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► **To cite this version:**

Michel Parrot. DEMETER observations of manmade waves that propagate in the ionosphere. Comptes Rendus. Physique, 2018, 19 (1-2), pp.26-35. <10.1016/j.crhy.2018.02.001>. <insu-01778900>

HAL Id: insu-01778900

<https://insu.hal.science/insu-01778900v1>

Submitted on 26 Apr 2018

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Comptes Rendus Physique

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Radio science for Humanity / Radiosciences au service de l'humanité

DEMETER observations of manmade waves that propagate in the ionosphere



Observations par Demeter d'ondes d'origine humaine se propageant dans l'ionosphère

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ARTICLE INFO

Article history:

Available online 6 February 2018

Keywords:

Ionosphere
Manmade waves
Propagation

Mots-clés :

Ionosphère
Ondes d'origine humaine
Propagation

ABSTRACT

This paper is a review of manmade waves observed by the ionospheric satellite DEMETER. It concerns waves emitted by the ground-based VLF and ELF transmitters, by broadcasting stations, by the power line harmonic radiation, by industrial noise, and by active experiments. Examples are shown including, for the first time, the record of a wave coming from an ELF transmitter. These waves propagate upwards in the magnetosphere and they can be observed in the magnetically conjugated region of emission. Depending on their frequencies, they perturb the ionosphere and the particles in the radiation belts, and additional emissions are triggered.

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RÉSUMÉ

Cet article constitue une revue des ondes d'origine humaine observées par le satellite ionosphérique Demeter. Cela concerne les ondes émises par les émetteurs TBF et EBF, par les stations de radio, par le rayonnement des lignes électriques et par les expériences actives. Des exemples sont présentés dont, pour la première fois, l'enregistrement d'une onde émise par un émetteur EBF. Ces ondes se propagent vers la magnétosphère, et elles peuvent être observées au point conjugué magnétique de leur région d'émission. Selon leurs fréquences, elles perturbent l'ionosphère et les particules dans les ceintures de radiation, et de nouvelles émissions sont déclenchées.

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<https://doi.org/10.1016/j.crhy.2018.02.001>

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1. Introduction

DEMETER was an ionospheric micro-satellite in operation between June 2004 and December 2010. Its orbit was circular (660 km), polar, and nearly sun-synchronous (10.30 LT and 22.30 LT). Its payload measured electromagnetic waves in different frequency ranges from ULF to MF, and also plasma parameters (for example the electron and ion density). The description of the experiments can be found in [1]. The VLF electric and magnetic spectrograms were always onboard calculated with a low time (2 s) and frequency (19 Hz) resolution all around the Earth, except in the auroral zone (invariant latitude $>65^\circ$). The MF electric field spectrogram (up to 3 MHz) is also continuously recorded. From time to time, the magnetic and electric field experiments are switched in burst mode where waveforms are registered up to 20 kHz in order to have a better frequency and better time resolutions.

Normally the field strength of the electromagnetic waves decreases with distance from the source, but in the ionosphere or the magnetosphere it could be enhanced due to interaction with energetic particles. The aim of this paper is to show examples of manmade waves emitted from the ground and recorded in the ionosphere by DEMETER at various frequencies.

Waves emitted by VLF transmitters are presented in section 2, by ELF transmitters in section 3, and by electricity networks in section 4. Section 5 displays examples of ELF waves generated at high latitudes by powerful HF emissions for scientific purpose. Conclusions are given in section 6.

2. VLF transmitters

Ground-based VLF transmitters are used for communications by the army in different countries. They are powerful in order that the signal can be received at very large distances. Normally, the emitted wave propagates in the waveguide formed by the Earth surface and the bottom of the ionosphere, but this wave can escape in the ionosphere. Their effects have been studied for a long time because the wave propagates in the magnetosphere mainly along the magnetic field lines

