JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 115, A02210, doi:10.1029/2009JA014636, 2010

An unusual VLF signature structure recorded by the DEMETER satellite

Csaba Ferencz,[1] János Lichtenberger,[1] Dániel Hamar,[1] Orsolya E. Ferencz,[1]
Péter Steinbach,[2] Balázs Székely,[1] Michel Parrot,[3] François Lefeuvre,[3]
Jean-Jacques Berthelier,[4] and Mark Clilverd[5]

Received 9 July 2009; revised 18 August 2009; accepted 9 September 2009; published 17 February 2010.

[1] A type of electromagnetic phenomenon has been found in the electric VLF data measured by the low Earth orbit DEMETER satellite, which was nonidentified earlier as a different class of electromagnetic VLF events. The phenomenon, termed as "swallow-tailed whistler" (STW) after its shape, seems to be similar to a whistler, but following the main trace, an additional trace appears with monotonously increasing frequency. The secondary trace, lasting less than 80 ms within the recorded 20 kHz bandwidth joins at a given Starting Furcation Frequency. In a 7 month long time interval three series of strong STWs were found in a geographically confined search zone. Further, 10 weak STW periods have been identified by a thorough review of a 2 month long recording. Several STWs were found by the investigation of randomly selected DEMETER burst VLF recording acquired globally. On the basis of comparisons with previous studies, we can exclude that this phenomenon is generated by plasma processes in the vicinity of the satellite though the formation mechanism of this (ionospheric) signal is so far unclear. It is possible that this event type appeared in earlier records too, however, without identification.

Citation: Ferencz, C., J. Lichtenberger, D. Hamar, O. E. Ferencz, P. Steinbach, B. Székely, M. Parrot, F. Lefeuvre, J.-J. Berthelier, and M. Clilverd (2010), An unusual VLF signature structure recorded by the DEMETER satellite, *J. Geophys. Res.*, *115*, A02210, doi:10.1029/2009JA014636.

1. Introduction

[2] The successful launch of the DEMETER satellite on 29 June 2004 from Baikonur (Kazakhstan) established an important opportunity to investigate the different ULF-VLF phenomena appearing in the Earth's plasma environment. After a successful calibration of the satellite instruments the regular operation started in September 2004. The inclination of the nearly circular orbit low Earth orbit is 98° Centre National d'Etudes Spatiales, Toulouse, France DEMETER data server (available at http://demeter.cnrs-orleans.fr). (Starting orbit altitude was ~710 km, and it was decreased to ~660 km in December 2005. During the investigated period the orbit altitude was ~710 km.) The main purpose of the satellite is to provide a solid database to investigate possible electromagnetic effects of the earthquakes in the ionosphere before the seismic shock. On board the satellite two wave experiments are relevant to our investigation: the Instrumental Champ Electrique electric field instrument operating in DC-HF bands from DC to 3.175 MHz [*Berthelier et al.*, 2006], and the IMSC magnetic field experiment operating in VLF band from a few Hz to 17.4 kHz [*Parrot et al.*, 2006]. These experiments have two basic modes of operation. In the survey mode only the power spectra are stored, while in burst mode the full signal waveforms (the recorded raw signals) and the power spectra are stored and transmitted to the tracking stations. Burst mode is employed above previously defined, seismically active regions of the Earth.

[3] According to the primary objective of the DEMETER experiment our aim has been to detect and to investigate anomalous signal patterns on VLF recordings applying high temporal resolution wave analysis. This paper reports an unusual whistler-like phenomenon observed clearly by DEMETER. Here we characterize the features of the waveforms, compare them against known VLF signals, and we investigate the possible occurrence of this type of events in earlier satellite data and in ground-based measurements.

2. Data and Methods

[4] In this study the burst mode VLF data were used. In the completed first phase of our investigation a 5 month long (September 2004 to January 2005) recording and the preoperational stage data (July–August 2004) have been

---

[1] Space Research Group, Eötvös University, Budapest, Hungary.
[2] MTA-ELTE Research Group for Geology, Geophysics and Space Sciences, Hungarian Academy of Sciences, Budapest, Hungary.
[3] LPCE, Université d'Orléans, CNRS, Orléans, France.
[4] CETP, Observatoire de Saint Maur, Saint Maur des Fossés, France.
[5] British Antarctic Survey, Cambridge, UK.

0148-0227/10/2009JA014636$09.00

surveyed systematically in a geographically confined region with latitudes = 30°–53°N and longitudes = 5°–33°E (L = 1.26–2.65). This search region was chosen with respect to continuous ground-based wideband VLF recordings collected in France and Hungary. Simultaneously to this review a selected 2 month long (December 2004 to January 2005) time interval has been checked thoroughly. During the systematic survey, each satellite pass crossing the region specified above was analyzed. The analyzed data cover 36 h long recordings in this 7 month period, we have found "swallow-tailed whistlers" (STWs) in several data sections, which are 6.5 min long altogether. Analysis of randomly selected additional, more than 10 h recording, acquired in burst mode globally elsewhere made this investigation more complete in latitudes (L-shells).

[5] For the analysis of the data a conventional fast Fourier transform dynamic spectrum with a window size of 12.8 ms and 50% overlap, reassigned spectrogram and matched filtering were used.

3. Observed Phenomenon

[6] During the analysis of the ICE and IMSC signals a strange shaped, whistler like phenomenon was found. This type of signals, termed here as "swallow-tailed whistler" (STW), have whistler character, exhibiting strong signal trace furcation on broadband spectra with a swallow-tailed shape (Figures 1 and 3). The signals have clear contours. The conventional spectrogram is not able to show every characteristic parts of the signal structure in details, thus two other modes of visualization were used throughout the paper: the reassigned spectrogram [*Auger and Flandrin*, 1995] and matched filtering [*Hamar and Tarcsai*, 1982]. The three different ways of visualization of the STW phenomena ensure that the observed characteristic pattern is real, because it appears on all the three plots.

[7] In the spectrogram, individual STWs appear as a whistler (hereafter referred to as main trace, e.g., trace "*m*" in Figure 1d) accompanied with a secondary monotonically changing frequency signal part (e.g., trace "s" in Figure 1d) joined at a given Starting Furcation Frequency (SFF). The secondary trace appears as sharp as the main trace in the spectrogram, also exhibits dispersion and can be traced for less than 80 ms within the recorded VLF bandwidth. The amplitudes of the secondary trace are typically similar or larger than those of the main trace. The secondary trace does not have a clear, whistler-like character as the main trace has, moreover, some fine structural elements, i.e., irregularities appear along the secondary trace (see e.g., the arrows in Figures 1d, 1e, and 1f). It is important to emphasize that the terms "main trace" and "secondary trace" used hereafter are nomenclature terms only for the features what we see in the spectrogram and at the moment it is not possible to determine if they correspond to a single or different modes of propagation.

