Investigation of atmospheric high-energy phenomena onboard International Space Station: microsatellite "Chibis-AI" and VHF interferometer "Kite"

M. Dolgonosov, V.Gotlib, V. Karedin, A. Kosov, V. Nazarov, L. Zelenyi, S. Klimov

Space Research Institute of the RAS, Moscow, Russia

Abstract. Space Research Institute of the RAS is gradually developing its own program of the space-born experiments to study high-energy process in the terrestrial atmosphere. Terrestrial Gamma-ray Flashes (TGFs) and Compact Intracloud Discharges (CIDs) are among principal goals of the scientific research of the program. To conduct research is supposed to produce new «instruments»: microsatellite «Chibis-AI» and VHF interferometer «Kite» aboard International Space Station. Microsatellite "Chibis-AI" will be constructed on the platform originally designed at the Special Engineering Department of Space Research Institute of the Russian Academy of Sciences in 2011. It's forerunner «Chibis-M» was successfully launched in 2012. Expected date of «Chibis-AI» launch is 2019. The principal idea underlying design of the scientific payload of the microsatellite "Chibis-AI" is the joint observations of the TGF and CID emissions by different detectors installed onboard: Radio Frequency Analyzer (RFA) and Neutron and Gamma spectrometer (NGS). RFA contained two passbands in the range 15-26 and 26-48 MHz with a digitization at 96 megasamples/s. NGS is based on LaBr3(Ce3+) crystal with the maximum achievable today spectral resolution and efficiency of gamma rays in the energy range 100 Kev – 10 MeV among scintillation crystals. The microsatellite orbit will be circular with inclination 51° with initial elevation above sea level around 550 km. VHF interferometer «Kite» to be installed in 2019-2020 aboard ISS. To implement interferometric scheme 4 antennas will be installed on the ISS surface. The passband of the instrument will be ~ 50-100 MHz. Technical details of both experiments, its current stage and features as well results of the previous experiment «Chibis-M» will be discussed.

1. INTRODUCTION.

Nature of gamma-ray flashes, bursts of powerful VHF radiation and lightning activity in the Earth's atmosphere at present is largely unclear. This problem of physics of high-energy processes, despite of the long history of studies of each of these events individually, currently does not have a comprehensive solution. To date, it was accumulated a significant amount of data on high-energy processes in the Earth's atmosphere such as Thunderstorm Ground Enhancements and Terrestrial Gamma-ray Flashes (TGE and TGF respectively). The greatest number of TGFs has been detected by the orbital mission RHESSI [*Grefenstette et al.*, 2009] and GBM/Fermi [*Briggs et al.*, 2010]. In addition, TGF was recorded in the space experiments «Agile» [*Marisaldi et al.*, 2010; *Tavani et al.*, 2011], LAT/Fermi [*Grove et al.*, 2013], as well as it was detected by DRGE detectors on the satellite "Vernov" [*Bogomolov et al.*, 2016]. With regard to Thunderstorm Ground Enhancements (TGE), on Aragats mountain stations (Yerevan Physics Institute, Armenia) the catalog of TGE was formed with typical characteristics of thunderstorm activity, as well as the model of TGE was proposed [*Chilingarian*, 2014]. However, many properties of TGE, important for the construction of self-consistent model of high energetic phenomena in the atmosphere have not yet been elucidated. In particular, it is not defined the electric structure of thunderstorm clouds during TGE/TGF events, and conditions that determine the intensity and the energy spectrum of gamma-ray bursts and their directional pattern, source size and frequency of occurrence. In addition, the open question is the mechanism of formation and relation TGF with the special powerful short bursts of VHF emission associated with compact intracloud discharges [*Smith et al.*, 1999a, 1999b].

The starting point of cosmic investigation described above phenomena in VHF range were projects ALEXIS/Blackbeard [*Massey and Holden*, 1995; *Massey et al.*, 1998] and FORTE [*Jacobson et al.*, 1999; *Suszcynsky et al.*, 2000]. The last satellite was designed at Los Alamos National Laboratory in cooperation with the Laboratory of Sandia. Initially, the satellite was designed to detect nuclear weapon testing, and only later became also be used to study lightning activity from space. The main instrument of this satellite was the Radio Frequency Analyzer (range 30-300 MHz), having armed with two-polarization antenna, allowing to explore the "ordinary" and "extraordinary" modes of radio waves passing through the ionosphere. Triggering scheme implemented in RFA has been used to prevent its activation from artificial signals. One of the fundamental results on these satellites are detailed study of the so-called TIPPs (Transionospheric Pulse Pairs), discovered by satellite ALEXIS [*Massey and Holden*, 1995]. The name comes from the occurrence of two separated pulses, each a few microseconds long, separated by tens of microseconds. These emissions' instantaneous power was at least tenfold greater than that of VHF signatures ordinarily accompanying lightning. As it was shown in [*Jacobson et al.*, 1999, 2011; *Suszcynsky et al.*, 2000; *Jacobson and Light*, 2012] the origin of the pairs is closely related to the direct and reflected signal from an electrical breakdown in the upper atmosphere.

