2nd URSI AT-RASC, Gran Canaria, 28 May – 1 June 2018

What are the source of MF signatures recorded on DEMETER satellite?

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Abstract

We found new signatures on statistical maps of HF DEMETER data compiled for narrow frequency window and for seasonal variations. Beside the known signal enhancements between 1.8-2.9MHz above the powerful VLF transmitters that can be attributed to the effect of heating of the ionosphere by the VLF waves, we found signal decrease above the VLF transmitters. The low level of the seasonal variation on signal enhancement and decrease above the VLF transmitter may question the origin of the variation that could be attributed to high frequency part of terrestrial lightnings. We have found signatures of increased signal level over certain areas above 2.7MHz for local winter periods. They may be attributed to MF radio broadcast transmitters and can propagate in ordinary mode above the maximum local plasma frequency through the ionosphere as during the local winter. However some of the area found are not expected to exhibit radio broadcasting activity (Himalaya, Tibet, North sea), while there are areas spatially close the ones found, that do not exhibit such signatures (East US cf. West US or Central Europe cf. Western Europe). The absence of signal increase/decrease above the three Russian Alpha transmitters is not yet understood also.

1 Introduction

The High Frequency (HF) electric field observations on DEMETER satellite [1] cover the range from DC up to 3.33MHz. This HF recordings have already been used to survey the signature of ground based natural and man-made electromagnetic (EM) signals. [5] found the signatures of powerful lightnings in the upper part of Middle Frequency (MF) band, between 2-2.5MHz. They reported 130 simultaneous events in the DEMETER HF recordings and US National Lightning Detector Network data and concluded that the source of emissions were very close to the footprint of satellite path and the propagation through the ionosphere took place above the critical frequency of the F2 layer.

[6] found MF signatures, enhancements of signal intensity of terrestrial lightnings above powerful Very Low Frequency (VLF) transmitters in the 2-2.5MHz band. The relative enhancement of the signal level is around 80-100% and it is attributed to the heating effect of the transmitters' power. [4] presents a model on this heating effect, assuming the increase of the collision frequencies by a factor of two, resulted in the increase of the half angle of the transmission cone from 1° to 4°. [4, on Figure 1.b] presents a statistical map for the frequency range 1-1.6MHz, where the MF signal level is *decreased* above the VLF transmitters. The decrease is about 40-50%. However - apart from a short remark on page 1210 ("Apart for high latitudes, one does not observe any signature of 0+ whistlers"), it is not mentioned that the decrease of the signal level takes place above the VLF transmitters only.

We have created a series of higher frequency resolution statistical maps, completed it with seasonal investigations and extended it for the frequency range 3-3.3MHz. We found several new MF signatures that may not be easily explained by the models presented the papers above. This opens a series of questions that are not answered yet.

2 Statistical maps

The statistical maps presented here were prepared as follows. VLF (20Hz-20kHz) and HF (3kHz-3.33MHz) measurements of DEMETER satellite, recorded over the night time orbits from 2006 to 2009 were used. In the selected frequency band the intensity values were averaged in frequency, here we used 100kHz frequency range for averaging in HF data. After this, the measurements were spatially binned with $1^\circ \times 1^\circ$ resolution and averaged in each pixel.

To see where can one expect variations (signature) on signal level, we selected an area around NWC ($15^\circ \times 13^\circ$) and two others above Atlantic and Pacific oceans ($20^\circ \times 20^\circ$) as spatial noise reference background. This noise reference areas were selected to exclude the time and/or frequency dependent variations. The intensities were averaged over the signal ($\log_{10} P_{\mathrm{NWC}}$) and noise boxes ($\log_{10} P_{\mathrm{noise}}$). The variation of the signal to noise ratio in logarithmic scale is plotted in Figure 1. Above the local gyrofrequency, three bands are seen: a) between 1.2-1.8MHz, the relative signal level is decreased with a minimum at 1.5MHz, b) a sig-

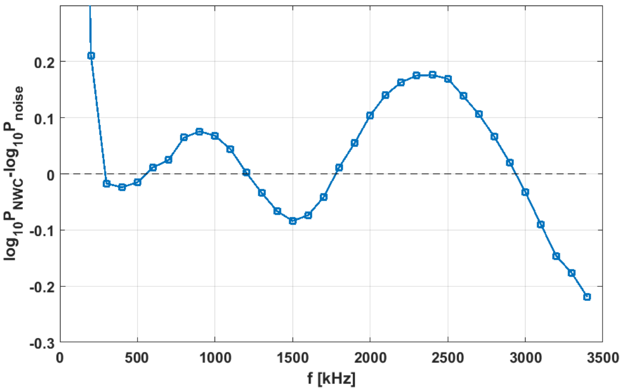

Figure 1. Variation of signal to noise ratio as a function of frequency. The signal is measured above NWC transmitter, noise is measured above the Pacific and Atlantic Oceans.

nal level increase from 1.8 to 2.9MHz withe a maximum at 2.4MHz and c) a gradual decrease above 2.9MHz. We selected a frequency for each bands (1.4, 2.4 and 3.3MHz) to analyze the spatial and temporal behaviour of the MF signatures complemented with a maps for 2.7MHz.