[8] Analysis of several STWs, detected above Europe along the geographical latitudinal range 30.9°–51.3°N showed that the dispersion values (D_0) of their main traces varied between 22 $s^{1/2}$ and 32 $s^{1/2}$ measured at the L values of 1.8–2.1. (Geomagnetic coordinates are given in Tables 1 and 2.) These D_0 values differ from the dispersion values of the simultaneously appearing short-path fractional hop whistlers and one hope whistlers (Figure 1). For example, after the STW series in Figure 1b (orbit number 1547) in 16 October 2004, 2056:07.1 UT (at 721.1 km height, geographical latitude 46.17°N, longitude 10.76°E, L = 2.1) or at the beginning of the STW series recorded on the orbit number 2187 in 29 November 2004, 2108:21 UT (at 720 km height, geographical latitude 45.2°N, longitude 8.1°E, L = 2.07) simultaneous appeared (Figure 2) short-path fractional hop whistlers ($D_0 \approx 1.92$ $s^{1/2}$), STWs ($D_0 \approx 25.4$ $s^{1/2}$) and most probably one hop whistlers ($D_0 \geq 60.0$ $s^{1/2}$). The magnetic latitude corresponding to the satellite position (L = 2.1 or 2.07) and the low and medium magnetic activity before the data acquisitions containing STWs (filled plasmasphere) yield one-hop whistlers with $D_0 = 50\sim80$ $s^{1/2}$, thus the main trace of the STWs could not be one-hop traces. However, oblique propagation of a fractional hop whistler may lead to such a dispersion [*Ferencz et al.*, 2001].

[9] So far we have found characteristic and unambiguous STW series in three different periods of the analyzed 7 month data set recorded above the previously described selected region (Figure 4 and Table 1). Thus, clear STW periods are rather rare. However, it was possible to detect ten groups of less intense, fragmental STWs with more detailed analysis in a 2 month recording, in December 2004 and January 2005 (see their summary in Table 2).

[10] Although before and after the periods of STW occurrences many conventional whistlers appear, during the STW occurrences all whistlers, having similar D_0 dispersion as the STW's main trace are found to be swallow tailed. Note that short-path, fractional-hop whistlers ($D_0 < 5$ $s^{1/2}$, reached the satellite almost vertically), merged with faint, uncertain occurrence of STWs were seen without exhibiting STW character (see e.g., in Figures 1b and 3). Very few whistlers with much larger dispersions than the dispersion of the main traces of the actual STWs, most probably one hop signals, were also seen without any STW character (Figure 2). Based on the limited number of observed STWs it can be said that the STW pattern appears gradually in its intensity at the beginning of an STW series and disappears in the electromagnetic background, finishing a sequence. The appearance rate of individual STWs is like the typical appearance rate of whistlers otherwise. Within one STW period the distinct signals exhibit similar shapes, with some remarkable alterations.

[11] 1. The SFF decreases monotonously with recording time (and because the satellite moved Northward, it decreases with increasing L-value, Table 1), with a rate of 0.18–0.25 kHz/s along the orbits shown in Figure 4, the single frequency (SFF) at which the two traces deviate varied between about 17.5 kHz and 4 kHz in the detected examples, see more in Figures 1, 2, 3, and 5; Table 2; and in section 4. For example the SFF of the STWs appeared in the orbit 1547 (up) seen in Figure 4, decreased monotonously from 17.5 kHz to 4.5 kHz. Note that a confirmed general behavior of SFF values according to geomagnetic coordinates, L value, local time, geomagnetic activity and satellite orbit direction cannot be drawn based on the analyzed data set.

[12] 2. In some cases the secondary trace in the spectrogram appears as to be rotated to the left around the SFF with the simultaneous decrease of SFF, i.e., the dispersion of the secondary trace increases together with the dispersion of the main trace (see Figure 5).