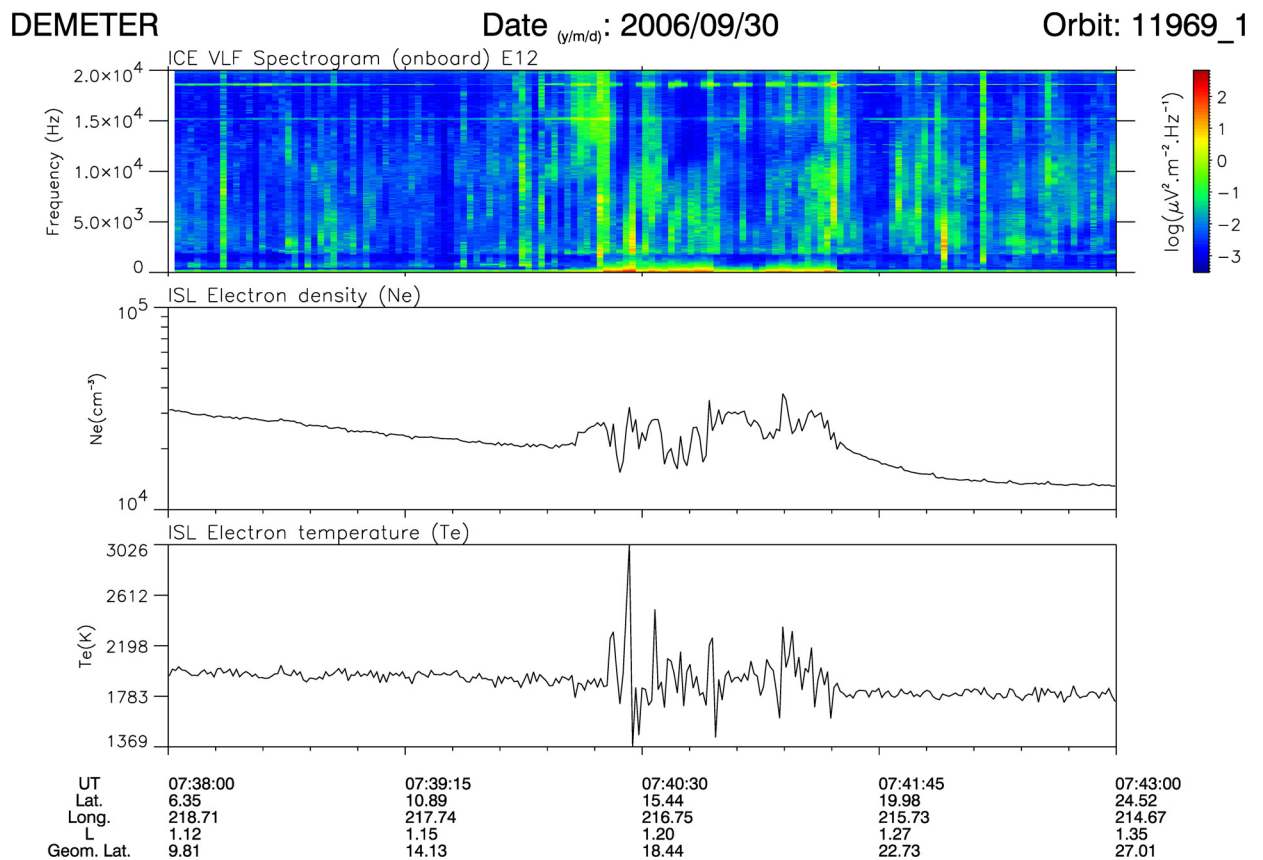


Fig. 1. The top panel represents the spectrogram of an electric field component recorded on 30 September 2006 between 07:38 and 07:43 UT. The frequency range is up to 20 kHz. The intensity is color coded according to the color scale on the right. The middle (bottom) panel displays the electron density (temperature). Below, the geographic latitude and longitude are indicated, together with the L -value and the geomagnetic latitude.

Fig. 1. Le panneau du haut présente le spectrogramme d'une composante du champ électrique enregistré le 30 septembre 2006 entre 07:38 et 07:43 TU. La gamme de fréquence est jusqu'à 20 kHz. L'intensité est codée en couleur suivant l'échelle de couleur à droite. Le panneau du milieu (bas) représente la densité (température) électronique. Les valeurs de la latitude et de la longitude géographique sont données en bas, ainsi que les valeurs de L et de la latitude géomagnétique.

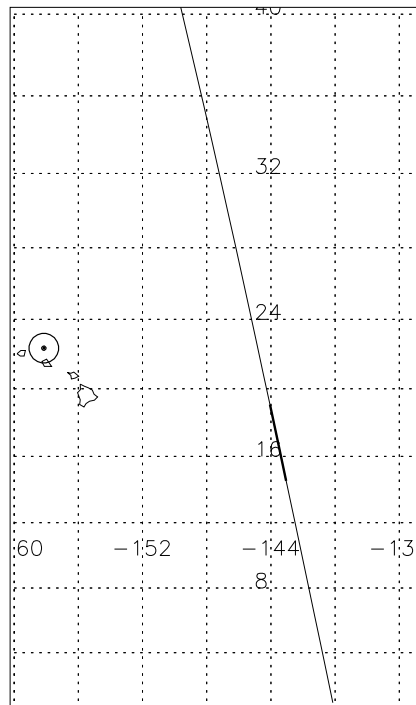


Fig. 2. The map shows the location of the VLF transmitter NPM. The part of the DEMETER orbit where data of Fig. 1 are recorded is indicated by the black line, which is enlarged at the time of the perturbation.

Fig. 2. Cette carte montre la position de l'émetteur TBF NPM. La partie de l'orbite de Demeter où les données de la Fig. 1 sont recueillies est indiquée par la ligne noire, qui est élargie à l'endroit de la perturbation.

and can precipitate the particles which are in the radiation belts [2]. DEMETER has observed these perturbations down in the ionosphere [3–5]. A further example is presented in Fig. 1, which displays the electric spectrogram, the electron density, and the electron temperature recorded on 30 September 2006 close to the NPM transmitter (see Fig. 2). NPM is a VLF ground-based transmitter that is located at 21.42°N and 158.15°W and emits at 21.4 kHz. Due to an aliasing problem (the slope of the cut-off electronic filter is very sharp, but NPM is very powerful), the transmitter frequency line appears at 18.6 kHz in the spectrogram. One can see a large perturbation of the electron density and temperature which occurs south of the transmitter, because the emitted wave mainly follows the magnetic field line. Simultaneously electrostatic turbulence can be observed at low frequencies (<200 Hz) in the spectrogram.

Disturbances due to NPM have been also shown in [6] and [7]. Other unexpected events related to the interaction of VLF transmitter waves with the ionosphere can be seen in [8].

At higher frequencies, DEMETER observes also other transmitters, but their frequencies have less interaction with the ionospheric plasma. For example, the LORAN (Long-Range Navigation) transmitters in the northern hemisphere emit 100 kHz radio waves for marine navigation, which can be registered at the DEMETER altitude [9]. Broadcasting stations can even be detected in space. Fig. 3 shows a map of the Earth where the intensity of the electric field recorded at 162 kHz is displayed. It is the frequency of the French station named “France Inter” of which the transmitter is located at Allouis (47°10' N, 2°12' E). It can be seen that the spot corresponding to the transmitter location is equatorward shifted due to the magnetic field. One can also observe other transmitters at the same frequency in eastern countries.

At HF frequencies not surveyed by DEMETER, it is also possible to record emissions coming from the Earth's surface. For example, the experiment WAVES onboard WIND has observed manmade radio transmissions at 10.375 MHz [10]. Based on such observations, the authors claimed that an extraterrestrial radio astronomer will conclude that the Earth planet is populated.

