Test of the SAS2

ULF-VLF electromagnetic wave analyzer in space environment – on board of the Compass-2 satellite

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The SAS2 measuring system, an advanced version of the SAS electromagnetic wave analyzer and sampler, successfully operated on board of the Compass-2 satellite launched in 2006. The main mission of this satellite was to be a technical test of a satellite series in space environment. These satellites are intended to research space weather, further they will observe possible precursory events of earthquakes. The measuring systems and instruments worked well. We found some interesting phenomena in the observed ULF-VLF electromagnetic database detected by SAS-K2: whistler-doublets (observed earlier in 1989, by the first version of SAS on board of IK-24), "spiky" whistlers (SpW, we identified this signal type first from database of Demeter satellite, and we presented the theoretical solution of these signals). Further signals, propagated in ducted whistler mode between two inhomogeneous surfaces (onion-skin) in the plasma, were successfully identified first time during this mission. These signals presumably propagated in higher mode (third order) in the magnetosphere. We delivered the theoretical solution of this phenomenon for UWB (ultra wide band) signals too.

1. Introduction

The monitoring of the electromagnetic environment of planets (primarily the Earth) essentially starts nowadays, however some experiments were conducted in the past. On the one hand, the required measuring and data-handling techniques have become available in the recent years; on the other hand, the needed wave propagation theory has been born only by now, as many theoretical breakthroughs were necessary in the case of these problems.

One of the early experiments was the IK-24 ("Active") satellite launched in 1989 [8], which carried onboard the Signal Analyzer and Sampler (SAS) instrument developed by us. By now it became obvious that the investigation, observation and continuous monitoring of the electromagnetic surroundings of planets and especially the Earth are undoubtedly necessary in order to understand and to model the processes of the planet. For this task we developed the advanced versions of SAS measuring system, the SAS2 and SAS3 (SAS2 for satellites and interplanetary space probes, while SAS3 for satellites and for board of the ISS, in order to detect very high resolution of waveforms). By the application of these data it is possible to obtain a more precise description of the terrestrial processes, to have a better understanding of the solar-terrestrial connections and the space weather, further to construct an adequate database for prediction of terrestrial seismic activities and earthquakes.

First of all, for the better understanding and application of signals registered onboard, and for deducing right conclusions from their shapes (i.e. evacuation of a city because of a likely earthquake) we have to describe the generation and propagation of these electromagnetic signals. As an example, let us consider one of the important problems, the ULF-VLF signals excited by lighting discharges (the whistlers). A highly accepted theory for the generation and propagation of these signals (e.g. [7]) says that these signals can only and exclusively propagate from the location of the exciting lightning to the conjugate point (the location of detection) of the geomagnetic field line on the Earth's surface in waveguides formed by ("spaghetti-like") plasma inhomogeneities (ducts). Another hypothesis assumes that these signals can get to the conjugate point without ducts. A third opinion considers onion-skin type inhomogeneities in the high atmosphere as waveguides.

The answer of this question is important for the right interpretation of the observed phenomena. In order to answer this, we have to know exactly the method of the propagation and the shape of the UWB signal [1] in this special environment, along with the different waveguide models. By the application of a sufficiently rigorous theoretical model and by simultaneous, continuous and automatic terrestrial and onboard measurements, the answer can be found [2,5]. Besides the continuous and effective developing of our theoretical models and solution methods, the Demeter mission and the advanced SAS2 with Compass-2 were essential steps forward in this way. Furthermore, we have started to install a global terrestrial measuring system (VR-1 and VR2), compatible with SAS2. This measuring network has been successfully operating at four points in the Carpathian basin, at two points at the Antarctica, two points in South Africa, in New Zeeland, and other places (in the near future e.g. two points in Finland). This terrestrial network works continuously, automatically recognizes, evaluates and classifies the whistlers, and since the first half of this year automatically delivers the plasma parameters, which was unavailable earlier. This is the AWDA system [11]. For this development it was necessary to work out the most accurate, new UWB wave propagation models, because the former theoretical approaches were not applicable for this task.

First we briefly describe the goals of Compass mission and the advanced SAS2, and then we outline the exact UWB description of the guided signal propagation in waveguides filled by magnetised plasmas and the clear evidence of the guided-mode propagation in the detected data of SAS2-K2 worked on board of Compass-2.

2. Advanced Signal Analyzer and Sampler in the Compass mission

The main goal of the Compass mission was to test and verify the measuring ideas and complete detector and instrumentation system of planned missions with the same scientific goals following the Compass. The general scientific goals of the complete mission are the research of the electromagnetic activity concerning the seismic events, especially the electromagnetic precursors of the earthquakes, the detailed investigation and monitoring of the electromagnetic environment of the Earth in the ULF-VLF bands, inside this area the detailed characteristics of the lightning activity and whistler propagation, and space weather relations.

The Compass-1 was launched on 10th December 2001, however, after the successful launch the satellite failed on orbit. The Compass-2 was launched on 26th May 2006 and reached the planned low circular orbit (inclination 79°, orbit height ~400 km). See the satellite in *Fig. 1* and the general sketch of the satellite in *Fig. 2.*

After the start of the operation serious problems appeared in the power system of the satellite, which was partly solved by November 2006. From that time during the active life of the Compass-2 the scientific sensors and measuring systems worked perfectly.