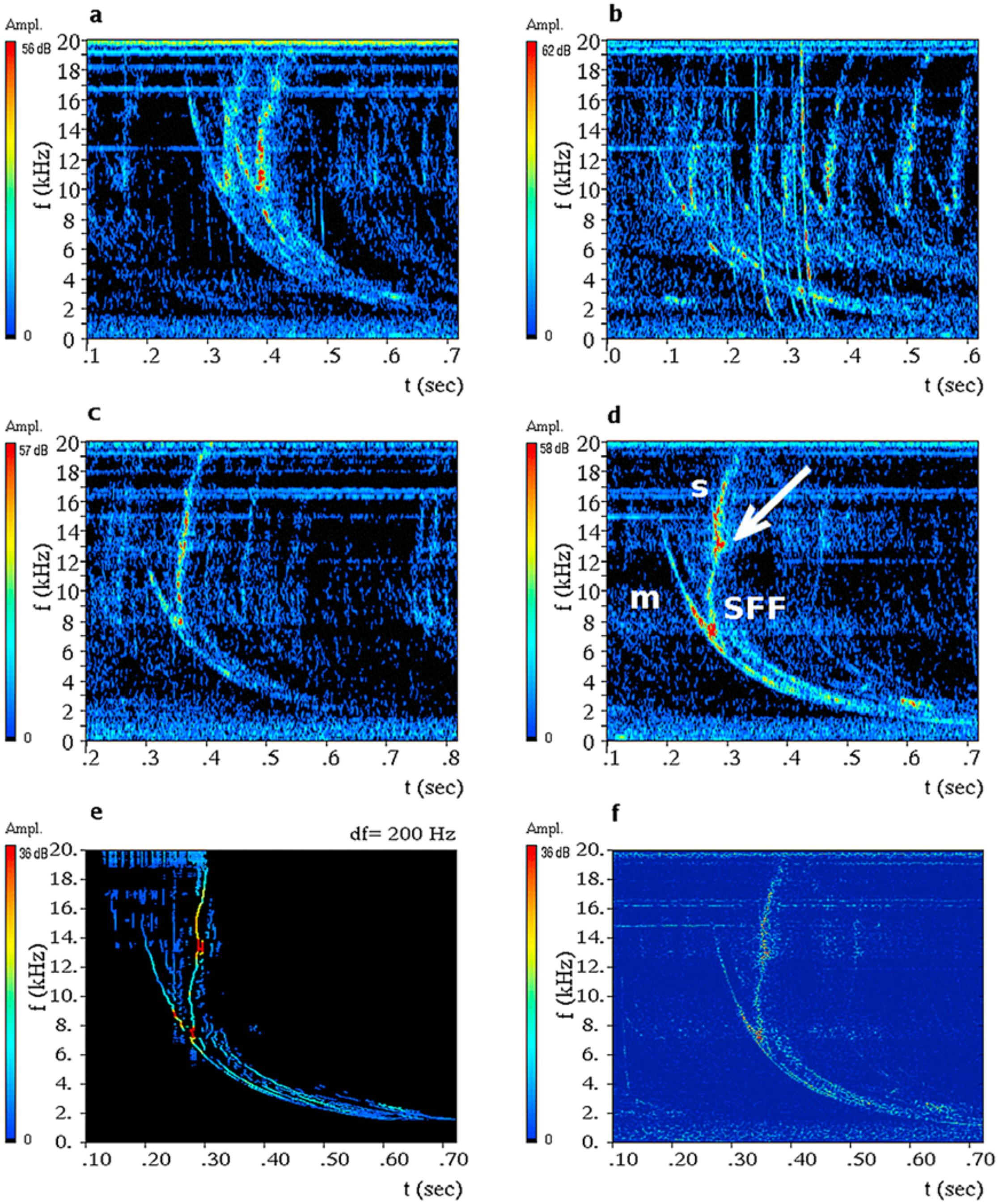

Figure 1. STW occurrences, i.e., the fast Fourier transform patterns of the recorded signals in a series on DEMETER VLF electric field burst recording (sensor E34, orbit 1547 ascending) on 16 October 2004. Note the different time scales of the individual panels. Time epochs and recording lengths (in parentheses) are (a) 2055:09.0 UT (0.8 s), (b) 2055:14.5 UT (0.8 s), (c) 2055:16.0 UT (1.5 s), and (d) 2055:19.7 UT (1.5 s). Also shown are the result of (e) matched filtering (i.e., curves of maximums) and (f) the reassigned spectrogram of Figure 1d.

[13] The few representative examples of STW occurrences presented above were all derived from the electric ICE burst VLF data of DEMETER experiment. Magnetic VLF recordings, because of the lower sensibility of the IMSC instrument (see the amplitudes comparing to noise background in Figure 6), did not show in most cases the effect itself, like in the case of the whistlers, or other typical VLF signatures with comparable intensity which appeared on ICE recordings in the analyzed time periods. Note that in case of very strong signals both ICE and IMSC sensors may detect the same STW, with different sensitivity and S/N ratio (see example in Figure 6), thus they are electromagnetic events.

Table 1. Geographic and Geomagnetic Satellite Coordinates and Recording Time Intervals of the Three Identified Periods of Strong Swallow-Tailed Whistlers with the Corresponding Orbit Numbers of the DEMETER Satellite

Orbit Number	Start of the STW Sequence, Date and Time	Beginning Geographic and Geomagnetic Coordinates	End of the STW Sequence, Date and Time	Ending Geographic and Geomagnetic Coordinates	SFF Values From Start to End (kHz)
1547 up	16 Oct 2004, 2054:43 UT	41.2°N;12.5°E and 42.0°N;93.3°E, L = 1.81	16 Oct 2004, 2056:09 UT	46.3°N;10.7°E and 46.7°N;93.3°N, L = 2.11	14.4–5.4
2172 up	28 Nov 2004, 2022:23 UT	42.6°N;20.3°E and 41.4°N;101.2°E, L = 1.84	28 Nov 2004, 2023:16 UT	45.7°N;19.2°E and 44.6;101.2, L = 2.02	17.3–7.4
2187 up	29 Nov 2004, 2108:21 UT	45.2°N;8.1°E and 46.1°N; 90.3°E, L = 2.07	29 Nov 2004, 2108:28 UT	45.6°N;7.9°E and 46.6°N;90.3°E, L = 2.09	9.8–7.2

[14] Although, because of the limited temporal and spatial coverage of the investigated "burst" recordings, we do not have reliable STW occurrence statistics yet, it is already obvious that STW events appear in local daytime and nighttime as well, see details in Tables 1 and 2.

4. Discussion

[15] A possible explanation of these strange signals could be related to the artificial effects of the satellite itself: onboard electric instruments might cause unwanted or intentional emissions, e.g., in active experiments like the intense HF Langmuir probe on DEMETER satellite (data user guide by D. Lagoutte et al., http://demeter.cnrs-orleans.fr/dmt/doc/dmt_data_user_guide_10.zip). In the modified plasma environment of the satellite a weak VLF signal might also trigger emissions. However, it is unlikely that STWs are of this origin. The Langmuir impulses with 1 s periodicity are always present, while in the infrequent occurrence of the STW sequences no periodicity can be recognized. Wideband noise, present on VLF recordings as seen in Figures 1 and 3, is almost unchanged during STW periods, dissimilar to the SFF values. Furthermore STWs appeared solely associated with whistlers suggesting that the origin of STWs is neither in the satellite's surroundings nor in a satellite–plasma medium interaction. (Note that correlation with seismic activity at both geomagnetic conjugate areas has been checked, without positive result.)

[16] Apparently branching, complex fast Fourier transform pattern of signals have been published since the late 1960s. These phenomena have been classified into several categories. Of those a few phenomena are comparable to STWs, but the identified phenomena all have remarkable, fundamental differences to the STW signals as discussed briefly below.

4.1. Whistler-triggered Emissions (Hooks)

[17] One class of whistler-triggered emissions has increasing frequency versus time signal. However, these emissions typically start above the respective whistler nose while the SFFs are far below the corresponding main trace nose. STWs do not exhibit that periodic and strongly dispersive behavior that these emissions (hooks) do [see *Helliwell*, 1965, Figure 7–8 and Figure 7–48, p. 259; *Nunn and Smith*, 1996; *Rycroft*, 1991]. However, Figure 5 shows that the main trace exhibits no special feature, but the secondary trace goes backward in time above the SFF, that is higher frequencies appear before SFF in time. Thus the secondary trace obviously cannot be triggered emission trace likewise the whole phenomenon.

4.2. Phenomena Similar to STW

[18] There are two well known phenomena exhibiting similar time-frequency pattern to STW at the first glance: the walking trace (WT) and the magnetospherically reflected (MR) whistlers and the subclass of the latter one, the nu (ν) whistlers. The pattern of WT whistlers are very similar to letter "X" (apart from the fractional hop leader), the nu whistlers look like letter "V" (or "ν"); STWs look like letter "Y." We do not know the origin of STWs yet, but we will

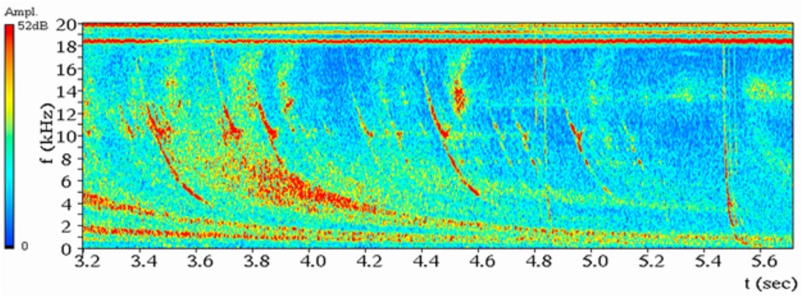

Figure 2. An example of common appearance of short-path fractional hop whistlers, STWs and most probably one hop whistlers at the beginning of an STW series on 29 November 2004 at 2108:21 UT on orbit 2187 up.