3. ELF transmitters

To communicate with submarines below the water (and even below ice), the Russian Navy has implemented an ELF transmitter named ZEVS which is located in the Kola peninsula, near Murmansk (Fig. 5). Oppositely to VLF transmitters that have aerial antennae, the emission in the ELF range needs specific devices to be efficient. ZEVS consists of two parallel horizontal grounded antennas about 60 km in length that emit at 82 Hz (there is a similar transmitter in the USA, but emitting at 76 Hz to avoid confusion). For the first time, such wave has been recorded by DEMETER, and an example is displayed in Fig. 4: it represents two spectrograms of an electric component and a magnetic component recorded during

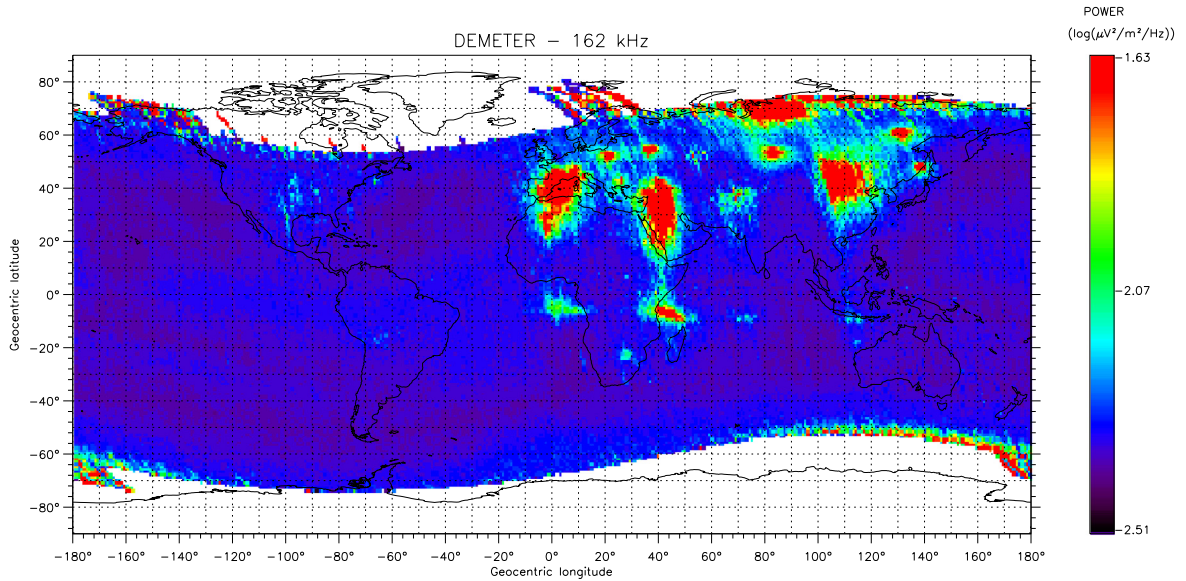


Fig. 3. The map shows the MF intensity of the electric field recorded at 162 kHz by DEMETER. It corresponds to an average value over three years (2005, 2006, and 2007). The intensity is color coded according to the color scale on the right.

Fig. 3. La carte montre l'intensité du champ électrique enregistrée dans la gamme FM à 162 kHz par Demeter. C'est une valeur moyennée sur trois ans (2005, 2006, et 2007). L'intensité est codée en couleur suivant l'échelle de couleur à droite.

