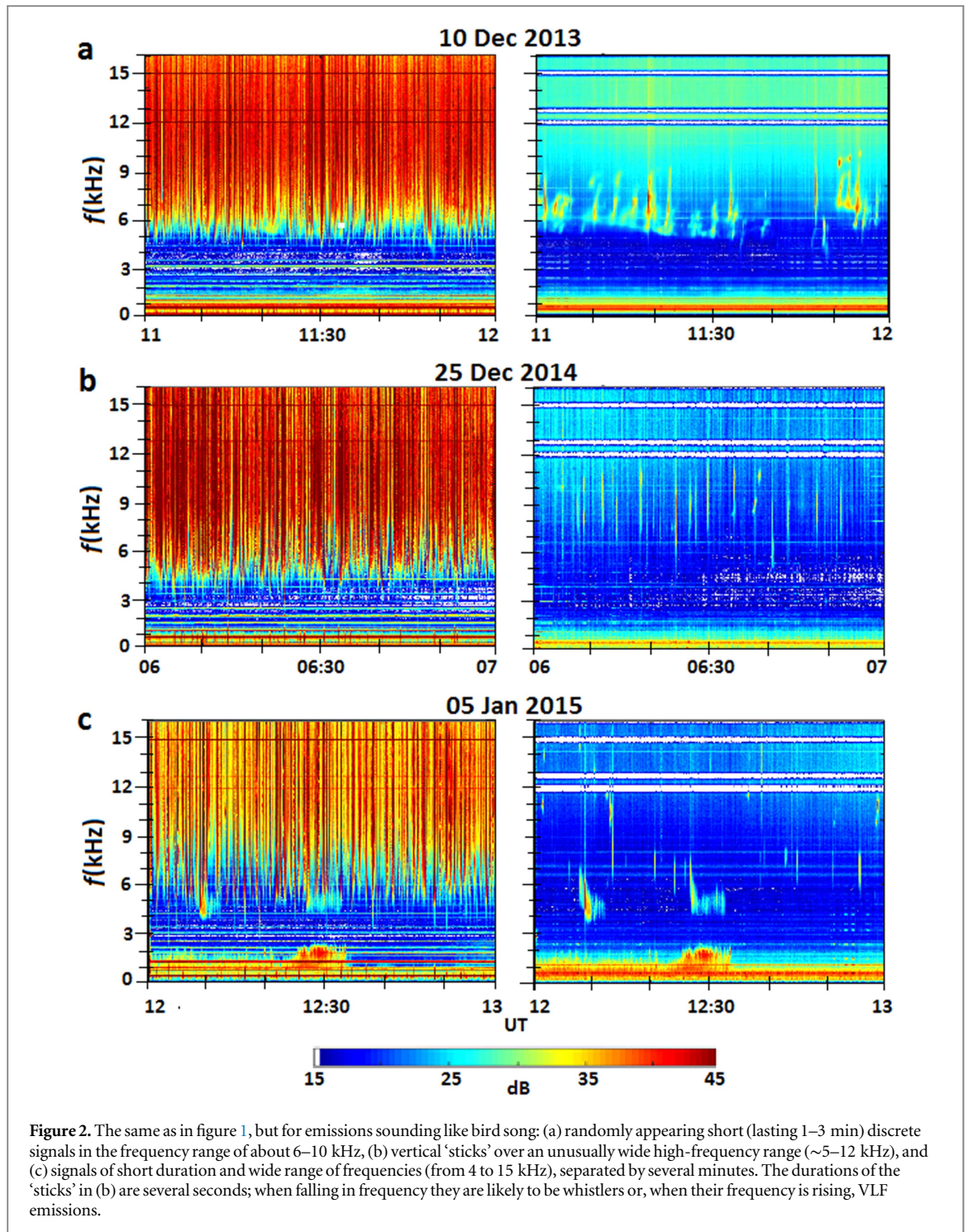


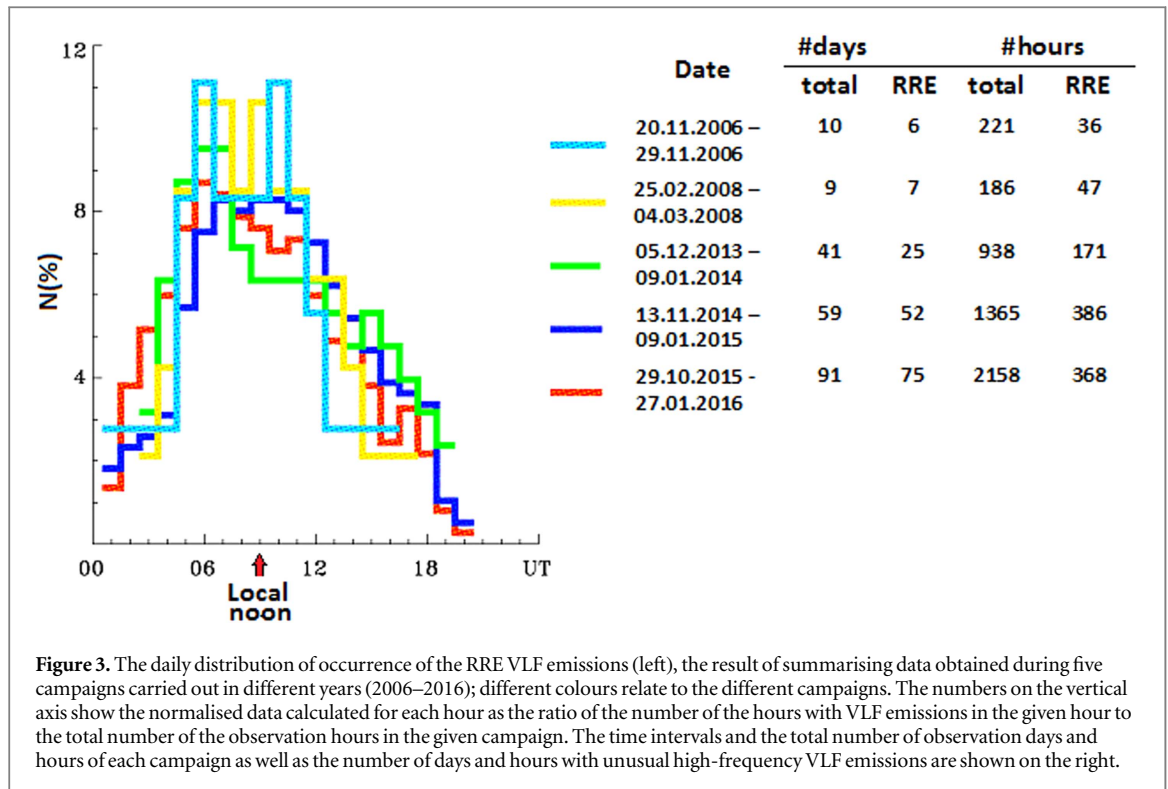
Figure 1. The dynamic spectrograms (0–16 kHz) of non-filtered (left panels) and filtered (right panels) VLF data with (a) repeated bursts of the 8–10 kHz hiss with a very sudden ending, (b) a very narrow (5–6 kHz) band of quasi-periodic emissions with a small-toothed rising tone structure, (c) a combination of hiss bursts at 6–9 kHz and subsequently of strong discrete 8–9 kHz signals of a few minutes duration, accompanied by typical chorus and hiss emissions at lower frequency (1–3 kHz), and (d) two bands of structured hiss emissions at 2–4 and 6–10 kHz, with a well-defined gap between 4 and 5 kHz.



yet looking like a band of continuous hiss with a small-toothed rising tone structure. Figures 1(c) and (d) exhibit the presence of relatively strong structured hiss-like bands of emissions, with a well-defined gap between 4 and 5 kHz. There were relatively strong structured hiss-like emissions at frequencies below ~4 kHz and ‘clouds’ of hiss of unusually high frequency, between 6 and 10 kHz, of 10–30 min duration, followed by very short (~1 min) bursts.