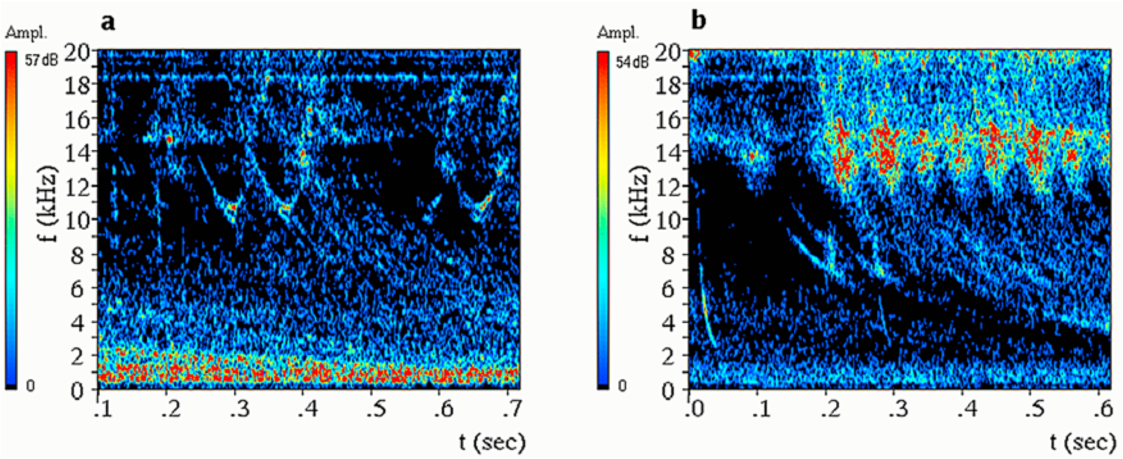

Figure 3. Two 1.5 s long sections of a long STW series from 2022:23 to 2023:16 UT on 28 November 2004, recorded in the DEMETER VLF electric experiment (sensor E12, orbit 2172 ascending). Starting times are (a) 2022:47.3 and (b) 2023:14.3 UT.

show that, similarly to the alphabet, where X, Y and V are different letters, WT, MR (and ν) and solar time whistlers are different phenomena, showing different observed STW features never be generated by the physical mechanisms behind WT or MR (ν) whistlers.

4.2.1. "Walking-Trace (WT) Whistlers"

[19] This type of whistler was identified by *Walter and Angerami* [1969] in data measured by the OGO 2 and 4 satellites. This phenomenon contains three parts, in which the first one (appearing as rising tone) is the WT whistler itself. The three parts propagate on different paths independently from each other. In contrast this is not true for STWs, they always form an "Y"-like pattern and the main and secondary traces of an STW form one complete signal structure. They propagate together, exhibit common propagation character, e.g., their dispersion increase together in the same manner with increasing latitude.

4.2.2. Magnetospherically Reflected (MR) Whistlers

[20] Signals interpreted as magnetospherically reflected (MR) whistlers first observed onboard the OGO 1 satellite [*Smith and Angerami*, 1968] and more recently aboard Magion 4 and 5 [*Shklyar and Jiøíèek*, 2000] may exhibit V-shaped feature as crossing whistlers traces in a compound echo train (e.g., see ray tracing simulation calculations from *Bortnik et al.* [2003]). In the characteristic furcation pattern of STW one single main trace is always associated with one single secondary trace, dissimilar to reflected group of whistler signal trains.

4.2.3. Nu (ν) Whistlers

[21] Nu (ν) whistlers are a subclass of MR whistlers and they are characterized by clear v-shaped traces on spectrograms [*Smith and Angerami*, 1968; *Shklyar et al.*, 2004]. According to its interpretation based on detailed, strictly monochromatic ray tracing modeling the complete signal pattern forms the Greek letter ν. "The energy at frequencies below the 'joining' frequency is not observed, presumably because it is reflected above the position of the satellite. Energy at frequencies above the joining frequency is reflected below the point of the observation, and hence two traces are seen. Since the reflection is only possible at frequencies below the lower hybrid resonance, it is concluded that the lower hybrid resonance (LHR) frequency at the satellite is somewhat greater than the frequency at which the two traces join" [*Smith and Angerami*, 1968, p. 7]. The part of the signal with frequencies lower than the LHR frequency at the reflecting region is reflected [*Kimura*, 1966] and thus observed later. The minimum frequency of a nu whistler, at which the traces join, corresponds to the LHR frequency in the vicinity of the observing satellite. Frequencies above this point are reflected at a region with higher LHR frequency. It is clear from the formation mechanism that the second trace of a nu whistler is the reflected "picture" of the first one. Another consequence of the cited generation mechanism is that the propagation direction of the two traces of a nu whistler is different, nearly opposite in space.

[22] A comparison of the STWs and nu whistlers yields important differences.

[23] 1. From the definition and model computations of nu whistlers follows that below the "joining frequency" no

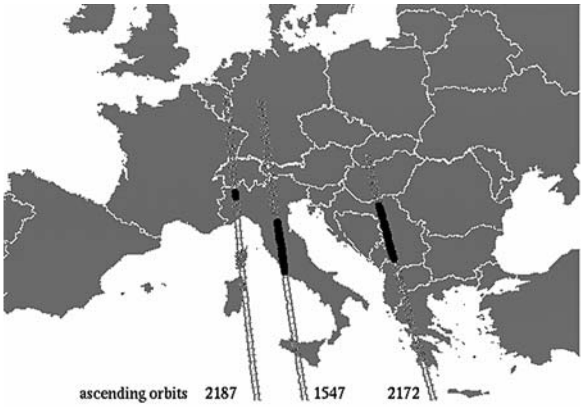

Figure 4. Three burst mode DEMETER satellite trajectories (double lined tracks), exhibiting clear STW pattern series in ICE VLF burst wave data (heavy line sections of tracks). For geographical positions and time intervals, see Table 1.

Table 2. Recording Details of Detected Weak, Fractional Short Period STW Events in a 2 Month Period of DEMETER VLF Data[a]

Orbit	Date and Time	Geographic and Geomagnetic Coordinates	SFF Values (kHz)
2288 up	6 Dec 2004, 1944:43 UT	30.7°N;32.5°E and 27.6°N;109.7°E, L = 1.32	3.6
2355 down	11 Dec 2004, 0906:12 UT	51.3°N;27.5°E and 48.6N;111.1E, L = 2.41	4.4
2399 down	14 Dec 2004, 0947:31 UT	34.4°N;12.4°E and 34.8°N;91.2°E, L = 1.45	4.3
2579 up	26 Dec 2004, 2002:21 UT	47.2°N;24.0°E and 45.2°N;106.3°E, L = 2.09	12.6
2797 up	10 Jan 2005, 1946:39 UT	45.2°N;28.5°E and 42.6°N;109.8°E, L = 1.94	5.9
2798 up	10 Jan 2005, 2125:52 UT	46.0°N;3.5°E and 47.7°N;86.1°E, L = 2.14	7.8
2806 down	11 Jan 2005, 0923:04 UT	44.8°N;21.1°E and 43.4°N;102.8°E, L = 1.96	8.2
2827 up	12 Jan 2005, 2113:11 UT	31.4°N;10.2°E and 32.3°N;88.3°E, L = 1.36	5.7
2929 up	19 Jan 2005, 2132:42 UT	32.2°N;5.2°E and 34.0°N;83.3°E, L = 1.41	5.1
3030 up	26 Jan 2005, 2013:16 UT	33.4°N;24.8°E and 31.7°N;103.0°E, L = 1.4	9.7

[a] The fractional short period is defined as <3–5 s. The 2 month period is from December 2004 to January 2005.

