Cross-sectional: MECHATRONICS, RADARS, CONTROL SYSTEMS;

SOME ASPECTS OF DEVELOPING A MULTIPURPOSE RADIO SYSTEM FOR MONITORING THE GEOSPACE

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Abstract:

Hardware and software principles of building a multipurpose radio system for monitoring the geospace are considered. It is shown that Ettus Research USRP is the most suitable platform for such system. A structure of a multipurpose radio system for monitoring the geospace and developed software for VISCR2 ionosonde (based on USRP N200) as a part of this system are presented. The first results of testing new sowtware are shown.

Keywords: *radar, software defined radio*, *ionogram, ionosonde, ionosphere, geospace*

1. Introduction

Monitoring the geospace using ground-based radars allows to obtain unique information during various natural phenomena in the near-Earth environment (like magnetic storms, meteoroids entering the atmosphere) and on the Earth (for example, earthquakes), as well as anthropogenic events (rockets launches, powerful explosions, and nuclear tests).

The Institute of Ionosphere conducts studies of processes in geospace using mainly such ground-based remote sensing instruments as very high frequency (VHF) incoherent scatter (IS) radar and coherent high frequency (HF) radar for vertical sounding of the ionosphere (ionosonde). These radio systems are installed in the Ionospheric Observatory located near the town of Zmiiv, Kharkiv region. The first experimental IS radar and ionosonde data were obtained in 1972, and since then, the hardware and software components of these radio systems are continuously being modernized. The updated components include radio transmitting and receiving devices, analog-to-digital converters (ADC), computer data processing systems, and programs are running on them (Emelyanov and Zhivolup, 2013).

In 2012, a new data acquitting and processing system for IS radar was developed. It is based on two four-channel ADC E20-10 modules and which allowed not only to duplicate existing IS radar data processing systems (“Kentavr” and multi-channel PC based correlator), but also to expand radar capabilities in general (Bogomaz et al., 2017a; Bogomaz et al., 2017b). The improvements are as follows:

1. The maximal sampling rate has increased significantly, up to 10 MHz. This allowed to obtain the correlation functions of the IS signal with a step of 5.1 μs (previous processing systems used a step of 30.6 μs), which is necessary to increase the accuracy of determining the density of hydrogen and helium ions in the upper ionosphere.
2. The system includes a high-performance modern PC that is capable of processing a large amount of data coming from the E20-10 module via a high-speed USB 2.0 bus (in previous processing systems, data ware transmitted via the parallel LPT port to low-performance personal computers, in which part of the information was intentionally ignored to support real-time operating mode), as well as visualize data and processing results on high-resolution displays (computers in previous processing systems worked in graphics mode 640 by 480 pixels with a palette of 16 colors).
3. The developed E20-10-based data processing system can be quickly adapted for specific experiments on the Kharkiv IS radar. For example, work in the such modes was implemented:

- Probing the ionosphere with paired pulses for the study of the middle and lower ionosphere (Bogomaz et al., 2018).
- Using two radar antennas (zenith-directed NDA-100 with a diameter of 100 m in active mode and full-steerable PPA-25 with a diameter of 25 m in active mode) simultaneously for studying processes in the lower ionosphere (Emelyanov et al., 2018).
- Using two radar antennas (NDA-100 in active mode and PPA-25 in passive mode) simultaneously for studying processes in the lower ionosphere (Emelyanov et al., 2020).

Although the developed data acquitting and processing system based on E20-10 ADC module has allowed obtaining much more information about the processes in geospace, it needs further improvement in order to reduce energy consumption and optimize data processing methods. But analysis of publications on radars developed recently has shown that it is more appropriate to develop a new, multi-purpose radio system that will determine the parameters of the geospace and objects in it to conduct sounding at HF and UHF radio bands used in vertical sounding and incoherent scatter techniques, with generating, receiving and signal processing using computer software and hardware systems.