One of the scientific measuring equipments is the advanced Signal Analyzer and Sampler (SAS2-K2, developed and produced by the Space Research Group of the Eötvös Loránd University and the BL Electronics) using Ukrainian sensors, two spherical electric sensors producing one (differential) electric signal appearing between the two spheres, and one electric search coil sensor producing one magnetic signal in the ULF-VLF bands. One of the sensors (ES) has two conductor balls positioned >1.5 m far from each other, the measured signal is the electric potential difference between the balls. The other sensor (MS) is a search coil receiving ULF-VLF magnetic signals parallel with its axis. The SAS2-K2 and the sensors worked perfectly with high symmetry between the electric and magnetic channels, with high sensitivity and low noise according to the original specifications.

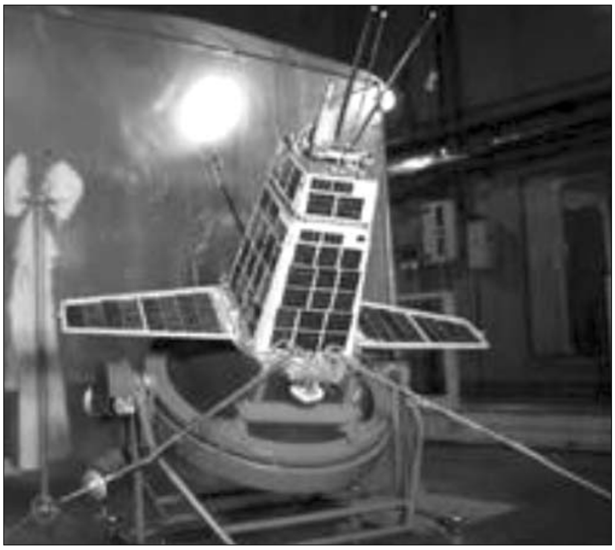


Figure 1.
The Compass-2 during the final phase of the ground tests

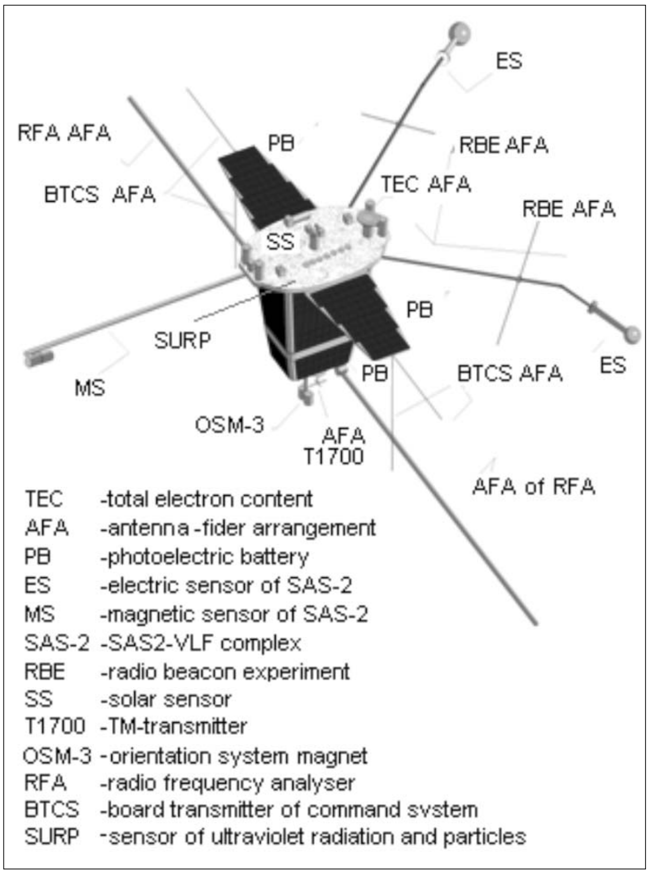


Figure 2.
The sketch of the Compass-2 satellite.
The sensors of the SAS2-K2 are the two ES electric and the MS magnetic Ukrainian sensors.

Figure 3.
The SAS2-K1 equipment for the Compass-1 satellite

This fact means a qualitative step forward in comparison with Demeter satellite, because the sensitivity of the magnetic channel on the Demeter is much lower than the electric one. Both the electric and the magnetic components of Compass-2 have been registered and evaluated with the same quality. The SAS2-K1 for Compass-1 and the SAS2-K2 for Compass-2 can be seen in *Fig. 3* and *Fig. 4.* Inside the box of SAS2-K2 two complete and identical SAS2 were integrated to increase the reliability of the whole mission, as it is possible to see in the block-diagram of the system *(Fig. 5).*

The original SAS2-K1 launched on board of Compass-1 had only one, two-channel SAS2 module (see in Fig. 3). The SAS2-K2 contained two, identical, two-channel SAS2, one active and one cold backup, in order to increase the reliability of the whole mission. This can be well seen in the block diagram (Fig. 5).

The main characteristics of the SAS2 wave analyzer are the following:

Frequency range
(search coil and the electric spheres, 1 pair):
  1 Hz – 20 kHz
Search coil transfer function:
  1 Hz – 1 kHz linear, 1 kHz – 20 kHz flat
Electric sensor transfer function:
  1 Hz – 20 kHz nearly flat
Noise bands:
  Magnetic sensor: 10 Hz – 2 pT / Hz1/2
    100 Hz – 0.2 pT / Hz1/2
    1 kHz – 0.03 pT / Hz1/2
    10 kHz – 0.05 pT / Hz1/2
  Electric sensor (1 pair):
    10 Hz – 40 nV / Hz1/2
    10 kHz – 20 nV / Hz1/2

The mass of the SAS2-K2 electronic unit (Fig. 3b) is 470 g. The total mass of the system with sensors etc. is 1260 g. The size of the electronic unit is 150x70x110 mm. The power consumption is ≤ 3 W, including the sensors, however, one electronic unit (the SAS2-A or the SAS2-B inside the SAS2-K2 box) is a cold backup.