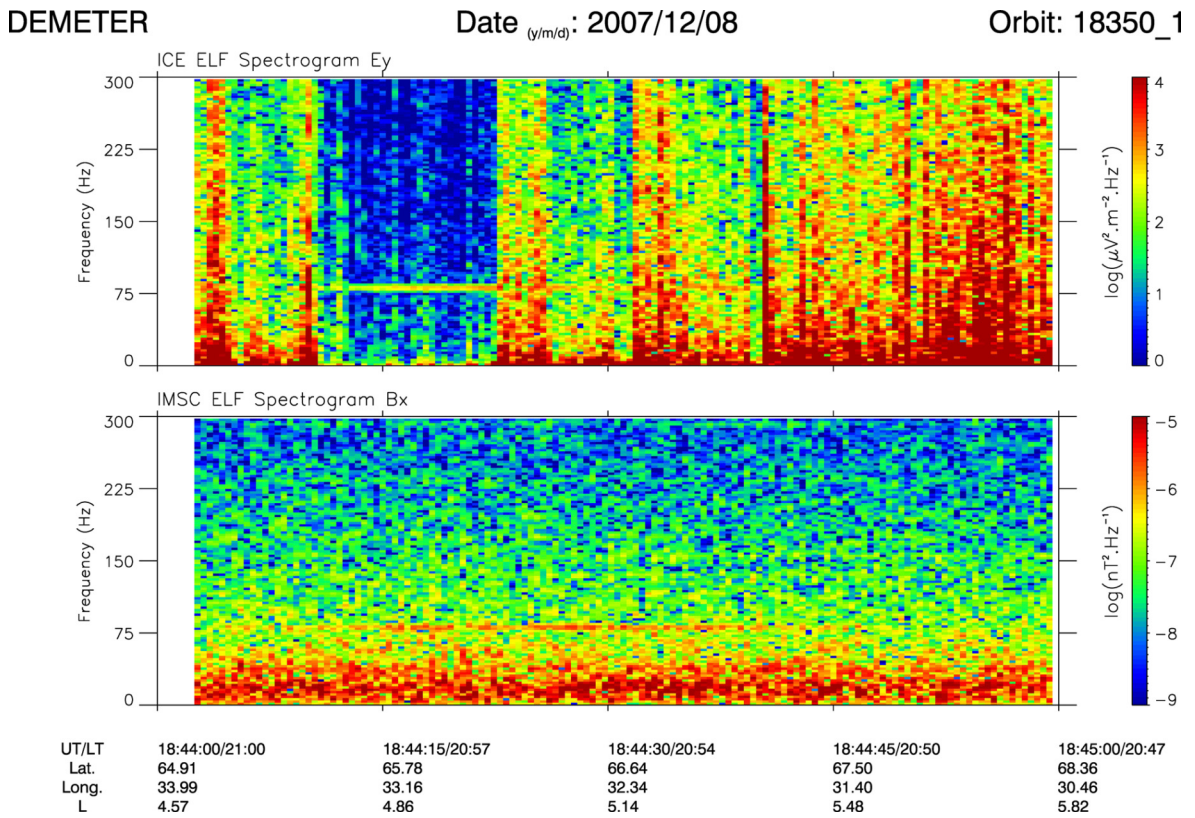


Fig. 4. Spectrograms of one electric component (top panel) and one magnetic component (bottom panel) recorded on 8 December 2007 between 18:44 and 18:45 UT. The frequency range is up to 300 Hz. The intensity is color coded according to the color scales on the right. In the bottom, the geographic latitude and longitude are indicated, together with the *L*-value.

Fig. 4. Spectrogrammes d'une composante électrique (panneau du haut) et d'une composante magnétique (panneau du bas) enregistrés le 8 décembre 2007 entre 18:44 et 18:45 TU. La gamme de fréquence va jusqu'à 300 Hz. L'intensité est codée en couleur suivant les échelles de couleur à droite. La latitude et la longitude géographique sont indiquées en bas avec la valeur de *L*.

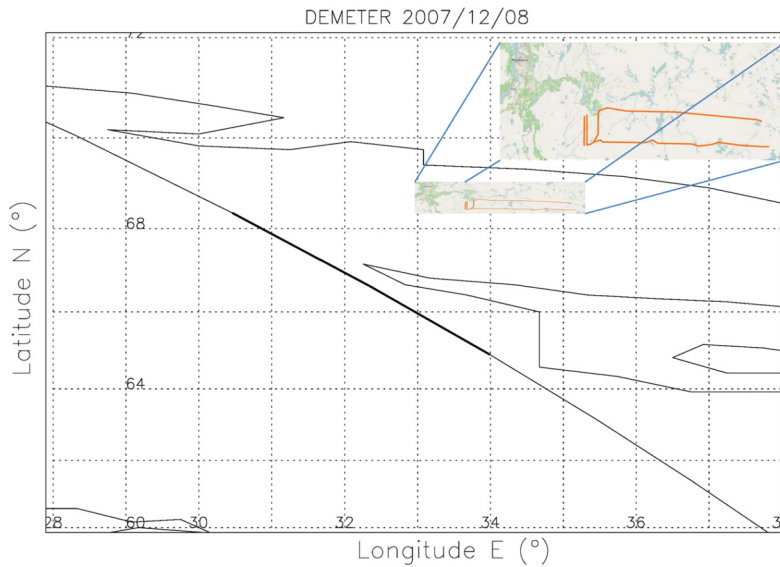


Fig. 5. Map of the Murmansk area. The orbit of DEMETER is indicated by the black line. The thick part corresponds to the data shown in Fig. 4. The insert (enlarged in the top right corner) is issued from the Wikipedia webpage of the ZEVs transmitter. It shows the location of the ground antennae (orange lines).

Fig. 5. Carte de la région de Mourmansk. L'orbite de Demeter est indiquée par une ligne noire. La partie épaissie correspond aux données de la Fig. 4. L'insert (agrandi dans le coin en haut à droite) vient du site Wikipédia de l'émetteur Zevs. Il montre l'emplacement au sol de l'antenne (lignes orange).