2. Prototypes

All monitoring radio systems being developed today belong to the class of software defined radio (SDR).

Low-cost HF software defined radar called the Penn State Ionospheric Radar Imager (PIRI) for use in ionospheric research is described in (Bostan et al., 2019). It is composed of commercial-off-the-shelf components and utilizing open-source software (GnuRadar) to perform pulse generation, pulse coding, downconversion, data acquisition, and signal processing. This system has better time resolution than ionosondes, is highly customizable, and it can be used to resolve the fine details of ionospheric features, as well as providing long-term ionospheric measurements at fixed frequencies.

A prototype IS radar system of Nanchang University, including system components and data processing, was introduced in (Li et al., 2020). This radar operates at frequencies from 490 to 510 MHz (i.e. in UHF range) and transmits just 100 kW peak power pulses, accounting for only 10% of the existing IS radars. However, this is enough to obtain reliable data up to an altitude of about 300 km.

SDR-based ionosondes designed recently are described in (Barona Mendoza et al., 2017; Zalizovski et al., 2018; Kalita et al., 2019). They operate in an active mode in contrast to a radio system presented in (Rejfek, 2019) working in a passive mode.

The above systems can monitor geospace as a media and obtain its characteristics and information about processes taking place there. Another objective is monitoring objects in the near-Earth space. An example of system for such purpose is described in (Holdsworth, 2020).

It is important to note that significant portion of systems listed above are built on USRP (Universal Software Radio Peripheral) developed by Ettus Research (National Instruments Corp., USA). This platform is a low-cost SDR that is commonly used for rapid prototyping and complex system design.

Table 1 summarizes the results of the review.

Table 1

Comparison of systems for monitoring the geospace

System (paper)	Range (HF, VHF, UHF)	Mode (active/passive)	Target (media/objects)	Ettus Research USRP is used (yes/no)
(Bostan et al., 2019)	HF	active	media	yes
(Li et al., 2020)	UHF	active	media	no
(Barona Mendoza et al., 2017)	HF	active	media	yes
(Zalizovski et al., 2018)	HF	active	media	yes
(Kalita et al., 2019)	HF	active	media	no
(Rejfek, 2019)	HF	passive	media	yes
(Holdsworth, 2020)	VHF	active	objects	no

As it can be seen, using of USRP platform is advisable for developing a new multipurpose radio system for monitoring the geospace.

3. Hardware

Analysis of existing systems for monitoring the geospace has given an opportunity to build a diagram which can be used for developing a multipurpose system based on multiple USRPs (Figure 1). The most suitable are USRP N2xx series (N200 and N210) which are recommended for Multiple-In-Multiple-Out (MIMO) applications. Two USRPs can be synchronized using a MIMO cable and if there is a need to synchronize more devices, the Ettus Research OctoClock can be used. To synchronize all the parts of the system, using the GPS-disciplined oven controlled crystal oscillator (OCXO) is strongly recommended. Ettus Research distributes an upgraded version of the OctoClock CDA-2990, which includes an internal GPS-disciplined OCXO (OctoClock-G CDA-2990).

Analog frontends include attenuators, filters, low-noise amplifiers for receiving signals, as well as filters, antenna switchers, power amplifiers, and various measurers for transmitting signals. The frontends work with receiving and transmitting HF and VHF antennas and interact with USRPs through radio frequency (RF) and digital interfaces. Digital interfaces are used for controlling antenna switcher, attenuators and obtaining information about power transmitted and consumed, standing wave ratio (SWR), and heatsink temperature.