During the operation of the system it is possible to select, by ground commands, that the A or B unit is active inside the SAS2, to select the input gain of the input analogue (ULF-VLF) amplifiers and to select the main operation mode and the parameters of the selected operation mode including the sampling rate of the incoming (registered) signals. (The maximum sampling speed is 43.2 kHz for each channel and the gain of input amplifiers is changeable from -18 dB to +20 dB in three steps.

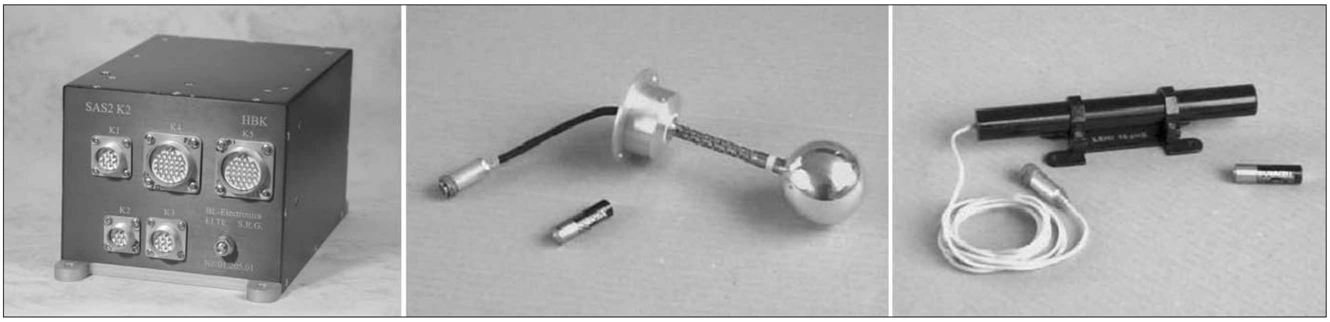
The SAS2 has three different memory modules beside the internal memory of the DSP. The first is the boot memory (128 kBytes EPROM) from which the operating program is loaded after the switch-in or power-on reset. The second is a 4 MBytes SRAM used for measurement data storage as circular buffer and telemetry buffer. The third is a 64 kBytes EEPROM to set and store the actual parameters and reference spectrum of the measuring (operation) modes.

Using this hardware and software possibilities, the SAS2 main operation modes are the following:

a) Monitoring of the average electromagnetic noise spectra of the two channels. The averaging time can be set by commands, by parameters from 1 sec high speed monitoring to 10 minutes long time averaging. This operation mode is running simultaneous with the *b)* or *c)* operation modes.

b) Triggered event detection: After the processing of the signals incoming simultaneously in the two channels, the processed signal (spectrum) of one selected channel is compared to a stored reference signal (spectrum) which is selected or modified by ground commands according to the actual onboard EMC etc. If the recorded spectrum is higher than the reference one on one or more spectral lines (see more about these criteria in [11]), it is accepted as a real event and valid trigger. Then the system reads the recorded signal values stored in circular buffer memory before a predefined time of the trigger signal and following the trigger signal to another predefined time (e. g. 0.5 sec before the trigger and e. g.

Figure 4.
The SAS2-K2 equipment for the Compass-2 satellite and the electric and magnetic sensors of the SAS2-K2, respectively