Moreover, this strange spectral world of differently structured high-frequency (>5 kHz) waves was only opened up after filtering out the sferics; to the best of

our knowledge, such signals have not been reported before. The dynamic spectra of these high frequency VLF emissions, termed recently revealed emissions (RREs), are plotted in figure 2. We call these peculiar daytime events ‘bird-emissions’ since when they are played through a loudspeaker they sound like bird song. For the most part, these ‘bird-emissions’ were observed at frequencies above ~5–6 kHz. On a 1 h spectrogram, these signals often resemble ‘sticks’ or ‘wands’. Actually, they are mostly hiss bursts with durations of a few seconds. Three examples of such emissions are presented in figure 2: (a) randomly



appearing short (lasting 1–3 min) discrete signals in the frequency range of about 6–10 kHz; (b) vertical ‘sticks’ over an unusually wide high-frequency range (~5–12 kHz); and (c) signals of short duration and a wide range of frequencies (from 4 to 15 kHz), separated by several minutes.

It is found that these newly discovered VLF emissions are very common daytime phenomena. So, during five Finnish local winter VLF campaigns (2006–2016) at different phases of the 11 year solar cycle, they were observed almost every day. In total, these emissions were detected on 165 of the 210 d of observation, i.e. on 78% of all days.

The diurnal distribution in hourly intervals is given in figure 3 for each campaign. The numbers on the vertical axis show the normalised data calculated for each hour as the ratio of the number of the hours with these RREs in the given hour to the total number of the observation hours in each campaign. It can be seen that all campaigns demonstrate the same rather similar feature, namely a remarkable enhancement in the local daytime. Without exception, these new VLF emissions are observed during rather quiet geomagnetic conditions after moderate geomagnetic disturbances or in the late recovery phase of magnetic storms. Because these RREs are observed during the local winter, when it is dark at high latitudes throughout the day, they suffer the minimum amount of attenuation as they propagate through the ionosphere to the receiver on the ground.

We also have analysed the fine structure, on time scales of a few s or more, of these previously hidden VLF emissions. Usually the studied events exhibit a

sequence of separate patches in the frequency–time domain, with a wide variety of spectral structures. Several individual examples of 3 min spectrograms of remarkably diverse signals in the frequency range 1–10 kHz from different campaigns are plotted in figure 4. Panel (a) demonstrates an example of the simultaneous generation of two separate ‘patches’ in the frequency–time domain, 1 min long, and at different frequencies in the 6–10 kHz band, with different onsets and dynamics of spectral structure. Such complicated wave features could indicate that the development of the magnetospheric plasma instability responsible for them is rather localised in time and space. Panels (b)–(c) show the strange frequency–time dynamic structure resembling several flying birds, with the emitted frequency rising with time. A combination of several short signals at different frequencies between 4 and 10 kHz is plotted in panel (c), where one can see the frequency of the signal increasing over about 30 s. In panel (d), the fine spectral structure of the quasi-periodic hiss-like emissions, shown in figure 1(b), is presented; hiss bursts of rising frequency with periodically repeated enhancements are seen. Panels (e) and (f) show two different bursts of waves lasting about 1 min; the overall frequency is increasing from 4 to 7 kHz (e) or decreasing from ~8 to ~5 kHz (f) as time progresses, and the strong emissions at frequencies below 2 kHz are typical chorus signals (Helliwell 1965) at this site. Because the wave frequency generated is directly proportional to the electron cyclotron frequency in the source region f_{ce} (which is proportional to L^{-3}), this observation may support the