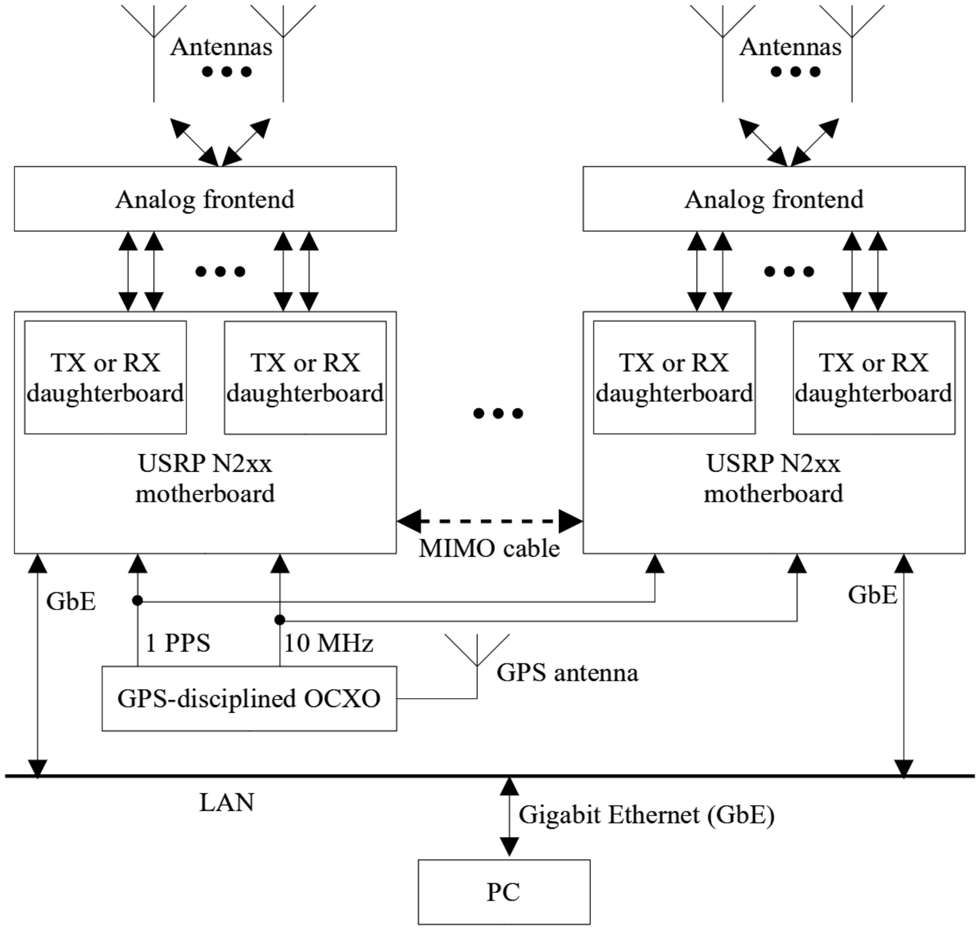

Figure 1. A structure of a multipurpose radio system for monitoring the geospace.

Depending on the range and operating mode, USRP can contain up to two daughterboards. It is supposed that the multipurpose radio system for monitoring the geospace is being developed will use boards listed in Table 2.

Table 2

USRP daughterboard can be used in the system for monitoring the geospace

Daughterboard	Frequency range	Mode
LFTX	DC–30 MHz	transmitting
LFRX	DC–30 MHz	receiving
BasicTX	1–250 MHz	transmitting
BasicRX	1–250 MHz	receiving

The USRPs are controlled by high-performance desktop personal computer through gigabit Ethernet local area network (LAN). Specification of a computer which is used currently for developing and testing is shown in Table 3.

Table 3

Specification of the computer used for developing and testing a multipurpose radio system for monitoring the geospace

Parameter	Value
CPU	Intel Core i5-8500
CPU frequency	3.0 GHz
CPU cores/threads number	6/6
RAM	16 GB, DDR4, 2666 MHz
SSD	256 GB
HDD	1 TB

4. Software

USRP Hardware Driver (UHD) is available on Linux, Windows, and Mac OS. Linux Mint 19 was chosen for the system development. UHD version 003.007.003 together with Boost C++ library version 1.55.0 are used. This combination showed a good stability in work. C++ programming language was chosen for software development.