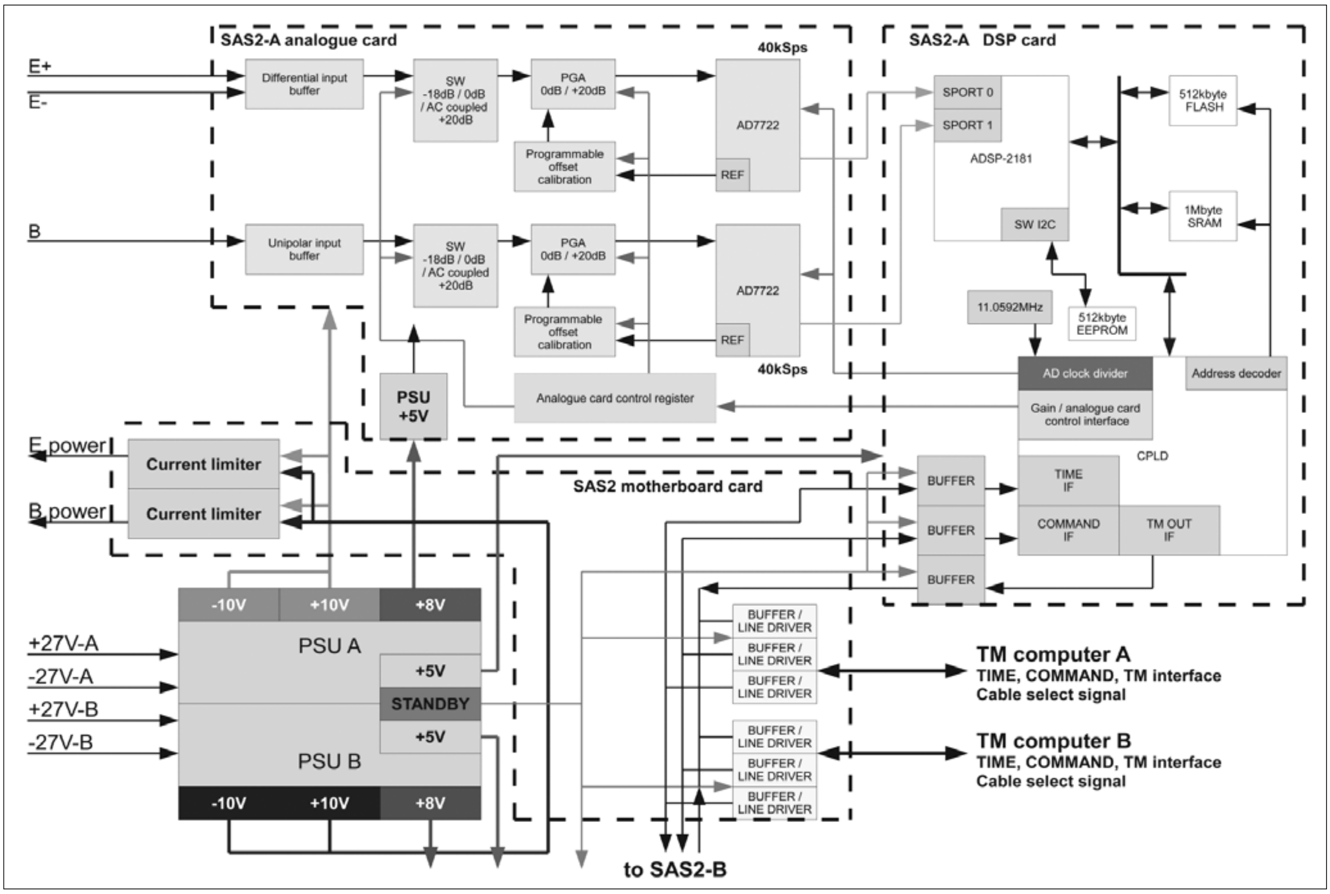


Figure 5. The block diagram of the SAS2-K2. The SAS2-A and SAS2-B units are identical

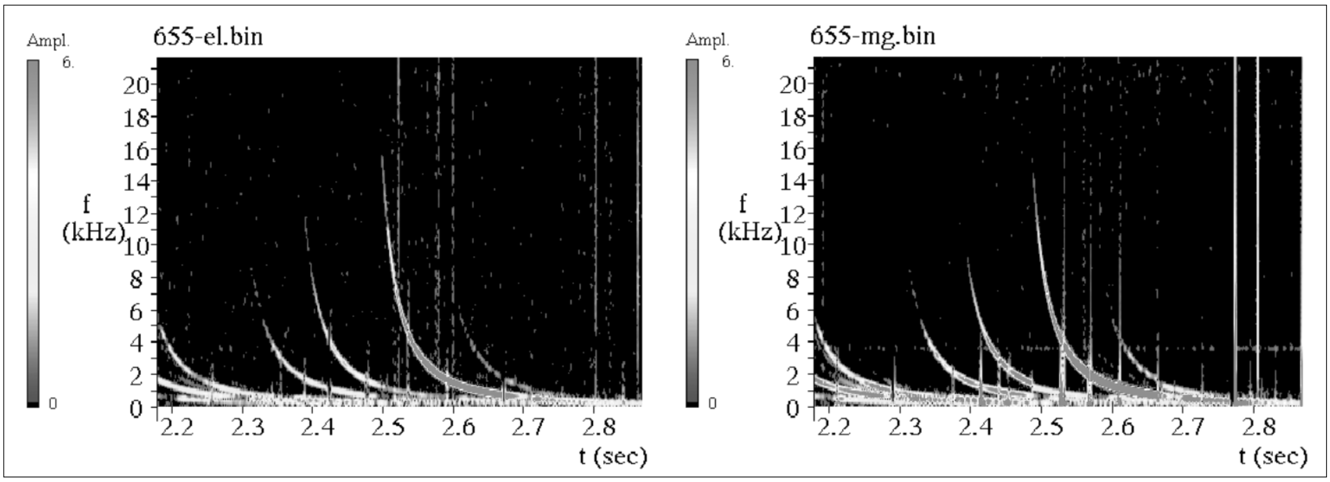
1 sec or 2 sec after the trigger). If the registration of the detected electric and magnetic signals during this time period is finished, the whole record is rewritten into the telemetry buffer.

c) Periodical, time controlled data collection: In this mode the SAS2 detects and stores the incoming data of the two channels with predefined sampling rate (normal “burst” mode) without triggered event detection using a command controlled (predefined) registration time schedule list.

The SAS2 system worked perfectly, and the technological test of the planned complete measuring system was successful, too. The SAS2 registered ULF-VLF signals with the planned specification, with low system noise and the electric and magnetic channels have the symmetry in the signal levels of the incoming electromagnetic events and noise, which is important in the electromagnetic research (see e. g. *Fig. 6*).

In Fig. 6, the first measured signal, a very intensive whistler group can be seen, with both the electric and

Figure 6.
One of the first data set measured by the SAS2-K2 on board of Compass-2, 29th Nov. 2006. UT 5.00.00 above Indonesia. We see here a very strong whistler group, i. e. the FFT pattern of the electric and magnetic components of these whistlers, respectively. The symmetry of the sensitivity of the detector channels is evident.



the magnetic components. In the followings we show briefly three types of detected signals and their interpretations.

