Diagnostics of Space Plasma on Board International Space Station - ISS

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Electromagnetic emissions observed in the nearest Earth environment are a superposition of natural emissions and various types of man-made noises. Also, as a consequence of catastrophic events on the Earth surface such as: thunderstorm activity, earthquakes, volcanic eruptions, electromagnetic signals are registered on board low orbiting satellites. Therefore, a more accurate physical description of such a complex and dynamic system calls for a long term multi-point and multi-scales coordinated monitoring of space environment.
The aim of OBSTANOVKA experiment on board ISS station is to monitor and diagnose the electromagnetic radiation and property of plasma around station, to enable the development theory of near Earth plasma interaction and for application purposes in space technology. To achieve these goals the Plasma-Wave Complex (PWC) was designed and constructed. Radio Frequency Analyser (RFA) has been developed jointly by SRC PAS in Warsaw and by IRF in Uppsala. New design radio receiver for frequency band 0.1-15 MHz, with three electric and magnetic field component of antenna system on board ISS was designed to monitoring and investigate the ionospheric plasma property and artificial noises generated around ISS. The instrument can be also used for monitoring the electromagnetic ecosystem for space weather purpose. New digital technology of this instrument creates a excellent possibility for monitoring the electromagnetic emissions in space and time domain.

1 Introduction

The magnetosphere-ionosphere-thermosphere system is strongly affected by electric and magnetic fields, particle precipitation, heat flows and small scale interactions. Therefore, a more accurate physical description of such a complex and dynamic system as the near-Earth space calls for a comparative study. The magnetised solar-terrestrial space plasma is a highly non-linear medium, which exhibits many different types of turbulence and instabilities. Those emissions are produced mainly by natural perturbations, but some of them also have anthropogenic origin. A study of mass, energy, and momentum transport in the solar-terrestrial plasma is directly related to the study of space plasma turbulence. The primary objective of the proposed investigation is, therefore, to monitor the Earth's space environment and obtain a much more complete picture of electromagnetic plasma turbulence in different space regions than those available hitherto. In order to reach this goal we need multi point diagnostics of space plasma properties.
Therefore, we must design and build the next generation of instruments for space diagnostics, so that the desired temporal and spatial resolutions of recorded data could be obtained. The "OBSTANOVKA-1" stage, located on International Space Station ISS, will be carried out to provide a databank of electromagnetic fields and of plasma-wave processes of near-Earth space. To achieve this goal within the framework of international cooperation, Plasma-Wave Complex (PWC) instrument has been designed and constructed . The PWC complex contain

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the combined wave sensor, flux gate magnetometer, Langmuir probe, spacecraft potential monitor, plasma discharge stimulator, Correlating Electron Spectrograph CORES, Radio Frequency Analyzer – RFA, signal analyzer and sampler, data acquisition and Control Unit, block of storage of telemetry information, grounding support equipment. The PWC instrument will be located on Russian Segment of ISS in spring 2011. This complex set of instruments will give unique chance to:

- to determine spectral density of electromagnetic, electrostatic and magnetic fields fluctuations in a range of frequencies from fractions of hertz up to tens megahertz resulting from the influence of the various natural and artificial origin;
- to measure vectors of intensity of magnetic fields and field-aligned currents (FACs);
- to determine spectral fluctuation of the charged particles flows and density;
- to estimate the conformity of measured electromagnetic fields to the operational requirements of space engineering products and technology, service systems and useful payload.

The results will be used in the field of applied geophysics, ecology, space weather monitoring, and also for the updating of operational requirements used in space engineering and technology.

2 Selected electromagnetic emissions in near Earth environment

Natural plasma emission has become object of interest since first receive on the orbit of spacecraft has been done. The HF wave activity in the ionosphere are characterised by whistlers, Cherenkov radiation, electron cyclotron emissions, Langmuir, Bernstein, upper hybrid, O mode, X-mode, Z-mode, and broad-band emissions.