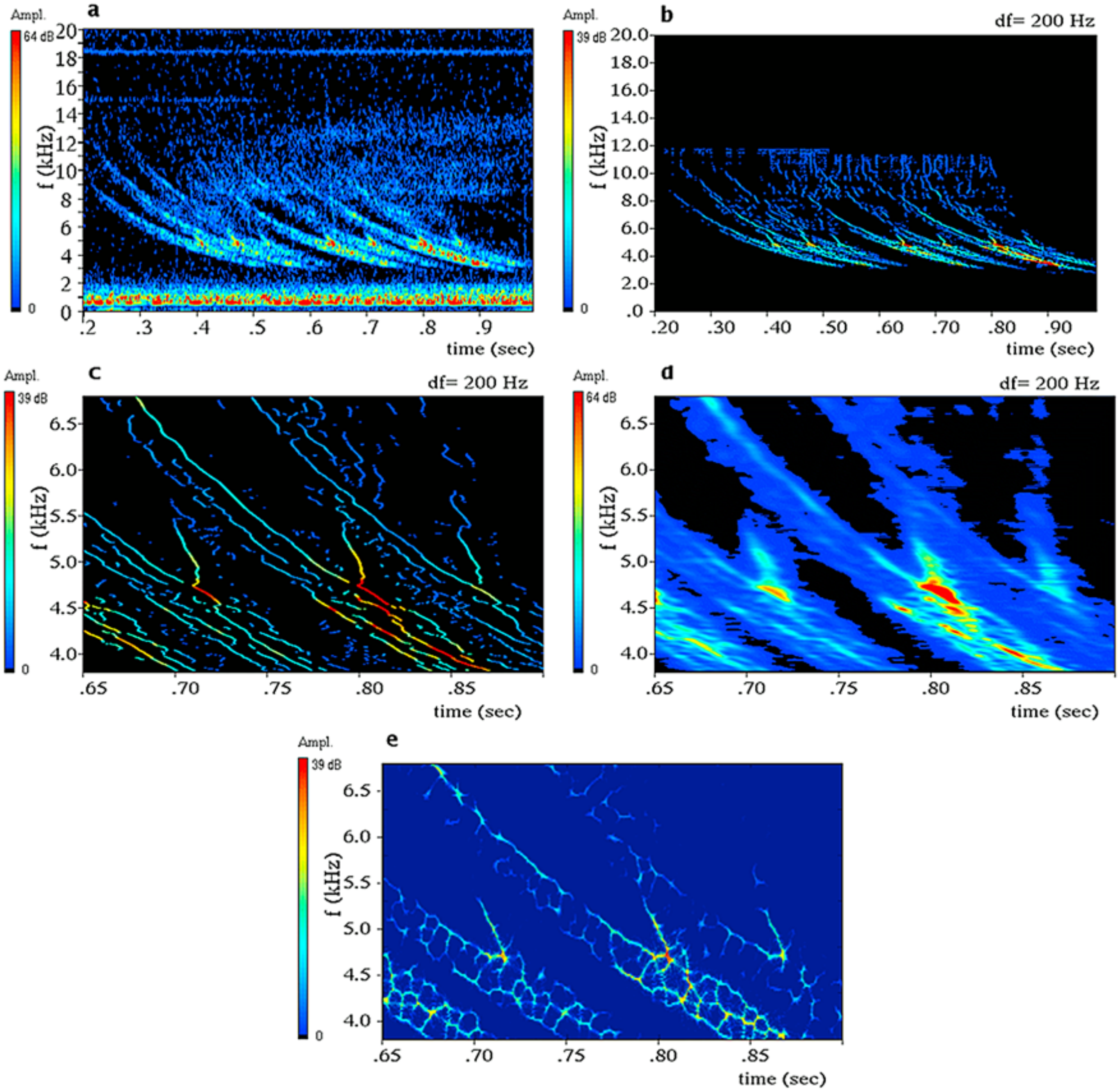

Figure 5. A group of fractional STWs in DEMETER ICE recording on 11 December 2004, after 0906:12.52 UT (orbit 2355 down, sensors E12, satellite position: 51.3°N; 27.5°E), using (a) fast Fourier transform and (b) matched filtering. Result of matched filtering: (c) signal maximums, (d) detailed signal distribution, and (e) reassigned spectrogram of an enlarged section of the STWs around the SFF presented in Figures 5a and 5b.

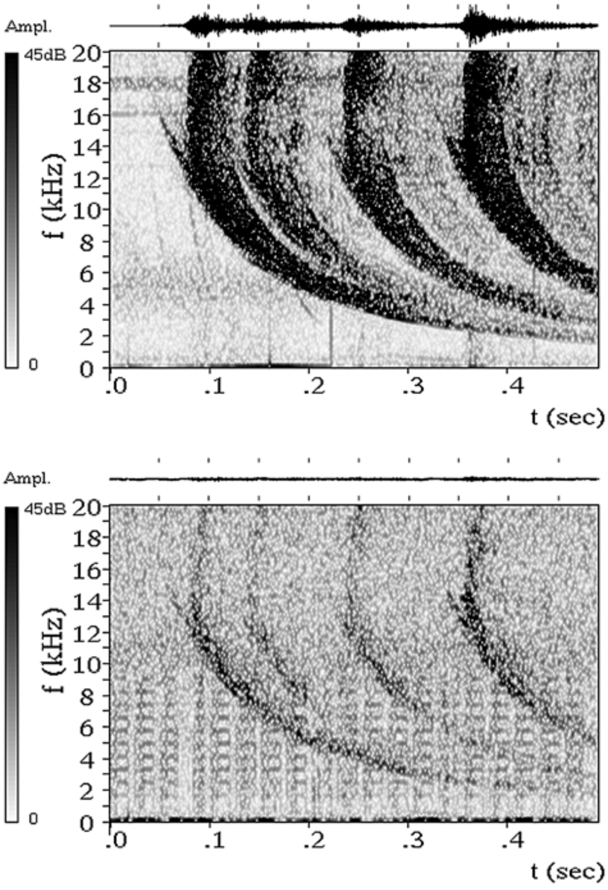

Figure 6. (top) Corresponding STW sequence in short sections of DEMETER VLF electric ICE and (bottom) magnetic IMSC recordings (0338:53 UT, 9 October 2004). Main features of the STWs can be recognized in both spectra. (Recorded in orbit 1435 0338:53 UT, 9 October 2004, geographic latitude −49.2°, longitude 288.4°, geomagnetic latitude −38.9°, longitude 0.13°, L = 1.66, height of the orbit 715.6 km.)

signal can be recorded, while the STWs always have a "leg," i.e., the "main trace" appears as a regular whistler-like component below the SFF. In connection with this statement one can suppose that the STW is a composition of a regular "ducted" whistler and of a nu whistler, formed by the above specified mechanism in a nonducted propagation. Main and secondary traces of STWs always exhibit a strict, common appearance and signal structure on spectra, without the separation of these signal parts (see e.g., Figures 7 or 1 and 3).