3. Examples from the electromagnetic events registered by SAS2

In the followings three examples are displayed from the SAS2 registrations. The first and the second data correspond to our previous theoretical results, the third one shows a new and unknown phenomenon.

3.1 Whistler-doublets

The first detected whistler-doublets appeared during the first SAS experiment, on board of the IK-24 ("Active") satellite – see *Fig. 7*, and more in [8]. The origin of this phenomenon was supposed to be a simple reflection arriving upward below the satellite – this hypothesis seemed to be supported by the time shifting of the two traces and the position of the satellite –, or to be a traveling time difference caused by the presence of two, neighboring plasma inhomogeneities (ducts). The time difference between the two traces in a whistler was 70 < 80 ms in the case of this data, which could make both explanations to be likely. It was also probable, on the basis of the very similar fine structures of the traces that the source (the generating lightning discharge) was identical for both signals, and the propagation paths were closed. But the verification of this interpretation by real wave propagation model calculations has been missing up to now, as the first really exact UWB propagation models were developed later.

The SAS2-K2 has detected whistler doublets, too (see in *Fig. 8*). The time difference in this case is 60 < 70 ms. However in this measured data there were no more doublets in 1-2 seconds, but similar doublets were registered in the same measuring record few minutes earlier. It means that whistler doublets can occur occasionally, but not systematically. The phenomenon is not accidental. Nevertheless, our former interpretation needs fundamental revision, because the orbit of the Compass-2 satellite is much lower than in the case of IK-24, the height of the orbit is ~400 km. This height is too low for such a big running time delay of a signal reflected backward to the satellite near the surface.

The Compass-2 orbits in the ionosphere, just like that of the Demeter satellite, are not too much above it. So, the way of generation by reflection can be excluded. But the other generation theory regarding the two, near, narrow waveguides with small diameters can also be excluded on the basis of the exact UWB solution. We have successfully deduced the UWB solution for waveguides filled by anisotropic, magnetized plasma and the registered doublets show no typical signs of guided propagation (the guided signals have typical forms, see Section 3.3). Thus it became necessary to reexamine this problem, and to find a new, consistent explanation of their generation (as the occurrence of the exciting lightning is possibly in connection with global climate processes and their changing).

3.2 Spiky Whistlers – SpW

We briefly reported this type of whistlers in our paper on registrations of Demeter satellite [2]. The exact identification and wave-theoretical description of this phenomenon, together with the whole UWB solution and model can be found in [3,5].

Here we summarize the essence of this theory. The lightning discharge excites dominantly a vertical current, so-called cloud-to-ground directed lightning. The excited electromagnetic signal starts to propagate in the Earth-ionosphere waveguide, and after traveling a longer distance in this waveguide the signal can connect out toward the higher atmosphere. Through the magnetized ionosphere plasma, the signal can reach the satellite. Because of the fact of guided propagation in the Earth-ionosphere waveguide, guided modes of different orders can appear in the spectrum, with different, harmonic wavelength limits depending on the distance between the Earth's surface and the bottom of the D-layer of the

Figure 7.
Whistler-doublets detected by first SAS experiment on board of IK-24, 14th December, 1990.

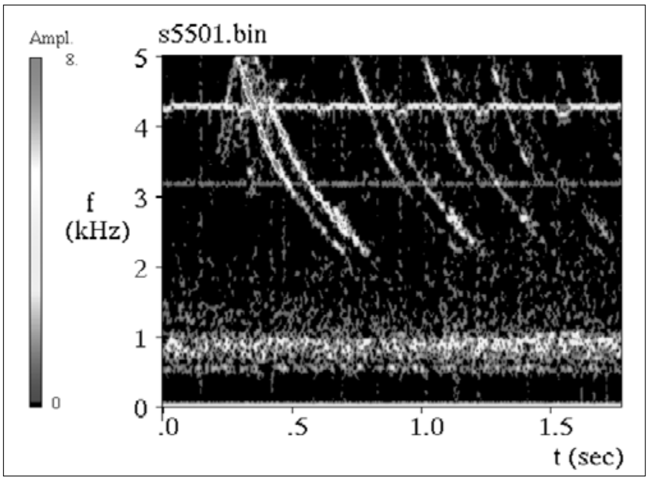
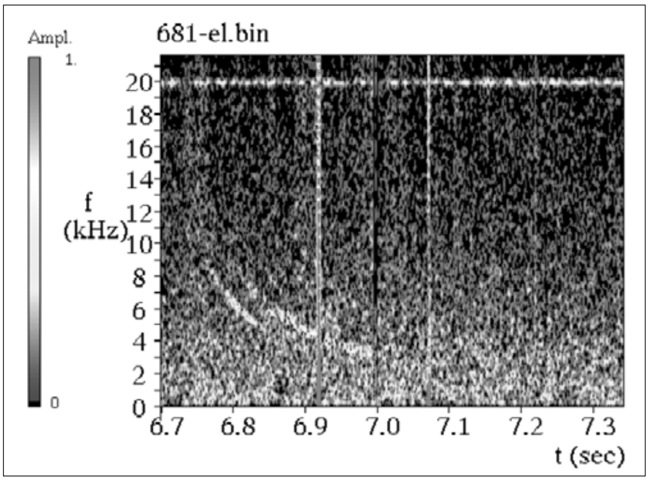


Figure 8.
Whistler doublet measured by SAS2 on board of Compass-2, 27th of January, 2007.