2.1 Pollutions detected in ionospheric plasma

The possibility that the ionosphere can be modified by powerful radio waves was first noted by Ginzburg and Gurevich [1,2]. The earliest space observations of ionospheric modification due to human activity were observed by the VLF wave measurements on board the Ariel-3 and Ariel-4 satellites, which showed an increased electron precipitation during high power VLF transmissions from the ground. The observed phenomena related to human activities, such as wave-particle interactions, precipitation of radiation-belt electrons, parametric coupling of whistler waves, triggering emissions, wave frequency shifts and spectrum broadening can be observed. Most of these disturbances were observed at lower frequencies and only a few were correlated with the disturbances generated by HF radio beams. Controlled injection of powerful HF radio waves has shown that non-linear interactions in the ionosphere give rise to enhance secondary electromagnetic radiation near a harmonic of the ionospheric electron cyclotron frequency.

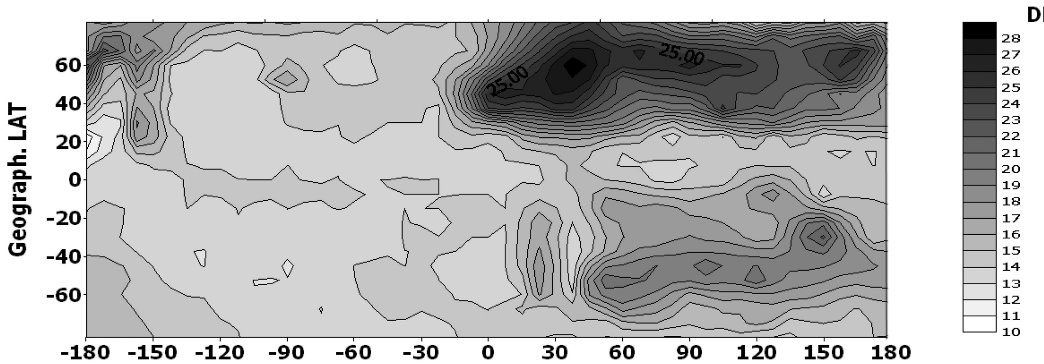

Fig. 1 The global distribution of the intensity of the electromagnetic emissions (integrated in the frequency range 0.1-14 MHz) recorded by SORS-1 instrument on board the Coronas-I satellite at 500 km altitude during night-time sector, under quiet geomagnetic conditions on 31 March 1994.

Experimental results from ionospheric HF pumping experiments in the night-side auroral region above Tromso in Norway, show evidence of the triggering of the local aurora [3]. It was suggested that these changes in the local ionospheric plasma are caused by the appearance of Alfvén turbulence and the formation of a local current systems. The Earth's ionosphere is subjected to various man-made influences. Electromagnetic emissions observed in the nearest Earth environment are a superposition of natural emissions and various types of man-made noises. The HF diagnostics on-board low-orbiting satellites in the topside ionosphere have detected increased intensities of about 20 dB/μV above the background radiation over the Euro-Asia region [4, 5]. As an example, in Fig. 1, the maps of HF noises before a strong geomagnetic storm on 31 March 1994 are presented for the 0.1-14 MHz band registered on-board CORONAS-I satellite. The enhancement of background radiation is prominent in the eastern hemisphere. The observed effect is markedly visible and stronger in the night-side ionosphere. Strong geomagnetic disturbances can broaden the area of the observed intensification of HF noises in comparison with the geomagnetic quiet time, but the intensity of the observed enhancement is not affected by geomagnetic disturbances. The model proposed by Rothkaehl and Klos [6] indicates that the observed broadband emissions in HF frequency range are a superposition of natural plasma emissions and man-made noises. Permanent pumping of the electromagnetic waves from the ground to the ionosphere and the penetration of energetic particles from the radiation belts can, as a consequence, disturb top-side ionosphere and lead to the generation of ionospheric plasma turbulence. Unfortunately, all HF frequency experiments were performed without good low frequency ionospheric plasma diagnostics. The examination of the data gathered on ARCAD-3 satellite helped to find the emissions in the VLF frequency range correlated it with broadband HF emissions detected over Europe and Asia region [7]. Assuming a simple model of two-component ionospheric plasma (cold background plasma and suprathermal electron beams) the coefficient of electromagnetic radiation created by the scattering of suprathermal electrons on the Langmuir or ion-acoustic turbulence was calculated. The theoretical analysis showed that this process is effective to create broadband emissions in the high frequency range. The consideration shows that the emitted power of observed broadband emission is in order of 10^{-18} Wm^{-2} Hz^{-1}. Moreover, theoretical analysis shows that the radiation belts can be a natural source of hot electrons, furthermore, the permanent pumping of strong electromagnetic waves into the atmosphere can cause an increased flux of precipitating energetic particles. The scattering of suprathermal electrons from the radiation belts on ion-acoustic or Langmuir turbulence is proposed as a mechanism of generation of broadband HF emissions.