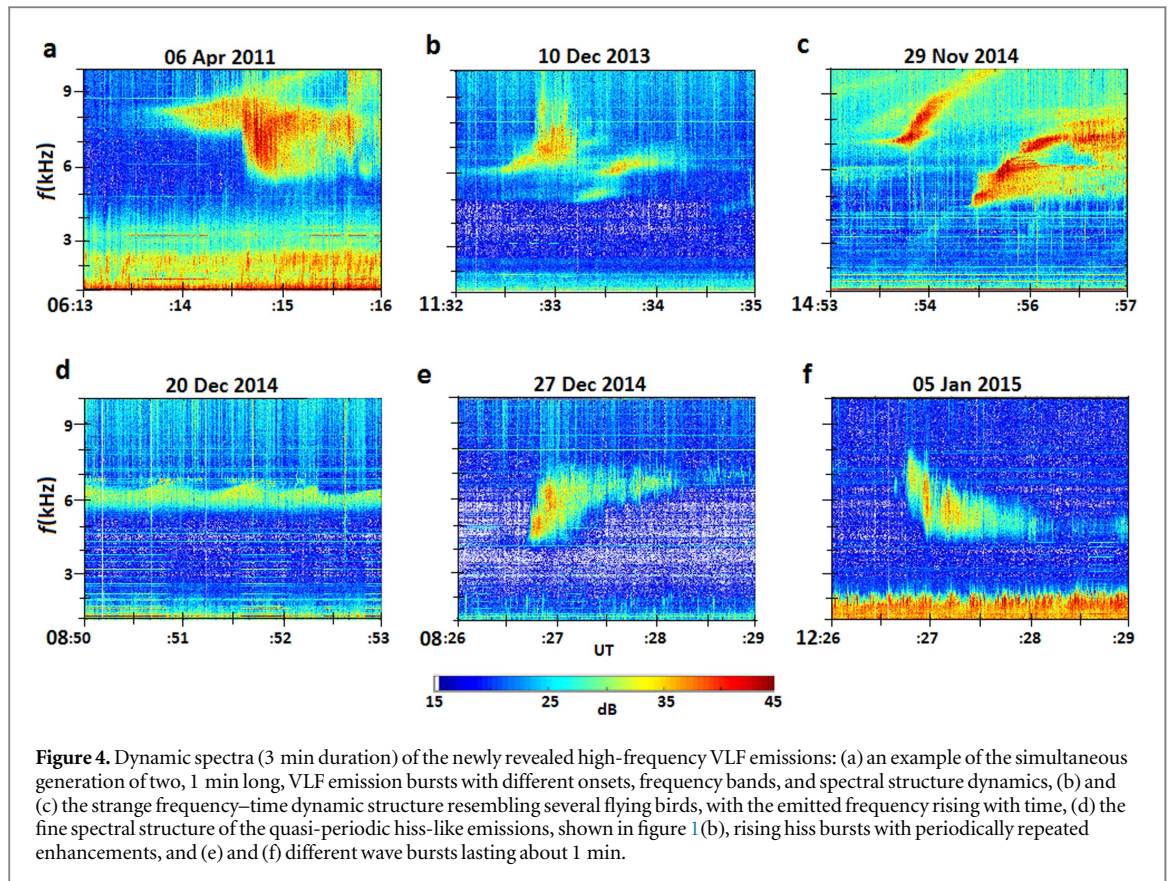


Figure 4. Dynamic spectra (3 min duration) of the newly revealed high-frequency VLF emissions: (a) an example of the simultaneous generation of two, 1 min long, VLF emission bursts with different onsets, frequency bands, and spectral structure dynamics, (b) and (c) the strange frequency–time dynamic structure resembling several flying birds, with the emitted frequency rising with time, (d) the fine spectral structure of the quasi-periodic hiss-like emissions, shown in figure 1 (b), rising hiss bursts with periodically repeated enhancements, and (e) and (f) different wave bursts lasting about 1 min.

hypothesis of the generation source shifting inwards (e) or outwards (f) across the L -shells.

Such a rich collection of very varied dynamic spectra of these high-latitude VLF emissions (as is evident in figure 4) at frequencies above 5 kHz must certainly be the result of spatially and temporally changing localised regions of electron cyclotron instability in the magnetospheric plasma. The detailed nature of these complex processes is still poorly understood and these new results raise a number of questions to be attacked in further research.