Panels on Figure 2 are similar to [4, Figures 1b and 1c], except that they are generated for 100kHz bandwidth, while Figure 3 shows two maps for the rage of 3.2-3.3MHz and for Northern and Southern hemisphere winter, respectively. Figure 4 is a similar map, but for 2.7MHz and for Northern hemisphere winter.

One may found a series of MF signatures on these maps:

1. signal enhancement above VLF transmitters and their magnetic conjugate areas (Figure 2, right panel). The list of these powerful VLF transmitters can be found eg. in [4, Table 1].
2. signal decrease above VLF transmitters and their magnetic conjugate areas (Figures 2, left panel and 3)
3. signal increase over several regions, some of them overlap with the signal decrease above the VLF transmitters: **a.** Eastern part of South Africa and Papua New-Guinea (Figure 3); **b.** North-East Russia, South-East China, above the Himalaya, Eastern part of US and Canada, West Canada and Alaska (Figure 3; **c.** Central Europe, the North sea, the Gulf bay, North-West China and Tibet (Figure 4)

This what we see, but there is an important signature missing on the maps: there are (at least) three powerful VLF transmitters in Russia, the Alpha navigation transmitters. Their signatures, similarly to te other VLF transmitters are seen on similar maps created from VLF recorded by the DEMETER - see e.g. [2, Figs. 8-11].

3 Discussion

In this section we will go through the signatures seen (or expected to see, but missing) and try identify the sources and the mechanism of propagation or note/list the exiting and not-yet-resolved contradictions among the various signatures.

Signal level increase around 2.5MHz. According to the model presented in [4], there always exists a narrow transmission cone (the half angle is 1°) that allows the "leakage" of MF energy around 2.5MHz due to the collisions. This explains the general noise background at midlatitudes. The heating by VLF transmitters may widen the transmission cone and this explains the increased signal level above the transmitters, but does not explain the increased signal level over the magnetic conjugate regions of the transmitters. But what is the source of enhanced signal at the conjugate regions? It is well known that VLF signals can propagate along the magnetic filed lines in density ducts (e.g [3]), thus one may expect the VLF transmitter signal to heat the conjugate ionosphere, increasing the collision frequencies and widen the transmission cone. This way, the MF frequencies generated by local lightnings propagate through the ionosphere and reach the satellite. The problem with this explanation is that most of the conjugate areas of the VLF transmitters are over the seas, where the lightning activity is very low. This is particularly true for the South Pacific, the conjugate area of the US mainland VLF transmitters. A feasible explanation is that the MF waves also propagate in ducted mode along the magnetic field line. This may be checked by ray-tracing or by searching for high frequency whistlers in HF burst mode recordings of DEMETER.

However - this is true both for signal decrease and increase - there is only a slight variation on signal level above the transmitters on season, while there is more than an order of changes in lightning activity over US, Europe and Australia (see $https://ghrc.nsstc.nasa.gov/hydro/details/lohrac$). Therefore lightnings may not be the sources of the enhanced signal level around 2.5MHz.

Signal level decrease around 1.4MHz and 3.3MHz. One may extend the model presented by [4] from 2.5MHz to lower (below 1.5MHz) and above (above 3.2MHz) frequencies. From the signal level decrease above the VLF transmitters, one may expect an opposite effect, a narrower transmission cone above the VLF transmitters - this task is left here for the future. The signature at the conjugate regions can be explained similarly to the case of signal enhancement.