In recent years, opportunities for experimental research significantly expanded by successful launching into orbit a microsatellite "Chibis-M" (January 2012) [*Zelenyi et al.*, 2014; *Dolgonosov et al.*, 2015]. The set of scientific instrumentation consisted of the following devices:

- Roentgen-gamma detector (0.02-1 MeV);
- Ultraviolet and infrared detector (180-400 and 650-800 nm);
- RF analyzer (26-48 MHz);
- Digital optical camera (spatial resolution of 300 m);
- Magnetic wave complex (0.1-40 kHz): induction magnetometer and ferroprobe magnetometer.

A special role was assigned to RF analyzer (RFA) as a fast instrument aboard Chibis-M (~10 ns resolution). RFA played the role of a trigger to switch on all other instruments for event recording. It was also implemented triggering scheme similar to those used by RFA onboard FORTE. The benefits of the scheme allowed to separate short (lasting a few microseconds) pulses of TIPPs from signals of anthropogenic origin. During Chibis-M operations it was detected almost 400 TIPP-like events. But in spite of stable performance of Roentgen-gamma detector it was not accomplished no one simultaneous measurement of the TGF event in radio and gamma-ray ranges. One of the main methodological problems revealed in frame of Chibis campaign was inability to determine the location of TGF/TIPPs emitter by one-point measurement. To resolve these issues, it was proposed new payload of the microsatellite «Chibis-AI» and VHF interferometer «Kite» onboard International Space Station.

2. THE CHIBIS-AI MICROSATELLITE AND ITS PAYLOAD

As it was mentioned above, the «Chibis-AI» mission is devoted to the study of energetic mechanisms that generate compact intracloud discharges and gamma ray flashes in the terrestrial atmosphere above the thunderstorm areas. The science objectives include:

- Global mapping and occurrence rates of TGF and CID
- Relation of TGF and associated electromagnetic emission, especially in VHF range
- Study of explosive dissipation of the energy in the ionosphere

According to the decision of the Coordinating Scientific and Technical Council of the Russian Federal Space Agency (no. 03 of December 24, 2012), the «Chibis-AI» project was included in the Long-term program of scientific and applied studies and experiments on the Russian Segment of ISS. Delivery of the Chibis-AI into low Earth orbit should be carried out via the ISS infrastructure. The transport and launch container (TLC) (see Figure 1) have been already developed and manufactured at the Special Design Bureau of the Space Research Institute of the Russian Academy of Sciences (IKI).

A longer discussion of the Chibis platform capabilities have been provided in [Zelenyi et al., 2014]. The project was in Phase B as of 2016. The Preliminary Design Review took place in October 2016.

Chibis orbit is low Earth orbit with inclination 51° and initial elevation ~550 km.

The scientific payload is constituted by electric and magnetic antennas, radio frequency analyzer and X-ray and γ-ray sensors. The onboard measurements will be complimented with ground-based observations and dedicated measurement campaigns by Taranis and onboard ISS (see below).

The sensor complement has a mass of ~12 kg and a power consumption of ~23 W. To maximize the scientific return of the data collected by «Chibis-AI», the scientific payload is operated as a single instrument. The strategy adopted is twofold: a continuous monitoring of low resolution RF and particle data is performed and transmitted. Under alert, all Chibis instruments should initiate a synchronized high resolution data mode. The relative time accuracy between the Chibis instruments is less than 10 ns, allowing meaningful intercomparison of the data sets.

To allow the comparison with ground based (WWLN data) and space-born measurements the absolute time accuracy onboard will be less than 10 μs. All instruments include memory to store high resolution data for a time interval including the event detection time.

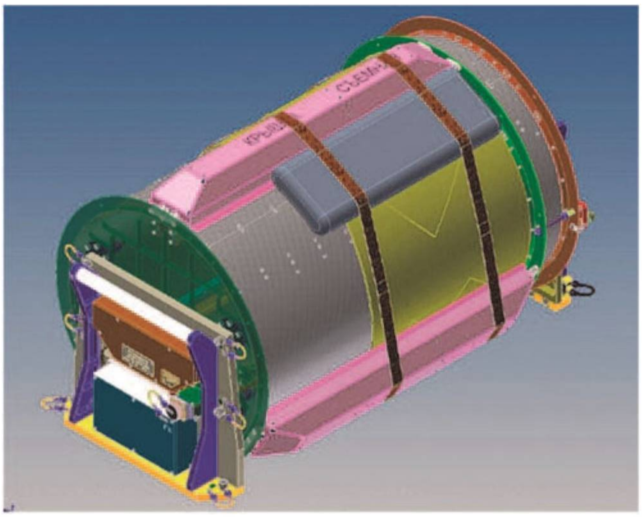

Figure 1. General view of of the transport and launch container developed to launch satellites from Progress cargoship.