Francis *et al* (1983) have reported receiving most unusual discrete VLF emissions in the high VLF range, from 6 to 9 kHz, at Halley, Antarctica ($L \sim 4.3$). The signals were generally a succession of chirps, each rising in frequency within 1 s, and often exhibiting a minimum intensity near 7.5 kHz; they also exhibited a ~ 4 min periodicity in occurrence. On the other hand, the frequency of chorus commonly observed at Halley during the local morning hours is ~ 2 –4 kHz. These signals were recorded on one day in June 1972 near local noon, during the recovery phase of a minor geomagnetic storm. Francis *et al* (1983) interpreted these emissions as being due to a cyclotron resonance instability occurring near the equatorial plane on a nearby $L \sim 3.6$ flux tube.

The interpretation of the minimum intensity of the signals at 7.5 kHz discussed by Francis *et al* (1983) is that this frequency is $0.5 f_{ce}$ at the equator on the geomagnetic flux tube. Signals below this frequency are guided by enhancements of plasma density in

magnetically field aligned ducts, whereas higher frequencies are in principle guided by field aligned depletions of plasma density (Smith *et al* 1960).

It must be mentioned that these unusual VLF emissions are not auroral hiss. Auroral hiss is a broadband and unstructured (in the frequency–time plane) signal which may last for several hours (generally between local noon and midnight) with very little temporal variation on time scales less than a minute (Sazhin *et al* 1993, LaBelle and Treumann 2002). Hiss between 3 and 9 kHz, and having multiple banded structures, has been observed at Porojärvi, also North of Sodankylä, during the local evening, and reported by Titova *et al* (2007).

The considered RREs could not be classified as the high-frequency VLF emissions recorded by (Francis *et al* 1983). There are several important differences between the RREs and the unusual VLF emissions at Halley Bay (Francis *et al* 1983). The duration of separate RREs is much longer and amounts ~ 30 –60 s or even more (as is seen in figure 4), as opposed to tenths of a second at Halley Bay (see figures 1 and 4 in Francis *et al* 1983). The RRE spectral structure is completely different (as one can see in some examples of the wave dynamic spectra presented in our figure 4), contrary to a series of short rising frequency emissions recorded at Halley Bay. Further, we have never seen the frequency gap between two high-frequency emission bands as was found at Halley Bay.

VLF observations made aboard satellites can provide useful complementary information. Titova *et al*

(2015) have studied natural VLF signals recorded aboard the Van Allen Probe-A when it was in the night sector near the geomagnetic equator at $L = 3.0\text{--}4.2$, on geomagnetic flux tubes passing through the area to the North West of Scotland. Simultaneously, the same signals, rising in frequency, typically from 2 to 5 kHz, were recorded on the ground at Kannuslehto ($L \sim 5.5$). These quasi-periodic discrete signals certainly have different characteristics from the RREs reported here. Recently, Němec *et al* (2016) have reported other quasi-periodic signals, occurring between 1.4 and 2.4 kHz (see their figures 2 and 3), observed both on the DEMETER spacecraft and on the ground at Kannuslehto. Again these have completely different shapes in the frequency–time domain from the RREs considered here. Further, Parrot *et al* (2015) have reported some new and unexplained VLF signals observed aboard the microsatellite DEMETER the topside ionosphere; however, all these were recorded at low and middle latitudes, but not in the auroral zone. The RREs reported here do not fit into any category of unexpected VLF radio emissions discussed by Parrot *et al* (2015).

4. Discussion

It is very important to emphasise that the recently revealed VLF emissions (RREs) are observed at frequencies above 4–6 kHz, and up to 10 kHz or even higher. It is generally accepted that the typical VLF emissions observed on the ground are generated in the magnetosphere due to the electron cyclotron instability (Trakhtengerts and Rycroft 2008). The frequency band of these waves is controlled by the electron gyrofrequency f_{ce} at the geomagnetic equator, where f_{ce} is the frequency of electron gyrating around the geomagnetic field line. The f_{ce} value is proportional to the local MF strength (Stix 1962); it is thus proportional to L^{-3} . Chorus observed near the magnetic equator close to $L \sim 5.5$ aboard the Van Allen Probe-A spacecraft (Santolik *et al* 2014) occurs at frequencies below 2 kHz, at $<0.5 f_{ce}$.