Missing MF signatures above the Russian Alpha VLF transmitters. These transmitters are also powerful ones, the International Telecommunication Union (ITU) frequency list reports 500 kW of power for these transmitters at all the three locations (Krasnodar, Novosibirsk and Khabarovsk) and at each frequencies (they operate in a 3.6 sec long duty cycle stepping among three frequencies, the pulse durations are 400msec with 200msec between pulses). The stepping between frequencies

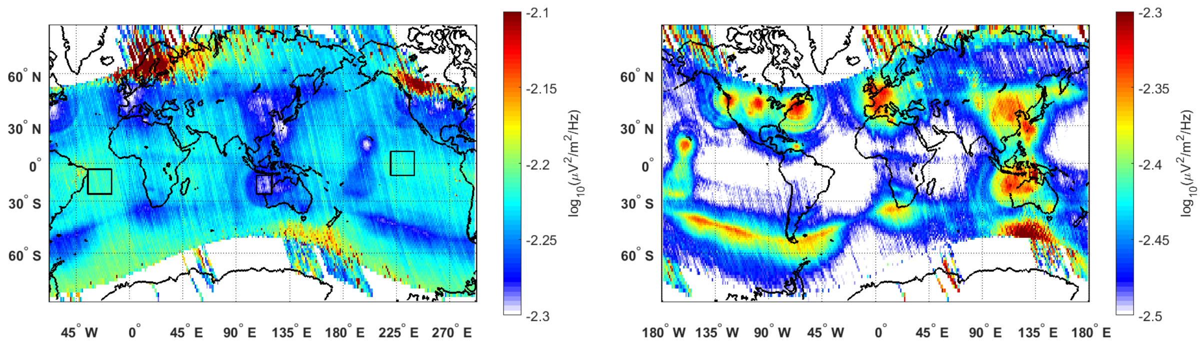

Figure 2. *Left* Intensity map of HF waveband averaged for the 1.3-1.4 MHz frequency range recorded between 2006 and 2009, separated to seasons. *Right* Same as left panel but the signal is averaged for the 2.3-2.4 MHz frequency range

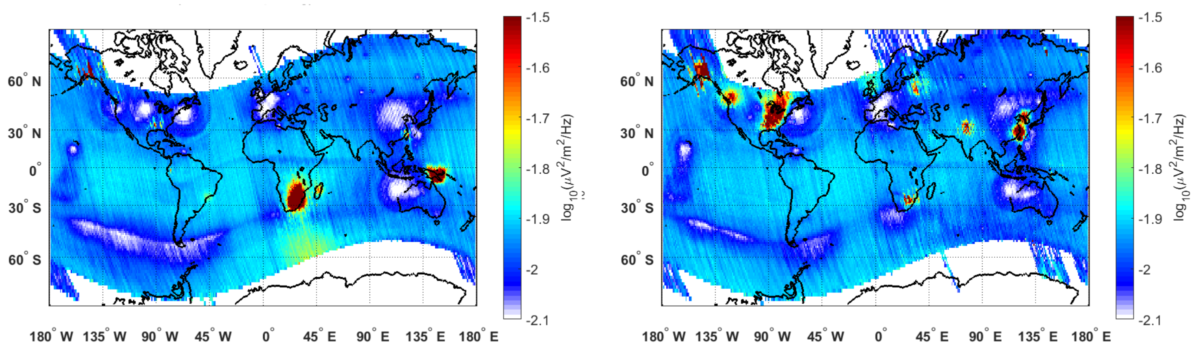

Figure 3. Intensity maps of HF waveband averaged in the 3.2-3.3 MHz frequency range recorded between 2006 and 2009. *Left* panel shows the Southern winter season (April-August), *right* panel is the map of Northern winter season (November-February).

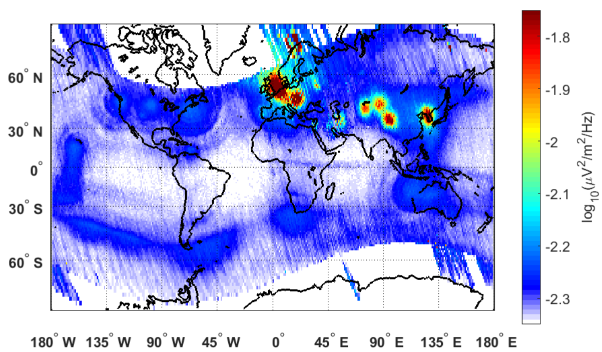

Figure 4. Intensity maps of HF waveband averaged for the 2.6-2.7 MHz frequency range recorded between 2006 and 2009, for Northern winter season (November-February)

certainly decreases the average transmitted power, but as it was mentioned above, their signals are clearly seen on DEMETER VLF data, therefore similar heating is expected above these transmitters as seen above the other powerful VLF transmitters. Assuming that the source of the signatures are the terrestrial lightnings, we found similar lightning activity over e.g the NLK US Navy transmitter (near Seattle, WA, USA) or over GBZ and GQD transmitters in North-England to the one over Novosibirsk or Khabarovsk (see the lightning climatology maps, e.g *https://ghrc.nsstc.nasa.gov/pub/lis/climatology/LIS−OTD/HRFC/browse/HRFC_COM_FR*$_V$2.3.2015.*png*). The lightning activity around the Krasnodar transmitter is much higher than around the Siberian transmitters, thus one may expect stronger signature here. The 4 year averaged critical frequency map of F2 layer calculated for 22:30LT (the time of DEMETER passes over a location) and for winter periods for both hemisphere (not shown here) exhibits no significant differences for the European, North American and Russian regions, where the VLF transmitters are located. A deeper analysis of ionospheric conditions above these area may reveal the reason of missing signatures.