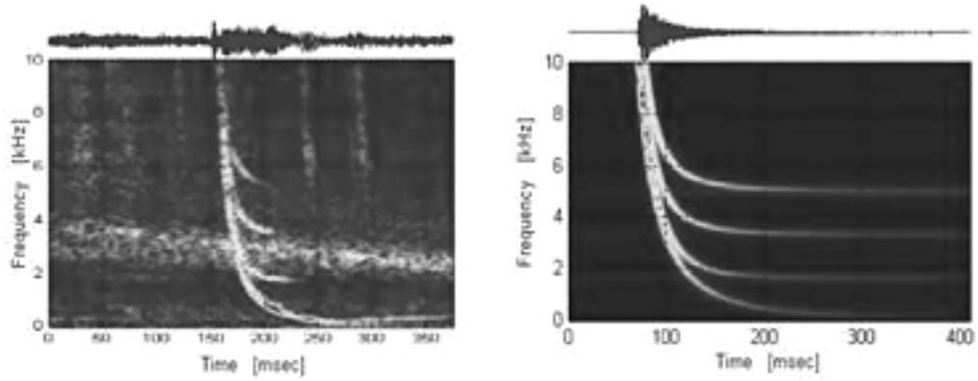


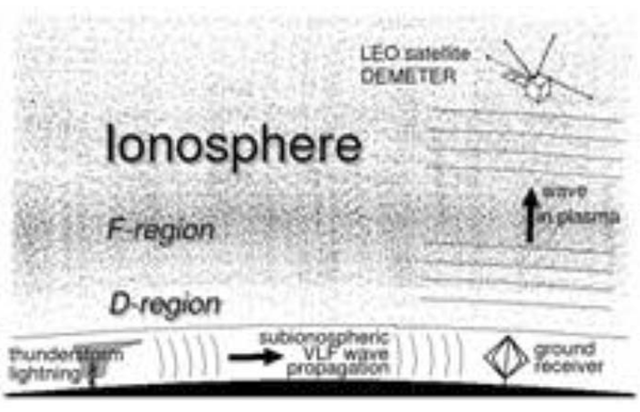
Figure 10.
FFT spectrograms and signal forms of a measured (Demeter satellite, 6th of November, 2004) and a calculated UWB signals [5]

ionosphere. Thus the spectrogram of the signal (e.g. the FFT pattern) will be “spiky”. This signal suffers dispersion during propagation toward the satellite, but preserves its original spiky structure. The sketch of the propagation can be seen in *Fig. 9.*, the signal calculated by our UWB model in comparison with data detected by Demeter satellite can be seen in *Fig. 10.*

We have also detected SpW-s on board of Compass-2, see *Fig. 11*. In this signal group, the second, third, sixth, seventh and ninth order modes can be identified and classified. From these modes, the third and ninth order modes are very sharp, the others are recognizable with small intensity, and no more modes propagated toward the satellite in this case.

We successfully verified the fact, that the Spw-s, which we identified first from registrations of the Demeter, occur frequently, as it was expected. Whereas the wavelength limits and frequency limits of the modes depend on the distance between the surface and the D-layer, by the application of Spw-s it is possible to obtain a real and continuous monitoring of the fluctuation of the height of the lower border of the ionosphere for the whole Earth’s surface, depending on the day, season, space-weather, seismic activity, and other global variations. The reasons of different changes are expected to be determined and classified using time series, and other significances resulted by continuous monitoring. This means one of the important research goals in the future.

Figure 9.
The generation mechanism and propagation path of spiky whistlers (SpW) [5]



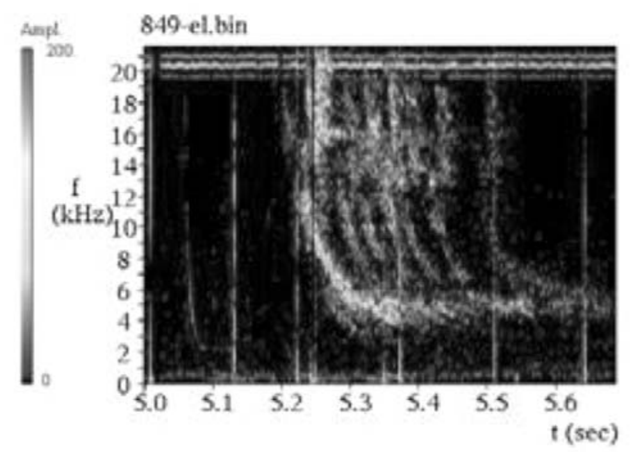
3.3 Direct verification for existence of guided whistlers

As it was mentioned in the Introduction, the appearance of whistlers at the Earth’s surface opens some questions, as these signals are excited by lightning discharges and through the magnetosphere they reach the conjugate (northern or southern) hemisphere. The modeling of the connecting out/in process is important in the study and observation of the high atmosphere, in determination of the plasma parameters of the magnetized plasma surrounding the Earth, etc. Because of the fundamental importance of this question we have started to install the globally extended AWDA network, with terrestrial VR-1 and VR-2 measuring stations compatible with our onboard instruments, which can detect, classify and fully automatically evaluate the whistlers in 24 hours a day [9-11].

The early investigations based on calculations of strictly monochromatic (sinusoidal), continuous signals in the VLF band by ray tracing methods and these results suggested the hypothesis, that the whistlers can only and exclusively reach the conjugate point of the geomagnetic field line, if there is a conducting tubular structure (duct) along the magnetic line, formed by the inhomogeneous plasma density [7].