VLF waves, which are generated near the magnetic equator in the magnetosphere, are guided by the geomagnetic field to the ionosphere. The ducted whistler-mode wave guiding structure (Smith *et al* 1960) is similar to that in fibre optics when light is guided by dielectric glass filaments. Ducted VLF emissions reaching the ground have an upper cut-off frequency at half the equatorial electron gyrofrequency f_{ce} . That is the maximum frequency which can propagate in a duct caused by a field-aligned enhancement of electron density (Carpenter 1968); this is a hard, theoretical limit which arises from magnetoionic theory. The second important fact is that only those waves, which penetrate through the ionosphere, can be recorded on the ground in the vicinity (typically $\sim 120\text{--}150$ km) of the footprint of the ionospheric exit point of the wave.

It should be noted that the equatorial electron gyrofrequency f_{ce} at $L \sim 5.5$ (i.e. the L value of our observation point Kannuslehto) is ~ 5 kHz. Assuming that ducting occurs across the equatorial region at $L \sim 5.5$, this corresponds to an upper frequency limit of $f \leq 0.5 f_{ce}$, i.e. $f \leq 2.5$ kHz. This is the theoretical limit above which we should not be able to detect emissions on the ground if they propagate roughly along the receiver's geomagnetic flux tube. However, the recently revealed VLF emissions are observed at much higher frequency, well above 4–5 kHz, often up to 10 kHz and sometimes up to 15 kHz. To the best of our knowledge, the RREs have not been observed by space-borne instrumentation. Further, it is difficult to explain how the waves with frequency higher than half of the electron gyrofrequency can be guided from the generation region at or near the geomagnetic equator to the ground.

Perhaps these waves are generated much deeper in the magnetosphere, at much lower L -values ($L \sim 3.5$) where the equatorial electron gyrofrequency f_{ce} is significantly higher, by a factor of ~ 4 . Then a new question arises: how do these waves cross a rather large range of L -values to be observed at high latitudes? This challenging problem is to be tackled in another paper. The detailed nature, generation region and propagation behaviour of these newly discovered VLF emissions still remain unknown. However, further research on them may shed new light on wave–particle interactions occurring in the Earth's radiation belts.

5. Summary

Based on these VLF (3–30 kHz) radio observations made in Northern Finland, we have discovered many new and unexpected natural electromagnetic emissions of magnetospheric origin at frequencies higher than 4 kHz. Previously, these were neither heard nor seen in their spectrograms because they were hidden by strong impulsive signals (sferics) originating in low latitude lightning discharges. Only after filtering these sferics out were the peculiar VLF emissions discovered. These RREs are probably generated close to the geomagnetic equator yet deep in the magnetosphere, at a considerably lower L -value ($L \sim 3.5$) than that of the observation site ($L \sim 5.5$). The details of the mechanism of the generation and propagation of these newly discovered VLF emissions remain unknown.

Acknowledgments

The research is supported by the Academy of Finland (grant no. 287988 for NK and LG), and the University of Oulu (grant for MR, for which he is very grateful). We are grateful to the technical staff of SGO for their valuable assistance in organising the field campaigns. The work of NG was partly supported by Program RAS no. 7.

Author contributions

JM and TT designed the research, performed most of the data processing and analysis, TT designed the digital electronics receiver and the filters, and supervised the observations, JM, NK, and MR took the lead in writing the manuscript, LG downloaded and analysed geomagnetic data, and IS undertook a statistical analysis of the VLF data. All authors discussed the results and contributed to the editing of the manuscript.