[24] Additionally, their dispersion also changes alike. Furthermore, there is a certain, roughly 1 s long gap between the nu whistler and the accompanied, but not necessarily observed whistler, in accordance with their different propagation paths between source and reflecting regions. In contrast, there is no significant time delay between the main trace and the increasing frequency secondary trace of an STW. Note that there may be a short time lag (<30 ms) and a compound signal fine structure around the SFF (see e.g., Figures 1a and 7). The above arguments suggest that the parts of a complete STW pattern propagate together; therefore, it cannot be interpreted as a combination of a ducted and a nu whistler.

[25] 2. By the investigation of the "traces" of the STW one can conclude that their accurate character, fine structure, curvilinear shape on spectra significantly differ, showing that the "secondary trace" is not simply a reflection of the "main trace," (see e.g., in Figure 1d or 1e). The secondary trace of some STWs exhibits "knots" or bending that are not observable on the main trace.

[26] 3. Comparing the dispersion values of the "main trace" of the STWs and of the short path fractional hop whistlers (see e.g., in Figure 1b and section 3) it is obvious that the observed STWs had much longer propagation path, i.e., they were not upgoing directly from the lower atmospheric region below the satellite. Also, MR-type reflection cannot occur in this region. The other possibility is the reflection caused by a density gradient can also be excluded, because this reflection produces a significantly different signal pattern [see *Ferencz*, 2005, Figure 2].

[27] The appearance and structure of STWs suggest that they form a single, complex signal propagating in a unit at the time of recordings opposite to the WT and Nu that parts of those propagate in different (opposite) directions. Unfortunately, the lack of enough measured wave components in VLF band on DEMETER prevents us to compute the wave normals of main and secondary traces for WTs, nu-s and STWs. If our description is correct we should obtain different wave normals for WT or ν main and secondary traces, while the same for STW traces.

[28] Consequently the formation of the observed STWs cannot be explained based on the current picture of either triggered emissions, or the medium, or the formation mechanisms of WT whistlers, MR whistlers or nu whistlers, or by reflections caused by density gradients of the ionosphere.

4.3. Possible Early but Nonidentified STW Detections on Board of Satellites

[29] We can not exclude that on board of OGO 4 STWs were recorded [see *Walter and Angerami*, 1969; Figure 10b] and was identified by *Walter and Angerami* [1969] as WTs with "irregular rising tones." However, to say any more about this old record it would be necessary to make

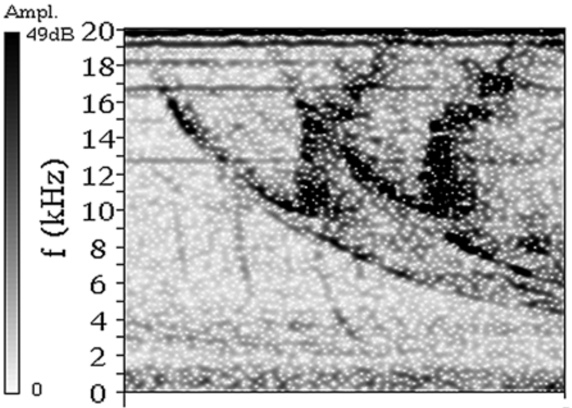

Figure 7. In time stretched subimage of the spectrum given in Figure 1a, showing the detailed signal structrure of the STW around its SFF.

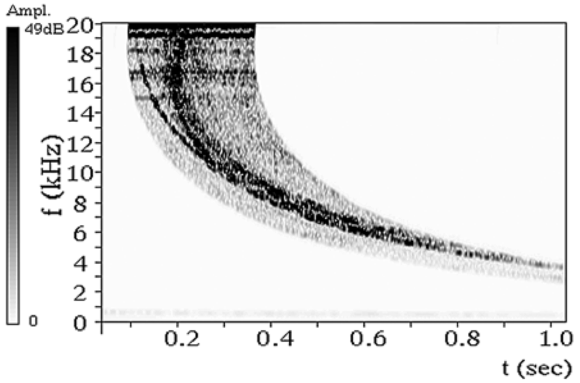

Figure 8. Result of a real modeled one-hop whistler (the fast Fourier transform pattern) on a 1 s long spectogram, excited by a 280 ms long UWB waveform of a measured STW in the Figure 1 STW group and computed by using a real full wave, UWB propagation model.

a detailed analysis of these signals, which is not possible today.

[30] Another possible early STW record [*Smith and Angerami*, 1968] is one of the published MR spectrograms exhibiting similar patterns to MR whistlers, however, assigned as "unusual" whistlers having "some peculiar extra structure" (see OGO 1 data) [see *Smith and Angerami*, 1968, Figure 7]. Two double-whistlers can be seen in Figure 7 (around 1 and after 2 s, marked as MR− and MR+ components), where both the first and second traces have STW-like patterns. Without a detailed investigation *Smith and Angerami* characterized this recording as "unusual whistlers," supposing that this pattern is a result of an MR process. Remarkable that *Smith and Angerami* [1968] did not note the possibility that this observation could be explained as nu whistler, excited by "unusual" primary signal. We rather consider the exciting (primary) signals were STWs in this case.

[31] To assist the understanding of the possible changing of an STW pattern during a longer propagation in the magnetosphere we made model computations using the full-wave ultra wideband (UWB) propagation model working perfectly in the ionospheric, magnetospheric investigations [*Ferencz et al.*, 2001, 2007]. In this model computations we did not take into account any reflection mechanism, only longitudinal propagation and we used as excitation (source) signal an STW signal recorded by the DEMETER (see Figure 1). Using this excitation the spectrogram of the computed signal after a single hop propagation through the magnetosphere is presented in Figure 8. This computed signal form has remarkable similarities with the signal patterns from *Smith and Angerami* [1968, Figure 7], and therefore, we cannot exclude that the signals from *Smith and Angerami* [1968, Figure 7] mentioned above are STWs after a longer propagation through the magnetosphere.