This is not impossible, as the charged particles in the Earth’s atmosphere can easily move along the geomagnetic field lines, but this is hard for them into the

Figure 11.
SpW group detected by SAS2 on board of Compass-2 (16th of March, 2007)



rectangular direction. So an inhomogeneous density structure extends along the geomagnetic field lines in the magnetosphere.

But the large number of the whistlers would need the continuous presence of numerous “spaghetti”-like ducts with high stability. Another problem appears in the shape of the detected whistlers, which can be well described by free space propagation in anisotropic, magnetized plasma even in the approximate models or in the exact UWB models [1]. As a connection between the two possibilities, a shield-like structure of the ducting plasma inhomogeneities (“onion-skin”) can be also assumed in the high atmosphere, and this more stable and simpler structure ducts the whistlers along the magnetic field lines.

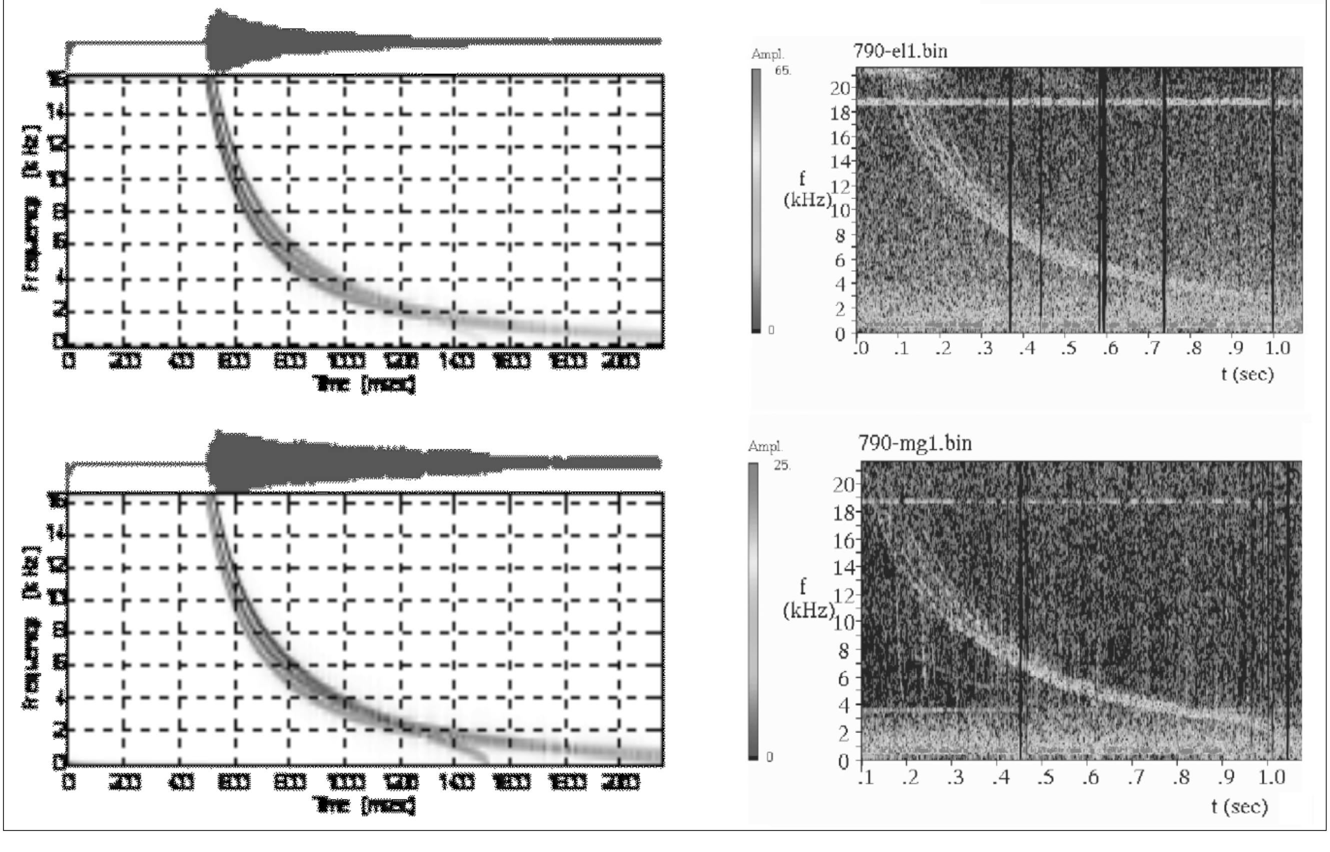
We successfully solved the propagation of UWB signals, impulses in rectangular waveguides filled by homogeneous, anisotropic, magnetized, cold plasma [4]. The results enlightened, on the one hand, that the wave pattern appearing during this propagation significantly differs from the free space propagation (as this was expected), on the other hand the shape of their spectrogram has no asymptotic limited wavelength, but the curvature of their spectral function turns to zero frequency in a finite time (this was unexpected). (Because of this unordinary result we have checked the model for two years, but no error was found in that.) This problem can only controlled by measurements, if the instrument can measure not only in the VLF, but in the ULF-ELF band also with high sensibility, and the convergence of the dynamic spectrum of the signal to zero can be well analyzed on the registered data. The SAS2-K2 fits well to these requirements.