A program for an active multipurpose radio system for monitoring the geospace should form arrays describing signal is being transmitted, synchronize receiving and transmitting, and store data containing received signal to files on disk. Data processing is performed using software written in Python programming language.

An example of a radio system for monitoring the geospace is ionosonde. It is a HF radar that sounds the ionosphere by numerous of frequencies and produces dependency of virtual height of the reflection from ionosphere layers on frequency. Virtual height *h*' corresponds to time from the radar to the ionosphere and back if velocity of signal propagation equals to speed of light (the speed of a radio wave propagation in ionosphere is less than speed of light, depends on electron density in the media, and it is unknown in this task). A typical vertical ionogram obtained on October 9, 2019 by VISRC2 ionosonde is shown on Figure 2.

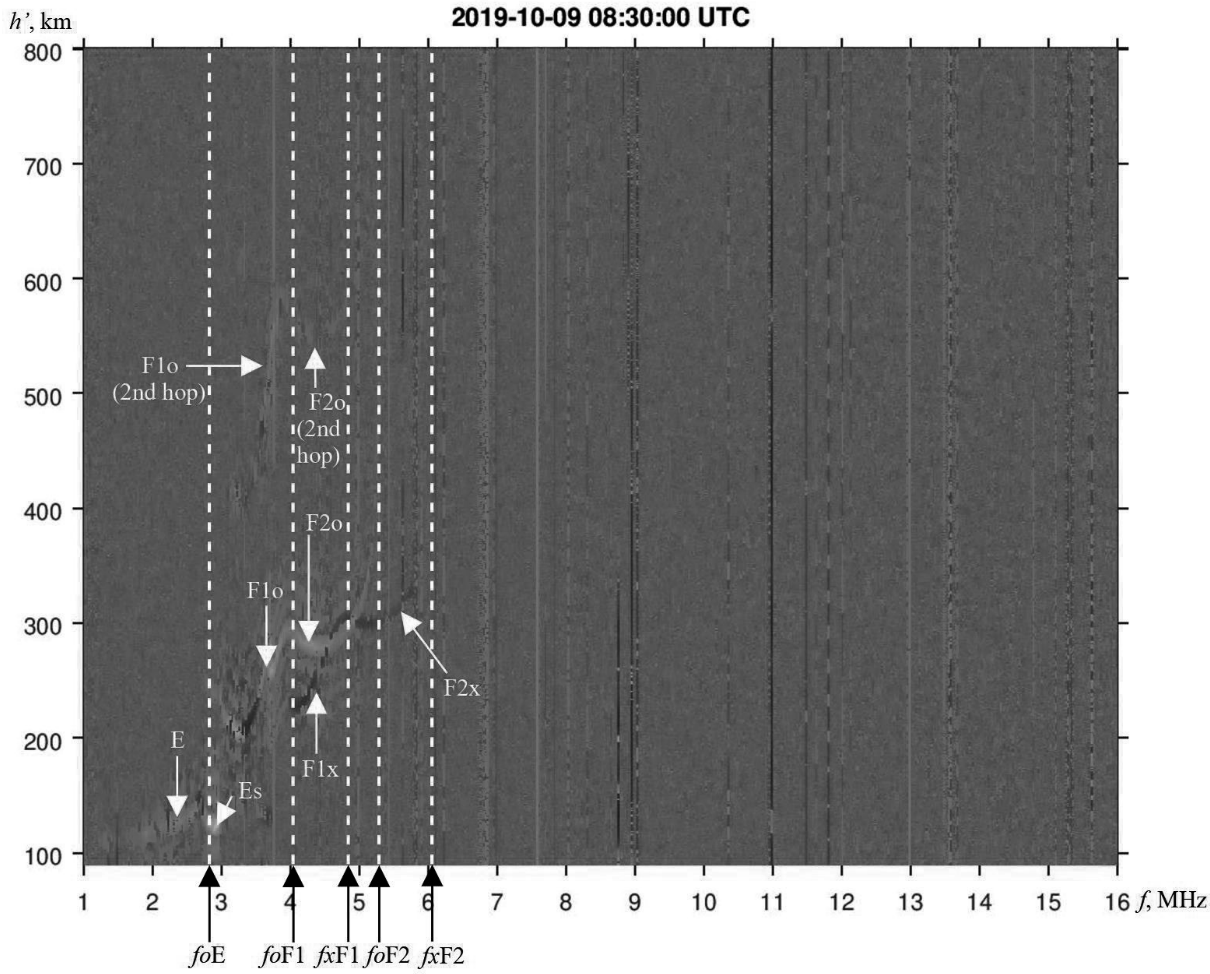

Figure 2. A typical vertical ionogram obtained on October 9, 2019 by VISRC2 ionosonde installed in the Observatory of the Institute of Ionosphere

VISRC2 ionosonde is developed and built at the Space Research Center in Warsaw, Poland, and installed in the Observatory of the Institute of Ionosphere (49.676° N, 36.292° E). It uses USRP N200 for generating and receiving signals. Software of the ionosonde is written on C++ and GNU Octave and is running in Linux operating system. On the ionogram shown on Figure 2, traces