2.2 The ionospheric plasma response to seismic activity

Recent monitoring of the space plasma environment has shown that the electromagnetic noises detected at the ionospheric altitudes can also be caused by cataclysmic processes occurring on the surface of the Earth [8]. A case study of HF-wave and gamma-ray measurements performed on-board CORONAS-I satellite shows enhancements of the whistler wave activity and soft gamma-ray fluxes, simultaneously, in ionospheric plasma over the seismic centre [9]. Parallel to the well-known effects related to the seismic activity in the topside ionosphere, such as small-scale irregularities generated by acoustic waves and large-scale irregularities generated by anomalous electric fields, the modifications of magnetic flux tubes are also common features [10]. The intensification of precipitating high-energy electrons and protons with simultaneous excitation of ELF and VLF noises above the earthquake epicenter was previously registered in the top side ionosphere as well. So it seems that changes in the magnetic flux tube topology can lead to increased precipitation of energetic electrons and, as a consequence, can yield excitation of the HF whistler mode very close to the local electron gyrofrequency. The precipitating energetic electrons generate the excitation of the HF whistler mode emission, via the incoherent Cherenkov mechanism. The proposed process has a cascade-like character [9].

2.3 The atmospheric discharge processes

Theoretical investigation and some observation campaigns show that whistler signals, generated by lightning discharges, can contribute significantly to the energetic balance in radiation belt regions. However, observations of hard X-rays associated with electron precipitation caused by lightning flashes are rare. Electromagnetic energy originating in lightning discharges escapes into the magnetosphere and propagates as a whistler mode wave. The whistler mode scatters energetic electrons, thereby generating bremsstrahlung hard X-rays. The theoretical investigation demonstrates that near the equatorial plane of the magnetosphere, whistler components above the nose frequency can accelerate energetic electrons. This acceleration takes place when the gyro-resonant electrons are trapped by the wave field. The acceleration rate in this regime is much larger than stochastic acceleration in the untrapped regime [11]. Highly anisotropic distributions of van Allen radiation belt electrons with 'pancake' pitch angle distributions can result from such an acceleration. As a results of such wave plasma interaction the enhancements of emission below electron cyclotron frequency can be observe.

3 Radio Frequency Analyzer (RFA) on board ISS

The Radio Frequency Analyzer (RFA) is a joint Polish Swedish development effort of high-frequency (HF) radio wave instruments, designed with the objective to diagnose electric and magnetic vector fields, $\mathbf{E}$ and $\mathbf{B}$, respectively, in space plasma Fig. 2. The instrument characteristic parameters are listen in Table 1. The main purpose of this instrument is to measure natural and man-made electromagnetic emissions in the frequency range from 100 kHz up to 15 MHz. This frequency range covers high frequency whistler waves, Langmuir and upper hybrid modes of the natural space plasma emissions. Consequently this will allow to investigate following main topics:

- understanding the consequence of human activity in the nearest space environment
- description global changes in the ionosphere-magnetosphere system
- selection and description artificial and natural noises detected in the ionosphere
- analyse interaction between the ISS infrastructure and surrounding plasma
- diagnose changes of detected signals on the board of **ISS** during discharges process related to the Space Shuttle docking.