4.4. Possible Ground-based STW Detection

[32] Simultaneously to the DEMETER operation ground-based VLF recordings were conducted in France and in Hungary as well. Signals, exhibiting the STW feature were not observable on one-hop whistlers recorded simultaneous with the DEMETER recordings on the ground at these sites, selected by automatic whistler detection procedure [*Lichtenberger et al.*, 2007, 2008], running on continuous ground VLF data. However, archived high-latitude VLF ground data acquired at the British Antarctic Survey Halley-Station, Antarctica (L = 4.5) in July 1995 yielded an example of a whistler with a STW-like pattern, illustrated in Figure 9. Beside the comparable general shape of the STWs and the illustrated ground recording on fast Fourier transform spectra it is convincing that the detailed signal pattern of the STWs around their SFF (e.g., Figure 7) and the furcating region exhibit remarkable similarity. The existence of a probable STW recorded on the ground is a contraindication of any reflecting generation mechanism of this phenomenon and thus support the idea of a single, complex signal with one or more copropagating modes. The enlarged spectrogram of the signals (Figure 10) recorded in Halley shows that this is a furcating signal and not two ones crossing each other.

[33] The above-described STW effect of the VLF signals propagating in the plasmasphere has not identified and reported previously. The STW phenomenon recorded by the DEMETER VLF wave experiment is a new type of signal, though the formation mechanism of STWs is not yet known. As it was presented above the major features of STWs cannot be explained neither by WT nor by MR (nu) whistler formation mechanism nor by reflection from ionospheric density gradients. If (one or more) ground-based STW-type recording exists, than this fact excludes any mechanism responsible in WT and MR (nu) formation in the case of STWs.

[34] Using the data of the DEMETER, the COMPASS-2 and other satellites it is necessary to investigate the occurrences of STWs in the future, in order to describe their distribution in space (geographically) and in time (e.g., seasonal dependence). Analysis of the possible mechanisms forming the STW signal, as well as including nonlinear processes in the exact UWB solutions of the Maxwell's equations is also needed. The relation of this phenomenon to the state of the magnetoionic medium traversed by the VLF wave, such as the possible sources of these signals,

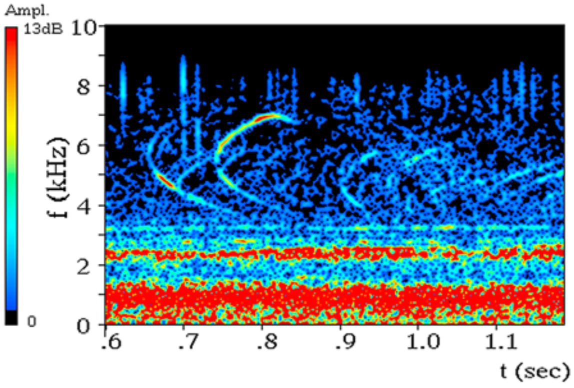

Figure 9. Ground-based, high-latitude whistlers, recorded at Halley-Bay, Antarctica (5 July 1995, 0500:57 UT) exhibit STW pattern in the dynamic spectrum.

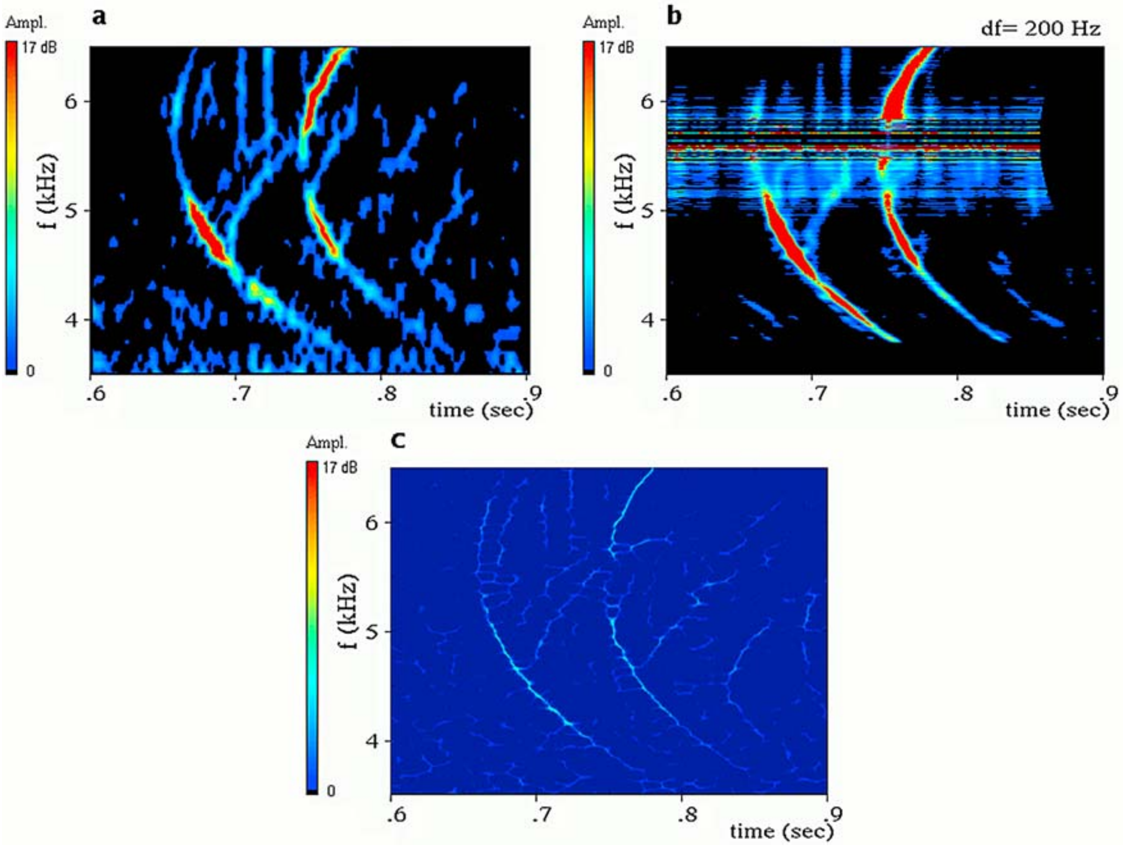

Figure 10. The enlarged section of the furcating region of the first STW-like signal in Figure 9 has remarkable similarities with the STWs received on board of DEMETER. (a) Fast Fourier transform, (b) matched filtering, and (c) reassigned spectrogram.

e.g., relations to the space weather phenomena, need also to be examined.