of E, Es, F1, and F2 ionosphere layers are clearly seen. Ionosonde is able to separate ordinary and extraordinary ("o" and "x" indices respectively on Figure 2). Using critical frequencies foE, foF1, fxF1, foF2, and fxF2, it is possible to calculate electron densities in maxima of ionosphere layers E, F1, and F2. A limitation of the ionosonde was its low flexibility. VISRC2 software initially was able to produce phase-shift keying pulses with constant code and element width (7-bit Barker code, 70 µs per element) and process signals obtained in the result of sounding the ionosphere by these pulses. Therefore a new program that manipulates VISRC2 ionosonde was developed. This program is a software base of the multipurpose radio system for monitoring the geospace is being developed in the Institute of Ionosphere.

5. The first results

Testing the new program was carried out on August 11, 2021.

Sounding using 7-bit Barker (+1, +1, +1, −1, −1, +1, −1) code has given an ionogram shown on Figure 3.

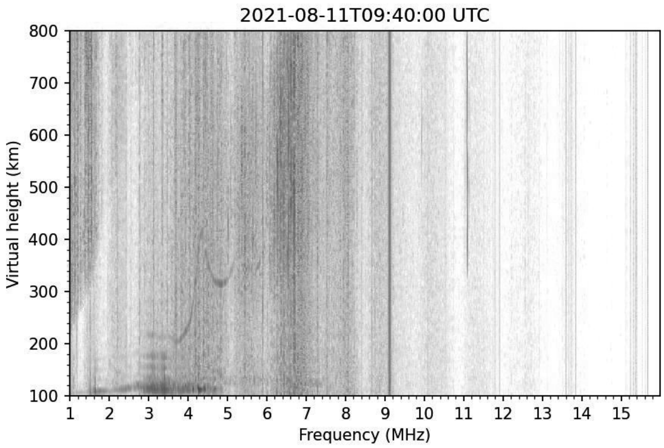

Figure 3. An ionogram obtained by VISRC2 ionosonde with a new program developed for using in the multipurpose radio system for monitoring the geospace

It can be seen that there are good visible traces of E, Es, F1, and F2 ionosphere layers (ordinary components) and extraordinary component of Es layer trace.

Ionograms obtained by sounding using 13-bit Barker code (+1, +1, +1, +1, +1, −1, −1, +1, +1, −1, +1, −1, +1) and different element width are shown on Figure 4.