References

- Adey WR 1993 Biological effects of electromagnetic fields *J. Cell Biochem.* **51** 410–6
- Babayev E S, Crosby N B, Obridko V N and Rycroft M J 2012 Potential effects of solar and geomagnetic variability on terrestrial biological systems *Advances in Solar and Solar-Terrestrial Physics* ed G Maris and C Demetrescu (Trivandrum: Research Signpost) pp 329–76
- Boudjada M Y *et al* 2010 Decrease of VLF transmitter signal and chorus-whistler waves before l'Aquila earthquake occurrence *Nat. Hazards Earth Syst. Sci.* **10** 1487–94
- Breus T, Cornelissen G, Halberg F and Levitin A E 1995 Temporal associations of life with solar and geophysical activity *Ann. Geophys.* **13** 1211–22
- Carpenter D L 1968 Ducted whistler-mode propagation in the magnetosphere; a half-gyrofrequency upper intensity cut-off and some associated wave growth phenomena *J. Geophys. Res.* **73** 2919–28
- Chibisov S M, Breus T K, Levitin A E and Dragova G M 1995 Biological effects of planetary magnetic storms *Biofizika* **40** 959–68
- Francis C R, Strangeways H J and Bullough K 1983 Discrete VLF emissions (7–9 kHz) displaying unusual banded and periodic structure *Planet. Space Sci.* **31** 537–57
- Gurfinkel Y I, Liubimov V V, Oraevsky V N, Parfenova L M and Yuriev A S 1995 The effect of geomagnetic disturbances in capillary blood flow in ischemic disease patients *Biofizika* **40** 793–9
- Gurnett D A 1966 A satellite study of VLF hiss *J. Geophys. Res.* **71** 5599–615
- Hayakawa M, Molchanov O A, Ondoh T and Kawai E 1996 The precursory signature effect of the Kobe earthquake on subionospheric VLF signals *J. Commun. Res. Lab.* **43** 169–80
- Helliwell R A 1965 *Whistlers and Related Ionospheric Phenomena* (Stanford, CA: Stanford University Press)
- Kennel C F and Petschek H E 1966 Limit of stably trapped particle fluxes *J. Geophys. Res.* **71** 1–28
- Kleimenova N G, Kozyreva O V, Breus T K and Rapoport S I 2007 Pc1 geomagnetic pulsations as a potential hazard of the myocardial infarction *J. Atmos. Solar-Terr. Phys.* **69** 1759–64
- LaBelle J and Treumann R A 2002 Auroral radio emissions: I. Hisses, roars, and bursts *Space Sci. Rev.* **101** 295–440
- Manninen J, Demekhov A G, Titova E E, Kozlovsky A E and Pasmanik D L 2014 Quasiperiodic VLF emissions with short-period modulation and their relationship to whistlers: a case study *J. Geophys. Res. Space Phys.* **119** 3544–57
- Manninen J, Kleimenova N G, Kozlovsky A, Kornilov I A, Gromova L I, Fedorenko Y V and Turunen T 2015 Strange VLF bursts in northern Scandinavia: case study of the afternoon 'mushroom-like' hiss on 8 December 2013 *Ann. Geophys.* **33** 991–5
- Manninen J, Kleimenova N G and Kozyreva O V 2012 New type of ensemble of quasi-periodic, long-lasting VLF emissions at the auroral zone *Ann. Geophys.* **30** 1655–60
- Manninen J, Kleimenova N G, Kozyreva O V, Bespalov P A and Kozlovsky A E 2013 Non-typical ground-based quasi-periodic VLF emissions observed at $L = 5.3$ under quiet geomagnetic conditions at night *J. Atmos. Sol.-Terr. Phys.* **99** 123–8
- Meredith N P, Horne R B and Anderson R R 2001 Substorm dependence of chorus amplitudes: implications for the acceleration of electrons to relativistic energies *J. Geophys. Res.* **106** 13165–78
- Molchanov O A and Hayakawa M 1998 Subionospheric VLF signal perturbations possibly related to earthquakes *J. Geophys. Res.* **103** 17489–504