A whistler group detected by Compass-2 on 28th of February, 2007 shows the form expected from our theoretical considerations (see *Fig. 12*). This is the first time, when a really ducted whistler can be presented. Using our theoretical model, we investigated the structure in which this signal form could appear. We can say on the basis of the calculations that the registered whistler propagated in a higher ducted mode along the magnetic field line. The ducting structure was not tubular, the signal propagated between surfaces, so the ducting structure was “onion-skin” like.

When we applied two surfaces in a 6 km distance from each other in our model calculation, the calculated and the measured data coincided with high accuracy. (The magnetic field is parallel with the bordering surfaces, and the direction of the propagation is parallel with the magnetic field.) The length of the propagation path is 30.000 km, the plasma frequency in the plasma model is 2.5 Mrad/s and the gyro-frequency is 900 krad/s.

The dynamic spectra of the first, second and third order modes can be seen in Fig. 12. As it can be seen in their dynamic spectra, the third order mode of the calculated signal coincides well with the measured signal. As a consequence of this result, it can be declared, that this signal is a ducted signal propagated in third mode

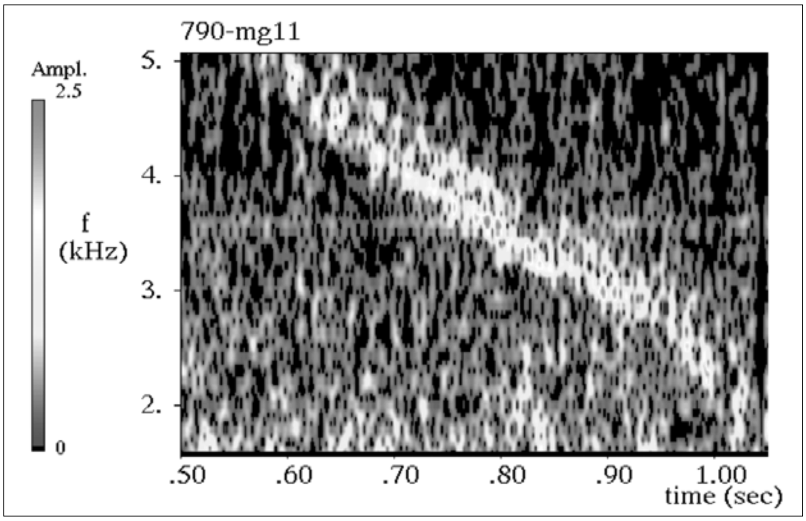
Figure 12.
First, second and third order modes of calculated UWB signals, in comparison with the dynamic spectrum of a whistler detected by Compass-2 on 28th of February, 2007



between two ducting surfaces. However, from these registrations the existence of the so-called ducts has not been verified, moreover, the presence of ducts is not indispensable for the propagation of whistlers. Furthermore it can be seen, that the whistlers having no significances of ducted propagation were not propagating in ducting structures. Because of this it is undoubtedly necessary to start intensive research in order to clarify the amount and the location of the ducted and the non-ducted propagation. (Reasonably, it is necessary to develop the UWB modeling of different propagation situations, too. This needs numerous theoretical breakthroughs as well.)

This unordinary, unusual signal form makes extensive, multilateral analysis and controlling necessary. Because of this we have examined the signal by digital matched filtering [6]. *Fig. 13* shows the FFT patters of the final section of the same signal, the matched filtered pattern of which can be seen in *Fig. 14*. The signal from and the method of its convergence to zero frequency (bending down) are unquestionable facts.

Figure 13.
FFT pattern of the final section of a measured ducted whistler



4. Summary

a) The technical probe of the Compass-2 and the on-board SAS2-K2 measuring system were successfully conducted.
b) The SAS2-K2 made it possible to get fundamentally new and important knowledge.
c) It is necessary to restart the investigation of the whistler-doublets, and to clarify the reason of the duplication in their spectra.
d) The SpW-s are applicable and effective tools in the continuous and global investigation of the dynamics of the lower border of the ionosphere.
e) We succeeded first time to demonstrate a ducted whistler signal, and to open the way for a more detailed investigation of the problem of ducted/non-ducted propagation, beyond the former theories on this topic.

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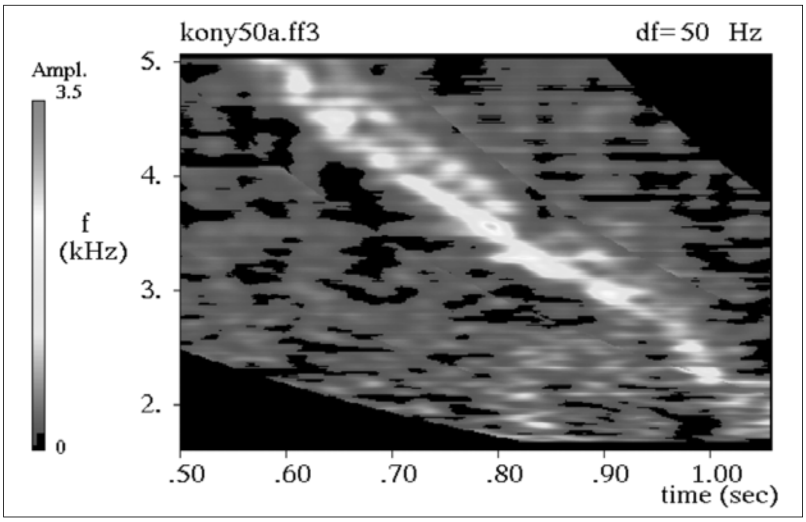
Figure 14.
Matched filtered pattern of the final section of a ducted whistler



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