DEMETER

Date _(y/m/d): 2006/01/01

Orbit: 07977_0

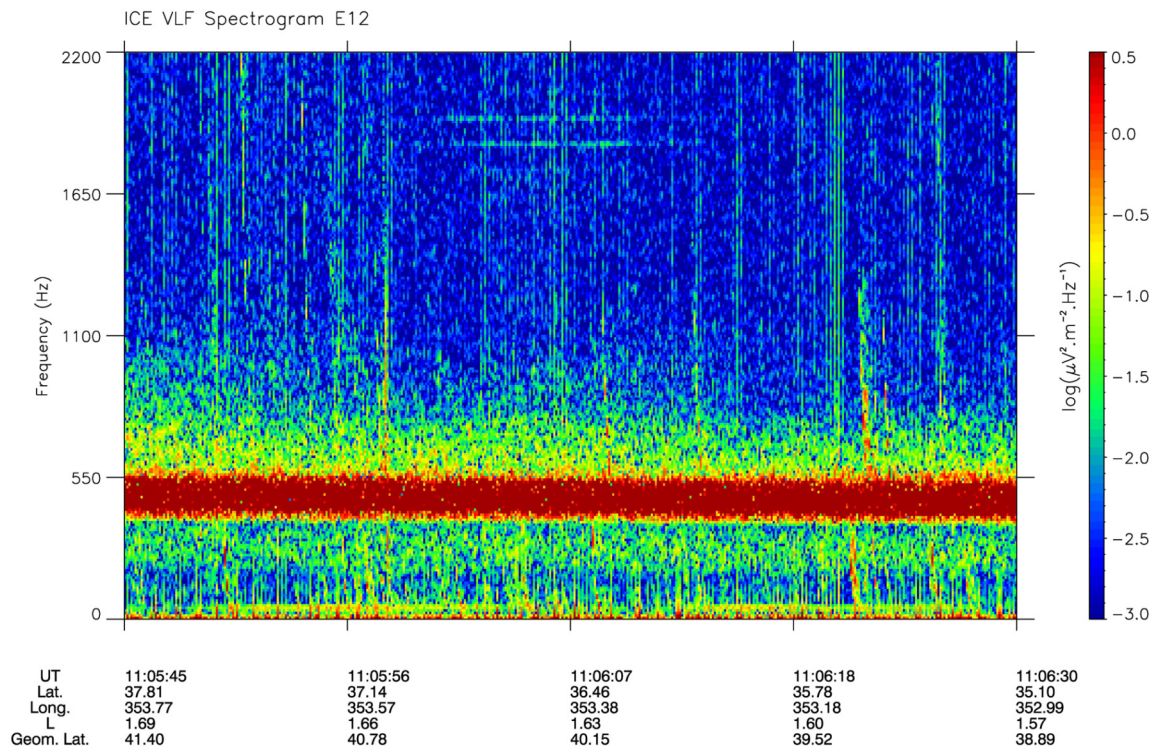


Fig. 6. Spectrogram of an electric field component recorded on 1 January 2006 between 11:05:45 and 11:06:30 UT. The frequency range is up to 2.2 kHz. The intensity is color coded according to the color scale on the right. In the bottom, the geographic latitude and longitude are indicated, together with the L -value and the geomagnetic latitude.

Fig. 6. Spectrogramme d'une composante du champ électrique enregistré le 1er janvier 2006 entre 11:05:45 et 11:06:30 TU. La gamme de fréquence varie jusqu'à 2,2 kHz. L'intensité est codée en couleur suivant l'échelle de couleur à droite. Les valeurs de la latitude et de la longitude géographique sont données en bas ainsi que les valeurs de L et de la latitude géomagnétique.

DEMETER

Date _(y/m/d): 2010/01/06

Orbit: 29507_0

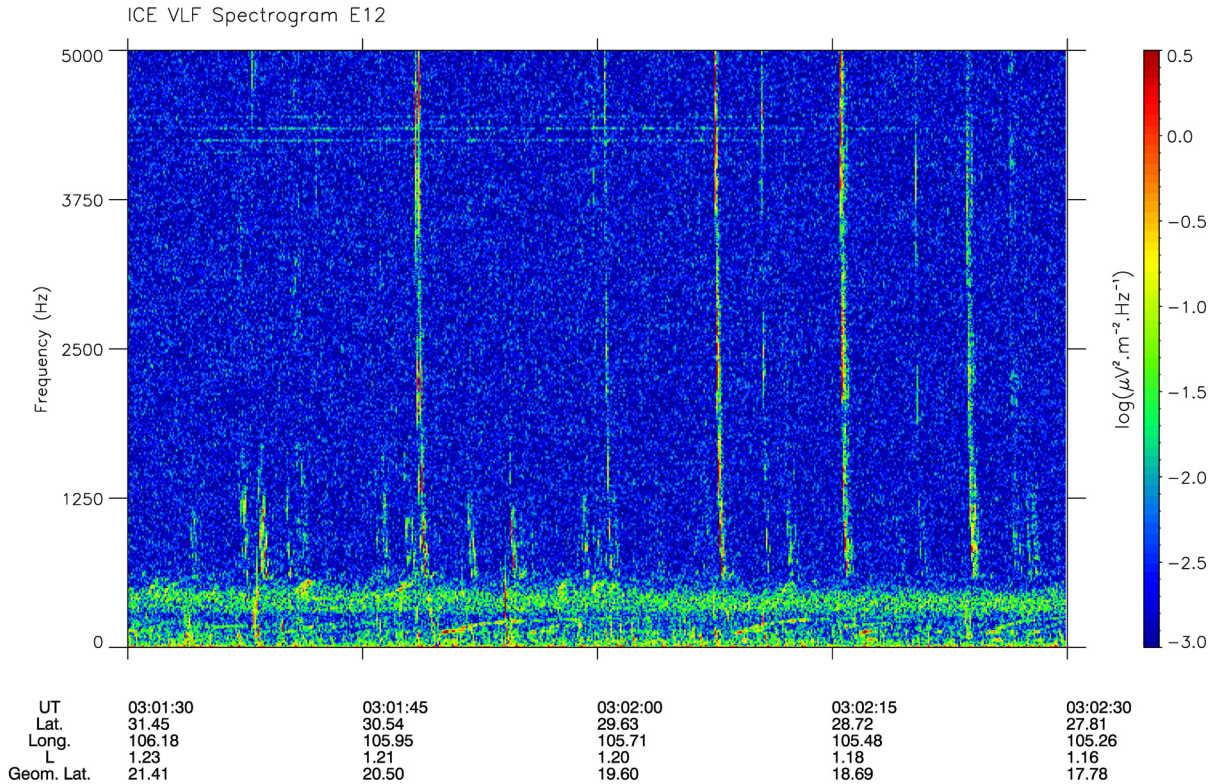


Fig. 7. Spectrogram of an electric field component recorded on 6 January 2010 between 03:01:30 and 03:02:30 UT. The frequency range is up to 5 kHz. The intensity is color coded according to the color scale on the right. In the bottom, the geographic latitude and longitude are indicated, together with the L -value and the geomagnetic latitude.

Fig. 7. Spectrogramme d'une composante du champ électrique enregistré le 6 janvier 2010 entre 03:01:30 et 03:02:30 TU. La gamme de fréquence varie jusqu'à 5 kHz. L'intensité est codée en couleur suivant l'échelle de couleur à droite. Les valeurs de la latitude et de la longitude géographique sont données en bas ainsi que les valeurs de L et de la latitude géomagnétique.

the night along the orbit shown in Fig. 5. The emission at 82 Hz is clearly seen in the two panels, although there is a lot of electrostatic turbulence (low-frequency wave) in the electric spectrogram because the satellite is close to the auroral zone. This wave propagates at very long distances in the Earth-ionosphere waveguide [11,12], but at higher altitudes in the ionosphere, the wave is only observed when the satellite is close to the emission area.