Table 1 Instrument main characteristic

General	
Mass [kg]	2.2 $(+10\%/-30\%)$
Power [W]	12.0 $(+20\%/-30\%)$
Voltage [V]	28.0 $(\pm 4[V])$
Dimension [mm]	$190.0 \times 150.0 \times 115.0$
Operational	
Discrete commands	1 command (ON/OFF)
TC stream	2-3 commands /day (session)
TC packet length	16 bytes
TM stream	$\sim$ 1 kb/ min ($\sim$ 20 bytes/sec)
TM packet length	256 byte
Internal memory buffer	256 kB-min 1 hours registrations
Functional	
Frequency range	100.0 [kHz] to 15.0 MHz]
Spectrum resolution	10.0[kHz] (0.1- 1.0MHz) 100 [kHz] (1.0-15.0 MHz)
Dynamic range [dB]	75.0
Data sampling rate [MHz]	40.0
Magnetic antenna noise level	$\sim$ -30.0 [dBpT/$\sqrt{Hz}$]
Electric antenna noise level	$\sim$ -27.0 [dBuV/m$\sqrt{Hz}$]

RFA analyser uses two antenna sets mounted on separate booms: a three-axial electric dipole antenna (1m from tip to tip), and a three-axial magnetic loop antenna (Fig. 3). The electric antennas are short relative to the wavelength and thus behave as high impedance capacitive loads. This antennas have its own, directly connected, low noise preamplifiers, which transform variable impedance of antenna to constant (Z=50 Ω) connection cable impedance. The gain of preamplifiers is fixed ($\sim$ 20 dB) to obtain relatively good signal to-noise ratio and to avoid signal distortion or saturation. Next, the signals come to ”Analog Front End” module where, after antialiasing filtration (18-order passive LC 18 MHz Butterworth low-pass filter - LPF), are distributed to vector receiver VRX and wave recorder WRC modules. Each analog input channel includes a programmable gain amplifier. The radio receiver VRX boards is fully equipped with three parallel channels, making vector field measurements of three component of electric or magnetic fields. VRX has three fully programmable digital mixers, which convert the digitized signal to a baseband signal by means of a numerical oscillator and a digital filter chain. The mixers can be set to perform digital frequency sweeps, which is the normal mode of operation or to perform digital down conversion to baseband at a fixed centre frequency, allowing the VRX to function as a narrowband I/Q (in-phase/quadrature-phase) receiver. The mixer reduces the sampling rate and corresponding bandwidth of the digitized signal, which also give an enormous increase in dynamic range. The dynamic range is increased by the reduction of sampling rate and averaging. We have chosen a 16 bit output from the mixers, which corresponds to a dynamic range of 96 dB. The raw VRX output data is formatted as a time series of 16 bit complex vectors (I1,Q1;I2,Q2;I3,Q3). For frequency sweeps, the centre frequency is changed in each time step. During one measurement cycle, the VRX module produces 6x1024, 16-bit samples (12 kB), in the form of real and imaginary in-phase and quadrature-phase (I, Q) pairs, for each frequency step. As this amount of data exceeds the capacity of the telemetry system, a special data compression and encoding algorithm was implemented in the CPU microprocessor. The main characteristics of the VRX are given in Table 2.