Seasonal/overlapping MF signatures around 2.7MHz and 3.3MHz. The signal enhancement over several regions listed in Item 3 above exhibit seasonal variations, they exist mostly during local winter periods, thus the first trivial explanation of their existence can be the lowered critical frequency (foF2<2.6MHz or <3.2MHz) of F2 layer over these areas - that assumes propagation above fof2. However, foF2 is generally small over much larger areas during local winter than these spots. Thus one may expect similar signal enhancements over much wider regions. A closer look revealed (not shown here), that there are cases when the spectral enhancements correspond to spectral lines over limited spatial areas - that is to radio broadcasting transmitters. The location and other parameters of recent and/or active MF radio broadcast transmitter can be found at *http : //www.mwlist.org*, but it is very difficult to find historical data on operation of those transmitters back to 10-15 years - therefore we assume similar coverage of transmitters. There are transmitters operating at/around these frequencies all over the world, many of them operates according to diurnal/weakly, but not seasonal schedule.

There are two major problems with the explanation of this signatures by MF broadcast stations:

1. why are these radio station signals are visible over e.g. East US and East Canada (Figure 3) and not over West US (there are MF radio stations over that area also)? Similarly, why it is seen over Central Europe, but not over e.g. France and Spain (Figure 4)?

2. Why it is seen over areas where no one expect such radio broadcast stations (e.g. the North sea, Himalaya, Tibet, Papua New-Guinea, North-West coast of Canada)? MF signals propagate over short distances only, particularly in hilly area, thus the source needs to be local.

An exciting question is what happens on (Figure 3) over the area between the Great Lakes and Eastern shore of the US, where the area of signal decrease for 3.3MHz above the NAA US Navy transmitter overlaps the signal enhancement may be attributed to MF radio broadcast stations during local winter periods - this is the period when the fof2 is generally much lower than 3.3MHz. One explanation may be that the EM waves from the radio broadcast transmitters propagate in ordinary mode, while the signals from the other source(s) are propagating in extraordinary mode and the mode conversion for this mode and for this frequency is not possible, thus the signal is absorbed/reflected back.

4 Summary and Conclusions

Creating statistical maps of MF signatures seen on HF DEMETER data for narrow (100kHz) frequency window and for seasonal variations, we found further signatures have not presented earlier ([5], [6], [4]). Signal enhancements between 1.8-2.9MHz above the powerful VLF transmitters can be attributed to the effect of heating of the ionosphere by the VLF waves that results through increased collision frequencies to widened transmission cones. The same effect may result the opposite (narrowed transmission cone and thus decreasing signal level) below 1.8MHz and above 2.9MHz - but this needs to be confirmed to extend the model of [4] for these frequencies.

However, the low level of the seasonal variation on signal enhancement and decrease above the VLF transmitter seen in MF DEMETER data may question the origin of the variation that thought to be attributed to high frequency part of terrestrial lightnings, because the seasonal variation of lightning occurrence around the VLF transmitters are much higher, it reaches one-one and a half order of magnitudes.

We have found signatures of increased signal level over certain areas above 2.7MHz for local winter periods. They may be attributed to MF radio broadcast transmitters and can propagate through the ionosphere as during the local winter, the fof2 generally below 2.7MHz. However some of the area found are not expected to exhibit radio broadcasting activity (Himalaya, Tibet, North sea), while there are areas spatially close the ones found, that do not exhibit such signatures (East US cf. West US or Central Europe cf. Western Europe). The absence of signal increase/decrease above the three Russian Alpha transmitters is not yet understood. Finally, the sources of the MF signatures could be lightnings and MF radio broadcast transmitters, however, based on "anomalies" found in the signatures, this cannot be confirmed yet, further analysis of existing and future experimental data is needed accompanied with extended model calculations.

Acknowledgements

M. Nagy was supported by the ÚNKP-16-3 New National Excellence Program of the Ministry of Human Capacities. This work was supported also by the National Research, Development and Innovation Office, Hungary through the grants NN116408 and NN116446.

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