4. PLHR

Power Line Harmonic Radiation (PLHR) consists of ELF and VLF waves at the harmonic frequencies of 50 or 60 Hz radiated by electric power systems on the ground. The frequency-time spectrograms of these events consist of several horizontal lines with separation of 50/100 or 60/120 Hz. Evidence of PLHR propagation in the magnetosphere was first obtained from ground-based observations [13]. A systematic study of PLHR observations by the micro-satellite DEMETER was performed in [14–17] (see also references to other observations therein). They showed that the frequency spacing of the lines corresponds well to the power system frequency in possible generation regions.

Fig. 6 presents an event recorded above Spain on 1 January 2006. Lines at frequencies close to 1846 Hz and 1946 Hz can be observed around 11.06 UT. The intense band of noise with a frequency below 550 Hz is natural and usually observed by DEMETER.

Another example of PLHRs is given in Fig. 7, where parallel lines at frequencies close to 4227 Hz, 4327 Hz, and 4428 Hz can be observed above China. The vertical lines correspond to waves (called whistlers) emitted in a large frequency range and induced by lightning strokes in the atmosphere below the satellite.

Odd harmonics of 50 Hz are preferentially observed [18,19]. The harmonics are not observed at an exact multiple of 50 Hz, because a small variation of the frequency of the delivered current induces a large change at high harmonic orders. For example, in Europe, the rules to be respected by the power plants are given by the European Norm EN 50160: 50 Hz \pm 1% (i.e. 49.5 Hz to 50.5 Hz) during 99.5% of the time, and 50 Hz + 4%/–6% (i.e. 47 Hz to 52 Hz) during the rest of the time.

DEMETER

Date _(y/m/d): 2009/10/03

Orbit: 28118_1

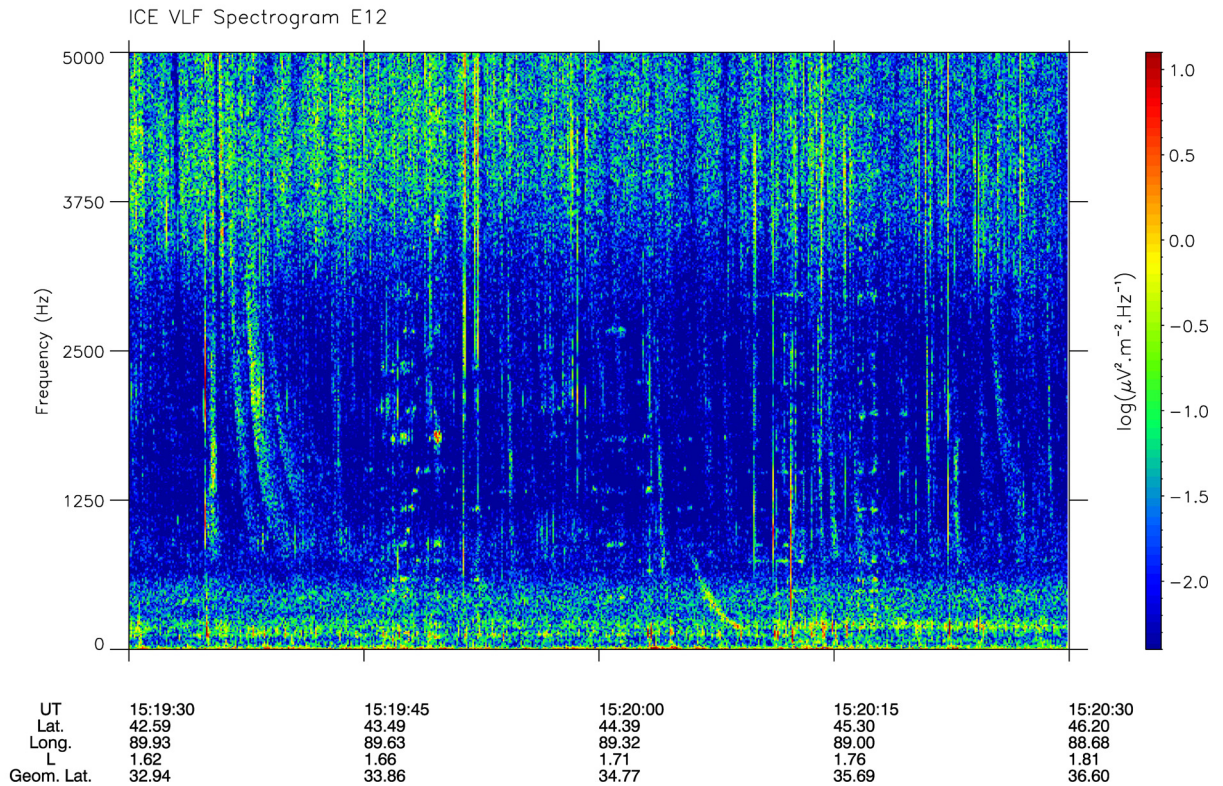


Fig. 8. Spectrogram of an electric field component recorded on 3 October 2009 between 15:19:30 and 15:20:30 UT. The frequency range is up to 5 kHz. The intensity is color coded according to the color scale on the right. In the bottom, the geographic latitude and longitude are indicated, together with the L -value and the geomagnetic latitude.

Fig. 8. Spectrogramme d'une composante du champ électrique enregistré le 3 octobre 2009 entre 15:19:30 et 15:20:30 TU. La gamme de fréquence varie jusqu'à 5 kHz. L'intensité est codée en couleur suivant l'échelle de couleur à droite. Les valeurs de la latitude et de la longitude géographique sont données en bas ainsi que les valeurs de L et de la latitude géomagnétique.