Using a long sounding pulse (i.e. when element width is 70 μs and pulse width is 13 × 70 = 910 μs) leads to possible loss of information from lower altitudes (up to 136.5 km). Using sounding pulses of 40 μs and 30 μs width gives minimal altitudes of 78 km and 58 km respectively.

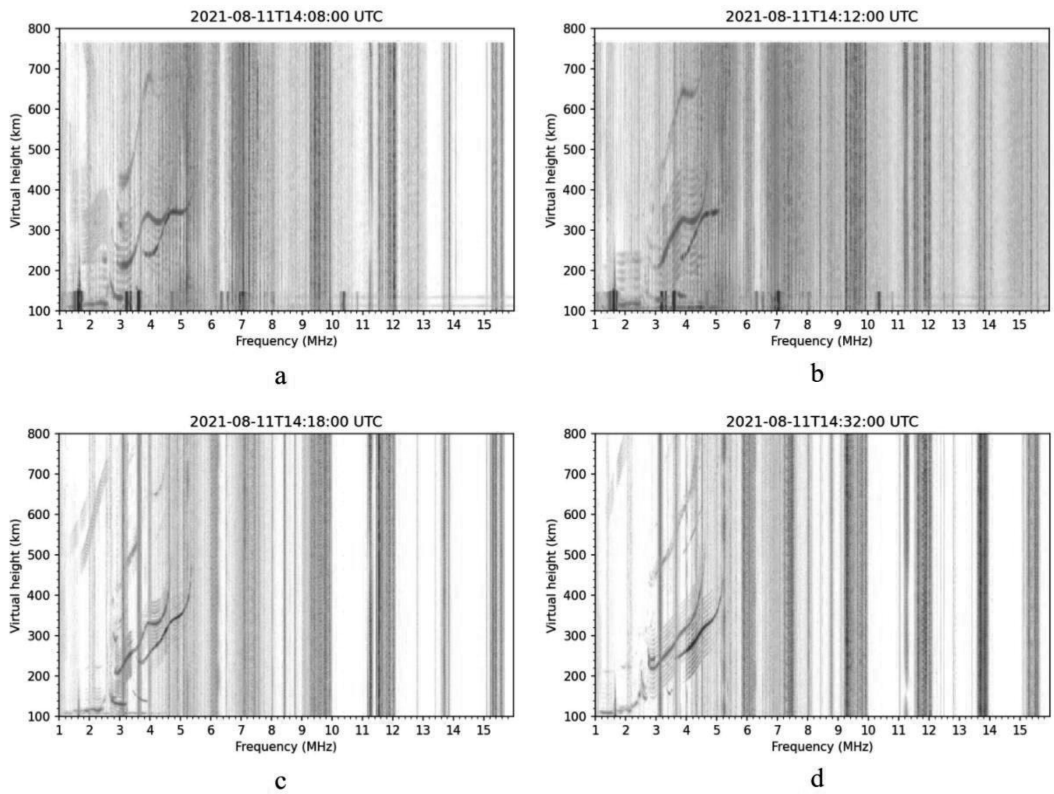

Figure 4. Ionograms obtained by VISRC2 ionosonde with a new program developed for using in the multipurpose radio system for monitoring the geospace. 13-bit Barker code is used. Width of each element is 70 μs (a, b), 30 μs (c), and 40 μs (d). Number of sounding pulses on every frequency is 8 (a, c, d) and 16 (b).

6. Conclusions

Developing a multipurpose radio system for monitoring the geospace has good perspectives due to its flexibility and mobility at the same time. It will allow decreasing energy consumption by radio monitoring hardware and improving quality of information about the near-Earth space and objects there.

A structure of the multipurpose radio system for monitoring the geospace being developed in the Institute of Ionosphere is shown. New software that is a part of this system was developed and successfully tested. Next steps in improvement the developed program are using decoding algorithm that produces zero sidelobes suggested by Lehtinen et al. (2004), noise reduction, and removal of radio frequency interference.

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