5. Conclusions

[35] The following conclusions can be drawn from this study. (1) A new VLF signal type has been identified in the wideband VLF recordings of the LEO DEMETER satellite termed as swallow-tailed whistlers (STW). (2) STWs appear in series lasting several tens of seconds. (3) In a several month long recording a dozen of strong and weaker STW series were found. (4) The characteristic feature of the STW is the branching into two traces: the main trace corresponds to a longer, probably oblique propagation path, possible fractional-hop whistler, the joining secondary trace appears only above a certain frequency, termed Starting Furcation Frequency. In this study SFFs were found in the range of 3.6–17.3 kHz. The secondary trace appears as sharp as the main trace and it is curvilinear, too. However, the fine structure of the main and secondary trace differ. (5) Within the observed STW series the SFF found monotonously to decrease with a rate of several tens of Hz/km along the circular orbit, the furcation pattern may change with the decreasing SFF, too. (6) If the dispersion of the main trace increases, the dispersion of the secondary trace increases, too. (7) The comparison with other, previously published signals having comparable fast Fourier transform features yielded that it is unlikely that STWs are generated in the nearby plasma environment of the satellite. (8) STWs were probably found in ground-based measurements and it is possible that STWs were detected, however not identified in earlier satellite experiments, too. (9) From theoretical point of view it is of importance to find a specific sort of signal-medium interaction which results in an STW if applied in the analytical UWB solutions of the Maxwell's equations [*Ferencz et al.*, 2001].

[36] **Acknowledgments.** Authors are grateful to the Guest Investigator program issued by CNES for the DEMETER mission for supplying the raw data. The projects TP 276 of the Hungarian Space Office and OTKA T037611 and F037603 of the Hungarian National Scientific Fund are acknowledged. B. Székely contributed as Békésy György postdoctoral fellow.

[37] Zuyin Pu thanks the reviewers for their assistance in evaluating this paper.

References

Auger, F., and P. Flandrin (1995), Improving the readability of time-frequency and time-scale representations by reassignment method, *IEEE Trans. Signal Process.*, *43*(5), 1068–1083, doi:10.1109/78.382394.

Berthelier, J. J., et al. (2006), ICE, the electric field experiment on DEMETER, *Planet. Space Sci.*, *54*(5), 456–471, doi:10.1016/j.pss.2005.10.016.

Bortnik, J., U. S. Inan, and T. F. Bell (2003), Frequency-time spectra of magnetospherically reflecting whistlers in the plasmasphere, *J. Geophys. Res.*, *108*(A1), 1030, doi:10.1029/2002JA009387.

Ferencz, C., O. E. Ferencz, D. Hamar, and J. Lichtenberger (2001), *Whistler Phenomena: Short Impulse Propagation*, *Astrophys. and Space Sci. Libr.*, vol. 262, 260 pp.,Kluwer Acad., Dordrecht, Neth.

Ferencz, O. E. (2005), Full-wave solution of short impulses in inhomogeneous plasma, *Pramana*, *64*, 249–268, doi:10.1007/BF02704879.

Ferencz, O. E., C. Ferencz, P. Steinbach, J. Lichtenberger, D. Hamar, M. Parrot, F. Lefeuvre, and J.-J. Berthelier (2007), The effect of subionospheric propagation on whistlers recorded by the DEMETER satellite—Observation and modeling, *Ann. Geophys.*, *25*, 1103–1112.

Hamar, D., and G. Tarcsai (1982), High resolution frequency-time analysis of whistlers using digital matched filtering, Part I: Theory and simulation studies, *Ann. Geophys.*, *38*, 119–128.

Helliwell, R. A. (1965), *Whistlers and Related Ionospheric Phenomena*, 349 pp.,Stanford Univ. Press, Stanford, Calif.

Kimura, I. (1966), Effects of ions on whistler-mode ray tracing, *Radio Sci.*, *3*, 269–283.

Lichtenberger, J., C. Ferencz, L. Bodnár, A. Hughes, A. Collier, C. Rodger, and M. Clilverd (2007), Automatic whistler detector and analyzer system network: A new tool for real-time monitoring of plasmasphere, paper presented at International Union of Geodesy and Geophysics General Assembly, Perugia, Italy.

Lichtenberger, J., C. Ferencz, L. Bodnár, D. Hamar, and P. Steinbach (2008), Automatic whistler detector and analyzer system: Automatic whistler detector, *J. Geophys. Res.*, *113*, A12201, doi:10.1029/2008JA013467.

Nunn, D., and A. J. Smith (1996), Numerical simulation of whistler-triggered VLF emissions observed in Antarctica, *J. Geophys. Res.*, *101* (A3), 5261–5277, doi:10.1029/95JA03143.

Parrot, M., et al. (2006), The magnetic field experiment IMSC and its data processing onboard DEMETER: Scientific objectives, description and first results, *Planet. Space Sci.*, *54*(5), 441–455, doi:10.1016/j.pss.2005.10.015.

Rycroft, M. J. (1991), Interactions between whistler-mode waves and energetic electrons in the coupled system formed by the magnetosphere, ionosphere and atmosphere, *J. Atmos. Terr. Phys.*, *53*(9), 849–858, doi:10.1016/0021-9169(91)90098-R.

Shklyar, D. R., and F. Jiøíèek (2000), Simulation of nonducted whistler spectrograms observed aboard the MAGION 4 and 5 satellites, *J. Atmos. Sol. Terr. Phys.*, *62*, 347–370, doi:10.1016/S1364-6826(99)00097-8.

Shklyar, D. R., J. Chum, and F. Jiøíèek (2004), Characteristic properties of Nu whistlers as inferred from observations and numerical modelling, *Ann. Geophys.*, *22*, 3589–3606.

Smith, R. L., and J. J. Angerami (1968), Magnetospheric properties deduced from OGO 1 observations of ducted and nonducted whistlers, *J. Geophys. Res.*, *73*(1), 1–20, doi:10.1029/JA073i001p00001.

Walter, F., and J. J. Angerami (1969), Nonducted mode of VLF propagation between conjugate hemispheres; Observations on OGO's 2 and 4 of the "walking-trace" whistlers and of doppler shifts in fixed frequency transmissions, *J. Geophys. Res.*, *74*, 6352–6370, doi:10.1029/JA074i026p06352.

J.-J. Berthelier, CETP, Observatoire de Saint Maur, 4 ave. de Neptune, F-94100 Saint Maur des Fossés, France.

M. Clilverd, British Antarctic Survey, High Cross, Madingley Road, Cambridge CB3 0ET, UK.

C. Ferencz, O. E. Ferencz, D. Hamar, J. Lichtenberger, and B. Székely, Space Research Group, Eötvös University, Pázmány P.S. 1/A, H-1117 Budapest, Hungary. (spacerg@sas.elte.hu)

F. Lefeuvre and M. Parrot, LPCE, Université d'Orléans, CNRS, 3A, Ave. de la Recherche Scientifique, F-45071 Orléans, France.

P. Steinbach, MTA-ELTE Research Group for Geology, Geophysics and Space Sciences, Hungarian Academy of Sciences, Pázmány P.S. 1/A, H-1117 Budapest, Hungary.