The variation can be even larger for islands not connected to the network: $50 \text{ Hz} \pm 2\%$ (i.e. 49 Hz to 51 Hz) during 95% of the time, and $50 \text{ Hz} \pm 15\%$ (42.5 Hz to 57.5 Hz) during the rest of the time.

Sometimes PLHRs cannot be firmly distinguished, but non-natural emissions are present, which can be attributed to industrial noise occurring below the satellite. An example is given in the spectrogram in Fig. 8, which has been recorded above China (see also [20]). One can see the industrial noise between 15:19:45 and 15:20:10 UT up to 3 kHz. Vertical lines are due to whistlers. Other examples recorded above Europe can be seen in [21].

The data shown in Fig. 9 is recorded in the Southern Hemisphere at a location that is magnetically conjugated to Finland where many PLHRs can be observed. One can see several triggered emissions and hooks that seem to be emitted at a parent line frequency close to 1765 Hz. It means that PLHRs propagate in the magnetosphere and can trigger new emissions at the equator due to interaction with particles. At the end they are observed in the hemisphere opposite to the PLHR emission. These hooks are very similar to those detected on the ground in [18,19,22].

5. Active experiments

ELF signals can be generated via modulated HF heating of the lower ionospheric D region where natural ionospheric currents occur. A powerful beam at high frequency ($>3 \text{ MHz}$) is directed upward, and the wave energy is absorbed by electrons of the current flows in the D region. Then, if there is an amplitude modulation of this beam at ELF frequencies, this induces a modulated current that radiates ELF waves [23,24]. Several HF heating experiments have been implemented: HAARP in Alaska ($62^\circ 18' \text{ N}$, $145^\circ 16' \text{ W}$), EISCAT in Scandinavia ($69^\circ 35' \text{ N}$, $19^\circ 12' \text{ E}$), and Sura in Russia ($56^\circ 13' \text{ N}$, $46^\circ 10' \text{ E}$). During specific campaigns, data registration by DEMETER has been extended to orbits over these heating facilities because they are located at high latitudes (see Fig. 3).

DEMETER

Date _(y/m/d): 2009/12/17

Orbit: 29222_1

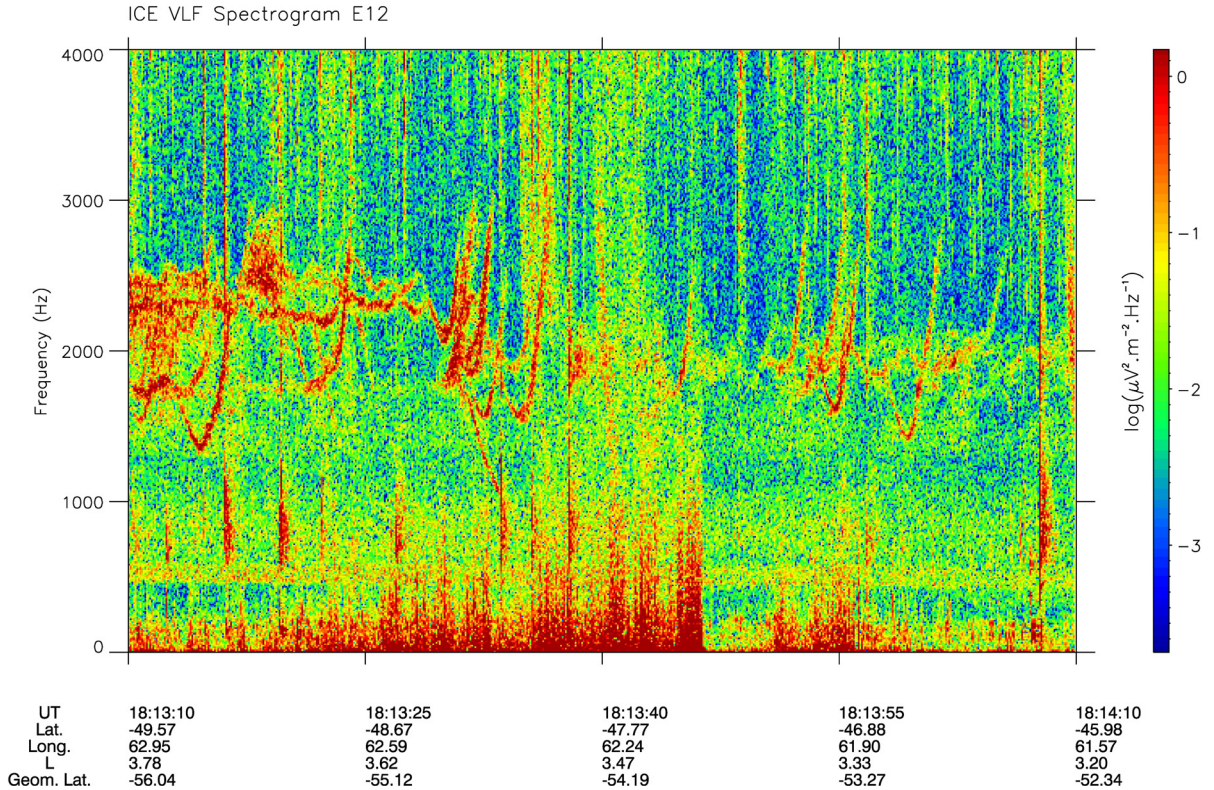


Fig. 9. Spectrogram of an electric field component recorded on 17 December 2009 between 18:13:10 and 18:14:10 UT. The frequency range is up to 4 kHz. The intensity is color coded according to the color scale on the right. In the bottom, the geographic latitude and longitude are indicated, together with the L -value and the geomagnetic latitude.