- Němec F, Bezdeková B, Manninen J, Parrot M, Santolík O, Hayash M and Turunen T 2016 Conjugate observations of a remarkable quasiperiodic event by the low-altitude DEMETER spacecraft and ground-based instruments *J. Geophys. Res.* **121** 8790–803
- Němec F, Santolík O and Parrot M 2009 Decrease of intensity of ELF/VLF waves observed in the upper ionosphere close to earthquakes: a statistical study *J. Geophys. Res.* **114** A04303
- Palmer S J, Rycroft M J and Cermack M 2006 Solar and geomagnetic activity, extremely low frequency magnetic and electric fields and human health at the Earth's surface *Surv. Geophys.* **27** 557–95
- Pisa D, Němec F, Santolík O, Parrot M and Rycroft M 2013 Additional attenuation of natural VLF electromagnetic waves observed by the DEMETER spacecraft resulting from preseismic activity *J. Geophys. Res.* **118** 5286–95
- Parrot M *et al* 2015 Unexpected very low frequency (VLF) radio events recorded by the ionospheric satellite DEMETER *Surv. Geophys.* **36** 483–511
- Rozhnoi A *et al* 2009 Anomalies in VLF radio signals prior the Abruzzo earthquake ($M = 6.3$) on 6 April 2009 *Nat. Hazards Earth Syst. Sci.* **9** 1727–32
- Rycroft M J 1991 Interaction between whistler-mode waves and energetic electrons in the coupled system formed by magnetosphere, ionosphere and atmosphere *J. Atmos. Terr. Phys.* **53** 849–58
- Santolík O, Kletzing C A, Kurth W S, Hospodarsky G B and Bounds S R 2014 Fine structure of large-amplitude chorus wave packets *Geophys. Res. Lett.* **41** 293–9
- Sazhin S S, Bullough K and Hayakawa M 1993 Auroral hiss: a review *Planet. Space Sci.* **41** 153–66
- Smith R L, Helliwell R A and Yabroff I W 1960 A theory of trapping of whistlers in field-aligned columns of enhanced ionisation *J. Geophys. Res.* **65** 1–20
- Stix T H 1962 *The Theory of Plasma Waves* (New York: McGraw-Hill)
- Thorne R M *et al* 2013 Rapid local acceleration of relativistic radiation-belt electrons by magnetospheric chorus *Nature* **504** 411–4
- Titova E E, Demekhov A G, Pasmanik D L, Trakhtengerts V Y, Manninen J, Turunen T and Rycroft M J 2007 Ground-based observations at $L \sim 6$ of multi-band structures in VLF hiss *Geophys. Res. Lett.* **34** L02112
- Titova E E, Kozelov B V, Demekhov A G, Manninen J, Santolík O, Kletzing C A and Reeves G 2015 Identification of the source of quasiperiodic VLF emissions using ground-based and Van Allen Probes satellite observations *Geophys. Res. Lett.* **42** 6137–45
- Trakhtengerts V Y 1963 On the mechanism of VLF radiation generation on the external radiation belt of the Earth *Geomagn. Aeron.* **3** 442–51
- Trakhtengerts V Y and Rycroft M J 2008 *Whistler and Alfvén Mode Cyclotron Masers in Space* (Cambridge: Cambridge University Press)
- Tsurutani B T, Falkowski B J, Verkhoglyadova O P, Pickett J S, Santolík O and Lakhina G S 2012 Dayside ELF electromagnetic wave survey: a polar statistical study of chorus and hiss *J. Geophys. Res.* **117** A00L12
- Volland H 1995 Longwave spheric propagation within the atmospheric waveguide *Handbook of Atmospheric Electrodynamics* ed H Volland vol 2 (Boca Raton, FL: CRC) pp 65–93
- Watanabe Y *et al* 1994 Cross-spectral coherence between geomagnetic disturbance and human cardiovascular variables at non-societal frequencies *Chronobiologia* **21** 265–72