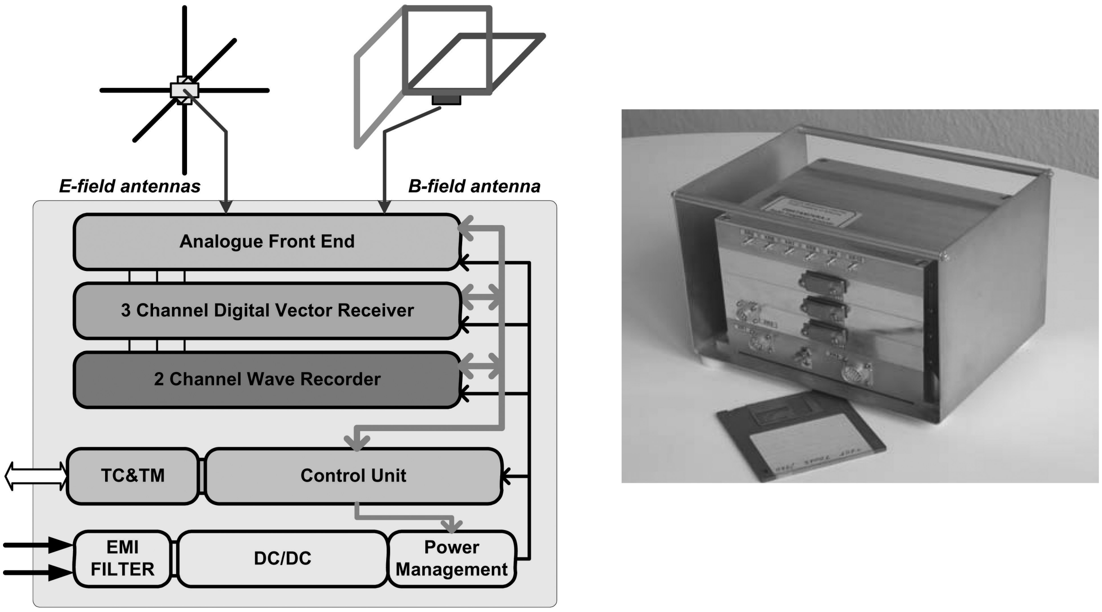

Fig. 2 Block diagram and photograph of RFA analyser.

Table 2 VRX main characteristic

Power	4.0 W (+5.0V & +3.3V)
Size	$160 \times 150 \times 25$ mm
Frequency range	0.10 - 15.0 MHz with 50dB aliasing rejection
AD converter	14 bit @ 40Ms/s
Digital mixer	16bit output I & Q baseband (100 dB precision)
Bandwidth	selectable from 1Hz to 196KHz (-3 dB) more or less continuous
Center frequency	is switchable every 50 μs
Number of channels	3 parallel inputs
Digital interface	synchronous serial

The wave recorder module WRC provides two channels of ADC converters (12bit, 40 MSPS). Acquisition and conversion are controlled by hardware logic according to pre-programmed mode of operation. The sampled data, in digital form are temporary stored in internal buffer. On-board memory can be used as a circular buffer or as a single sweep, depending on the mode of operation. Then, data are processed, analysed and compressed by on-board digital signal processor. The output data could be the raw waveforms, compressed waveforms or computed set of numbers (wave parameters) depending of employed algorithm. The measurement process is controlled by the Control Unit (CU), which is based on a virtual MicroBlaze 32-bit microprocessor implemented in a field-programmable gate array (FPGA). All the required control logic like: receiver module data link, telemetry interface, and instrument internal timer are also implemented in FPGA.

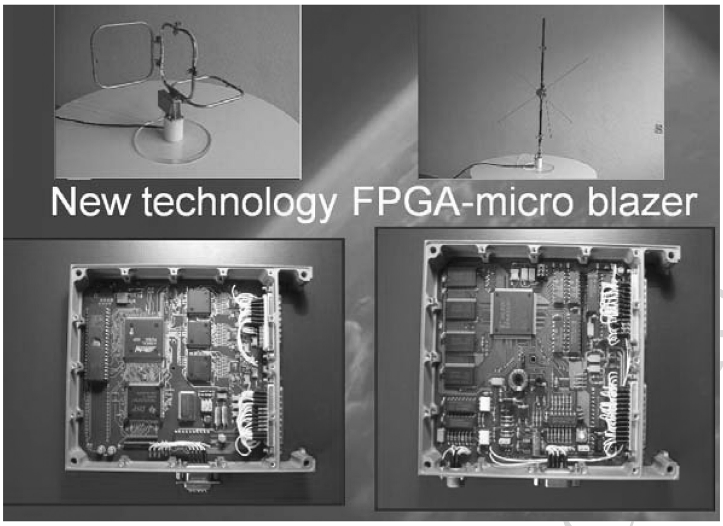

Fig. 3 Electric and magnetic field antenna of RFA and VRX and WRC receiver module.