Fig. 9. Spectrogramme d'une composante du champ électrique enregistré le 17 décembre 2009 entre 18:13:10 et 18:14:10 TU. La gamme de fréquence varie jusqu'à 4 kHz. L'intensité est codée en couleur suivant l'échelle de couleur à droite. Les valeurs de la latitude et de la longitude géographique sont données en bas, ainsi que les valeurs de L et de la latitude géomagnétique.

The data shown in Fig. 10 is recorded close to the magnetically conjugated point of HAARP. At 2 kHz, one can see the regular pulses triggered by the HAARP heating experiment in the Northern Hemisphere (ramps are also emitted from 1 to 2 kHz). But after propagation in the Southern Hemisphere, it is shown that these pulses trigger hooks almost similar to those triggered by PLHRs, which are displayed in Fig. 9.

6. Conclusions

It has been shown that many different manmade waves were emitted in a wide frequency range from the Earth's surface. They propagate in the ionosphere and then in the magnetosphere. Depending on their frequencies, they can interact in the magnetosphere with particles or not. The corresponding interaction mechanisms are well known (see, for example, [25] and references therein). The importance of these manmade waves in comparison with natural waves must be evaluated. In the past, some examples have been presented [26,27]. It is clear that VLF transmitters perturb the radiation belts [4,28], but it has been shown in [17] that PLHRs do not have a global influence on the VLF wave activity in the ionosphere, even if we have examples of triggered emissions. This VLF wave activity is mainly related to the thunderstorm activity (whistlers). Another explanation is that PLHR may influence this thunderstorm activity, but it is not confirmed.

Acknowledgements

This work is mainly related to data recorded by the micro-satellite DEMETER, which was operated by the French "Centre national d'études spatiales" (CNES). The authors thank J.-J. Berthelier, the PI of ICE, the electric field experiment on DEMETER, for having entitled them to use the data. The DEMETER data shown in this paper can be obtained at <https://cdpp-archive.cnes.fr/>.

DEMETER

Date _(y/m/d): 2007/08/23

Orbit: 16781_0

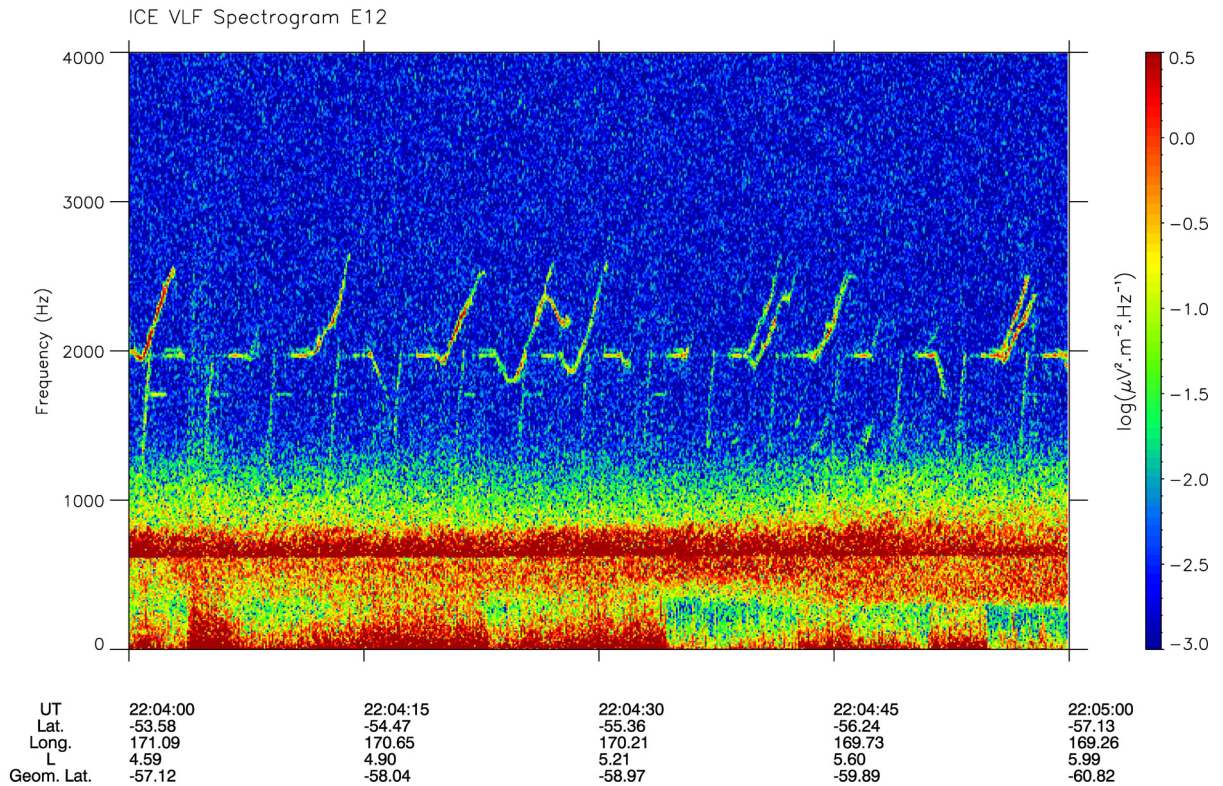


Fig. 10. Spectrogram of an electric field component recorded on 23 August 2007 between 22:04 and 22:05 UT. The frequency range is up to 4 kHz. The intensity is color coded according to the color scale on the right. In the bottom, the geographic latitude and longitude are indicated, together with the L-value and the geomagnetic latitude.

Fig. 10. Spectrogramme d'une composante du champ électrique enregistré le 23 août 2007 entre 22:04 et 22:05 TU. La gamme de fréquence varie jusqu'à 4 kHz. L'intensité est codée en couleur suivant l'échelle de couleur à droite. Les valeurs de la latitude et de la longitude géographique sont données en bas, ainsi que les valeurs de L et de la latitude géomagnétique.

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