In the operational configuration the instrument produces a sequence of dynamic spectra of EM fields vectors along the orbit. After switching on, the RFA automatically performs an internal self-test procedure and forms first housekeeping (HK) TM packet, then starts the default measuring cycle. The several types of measurement cycles could be commanded to perform preprogrammed sequences. The measured data (one set of spectra for one cycle) are stored in internal memory where the telemetry blocks are formed. RFA has five main modes of operation, OFF: The power supply is completely switched off.

The processors will boot themselves when power is switched on again, STANDBY: Power saving mode, only HK packets are produced, DEPLOYMENT: Antenna deployment mode, OPERATION: Fully operational mode, CALIBRATION: Internal instrument (receivers) calibration. The tasks to be handled by the on-board software are: internal mode control, switching and commanding of measurements module, tele-command (TC) verification, validation and execution, data collection and buffering; telemetry (TM) packet formatting and sending; housekeeping data collection. The serial TM interface support bi-directional asynchronous data transmissions using balanced digital voltage interface (RS-422), to provide data rate up to 19200 kbit/sec. The DC/DC module provides galvanic insulation between primary power lines, secondary power lines, and the satellite structure. Any persistent voltage on the main bus power line in the range between 24.0 V and 32.0 V, including a short circuit of the power line, is harmless to the instrument.
As a consequence that the RFA instruments will be located on the Russian Segment on ISS only occasionally for transmission to the Earth radio line of a radio amateur range (145 and 435 MHz), will be available. All data gathering in the frame of "OBSTANOVKA" experiment will be stored on the hard disk (not a part of instrument) with capacity of few hundred Gbytes. It is estimated that this volume will be stored during $\sim$ 180 days, i.e. each half year the hard disc will be changed and delivered to the Earth by nearest expedition. The natural ionospheric radiation range around the characteristic plasma emissions in HF are at the level of 10^{-10} W/m^{-2} Hz^{-1}, while the noises related to solar radio emissions are at the level of 10^{-16} W/m^{-2} Hz^{-1}. Theoretical considerations show that the emitted power related to human activity is at the level of 10^{-18} W/m^{-2} Hz^{-1}. Observations previously carried out on the low-orbiting satellites MAGION-3, CORONAS-I indicate that the sensitivity of our instruments is around the above values.

4 Summary

A description of near Earth space plasma behavior is a subject of investigation, both as a constituent of the geophysical environment, and as an element of physical processes in which particles and waves participate. Recent investigations have shown that also human activity can perturb the near-Earth space environment. They indicate that the observed significant enhancements of electromagnetic turbulence over Europe and Asia are caused by permanent pumping of electromagnetic waves into the ionosphere by a system of broadcasting stations. This effect can be intensified by precipitation of energetic particles from the radiation belts. The correlation between earthquakes and anomalous bursts of trapped particles, precipitating from the lower boundary of inner radiation belt was observed as an intensification of HF wave activity by in-situ topside experiments. It seems that changes of the magnetic flux tube topology, correlated with seismic activity, can lead to an increase in the precipitation of energetic electron fluxes and, as a consequence, lead to an excitation of the HF whistler mode. Theoretical investigations and some space-borne and ground-based experiments show that natural whistler waves generated by a lightning discharge in the Earth's atmosphere can accelerate the trapped radiation belt electrons. In order to better understand the problems discussed above, we urgently need multi-point and multi-scale measurements carried out by newly designed instruments with an improved temporal and spatial resolution. The new radio analyser located on the board of ISS can be a test bead for future new instruments devoted for monitoring 3 component of E and B field in space plasma. The RFA radio analyser is part of Obstanovka experiment on ISS. This experiment should help us to achieve a comprehensive understanding of the combined natural and anthropogenic plasma processes and their interactions with the geospace. Moreover the community of users potentially benefitting from these investigations is found in the civilian and the defense sectors and include the aviation industry, the satellite industry, the HF equipment manufacturers, the HF broadcast and communication services, and the trans-ionospheric radio operation (GPS, GLONASS, Galileo).

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