Below we provide technical details for instruments related only for high energy physics, namely, radio frequency analyzer (RFA) and neutron and gamma-ray spectrometer (NGS). NGS scientific instrument consists of neutron detectors module and gamma-ray spectrometer, joined by common electronics unit (Figure 2).

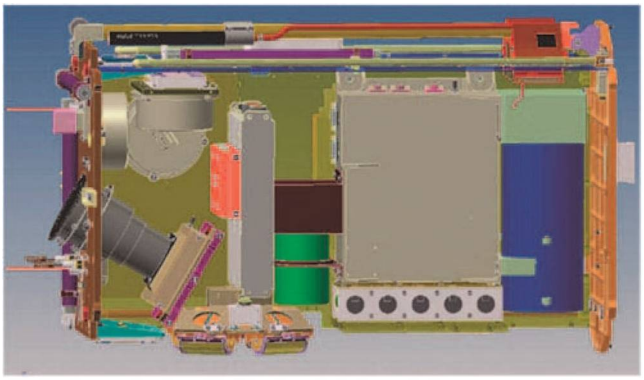

Figure 2. Mounting of assembled NGS instrument onboard "Chibis-AI" (green and brown boxes).

'Neutron' part of the instrument consists of high-energy neutron detector and thermal, epithermal, and fast neutron detectors. The former is a scintillation detector based of stilbene crystal of 21.5 inches diameter, surrounded by plastic anticoincidence shield that registers neutrons wenergies higher than 500 keV. Three detectors are based on He^3 proportional counters (LND 25281 type):

- no shielded counter;
- counter shielded by cadmium foil 0.5–1 mm thick (for neutrons with energies of 0.4 eV-1 keV);
- counter shielded by cadmium foil 0.5–1 mm thick and polyethylene (for neutrons with energies 0.1 keV — 500 keV).

Cadmium shields allow separating neutrons relative to their energy. Cadmium effectively absorbs thermal neutrons with energies less than 0.4 eV, so that by deducting counts registered by cadmium-shielded detector from number of counts registered by unshielded detector, one can obtain thermal neutron flux. Gamma-ray spectrometer registers gamma-ray with high sensitivity and energy resolution not worse than 3.5% at the energy 662 keV. It is supposed to use the LaBr3 (Ce3+) crystal, which has to date the highest spectral resolution and efficiency of gamma-ray registration in energy range 100 keV-10 MeV among scintillation crystals. Due to tight limits on mass and energy consumption, imposed by Chibis project on NGS instrument, germanium spectrometer, which has significantly better energy resolution (approximately 0.3% at the energy 662 keV), was not considered. NGS will be mounted onboard microsatellite with nadir orientation. NGS mount onboard «Chibis-AI» is shown on the Figure 2. Specification of the NGS instrument is provided in the Table 1.

Table 1. Specification of the NGS instrument

Measurements	in a range 0.1 – 10.0 MeV (LaBr3 or CeBr3 crystalls) Area ~ 60 sm2 spectral resolution 3.5% (662 keV)
Operation mode	«Standby» regime without scientific measurements and «Science» mode generating «burst» frame ~ 60 kilobytes
Power	7.0 W («Science» mode) and 4.5 W («Standby» mode)
Telemetry	45 Mb/day
Dimensions	263 x 258 x169 mm
Weight	5.6 kg

Table 2. Specification of the RFA instrument

Measurements	in range 15-26 and 26-48 MHz Time resolution <10 ns Length of the frame - 150 ms ADC dynamic range - 12 bit
Operation mode	Slow mode and fast mode (triggered)
Power	7.0 W
Telemetry	120 Mb/day
Dimensions	205 x 130 x 36,5 mm
Weight	1 kg

It was supposed that Chibis and ISS orbits should be similar. That is why it was decided to install similar instrument onboard ISS for assessing the fluxes of fast, epithermal and thermal neutrons to estimate neutron Earth albedo.

The new RFA proposed for «Chibis-AI» contained two pass bands in the range 15-26 MHz and 26–48 MHz with a digitization at 96 megasamples/s. The radio channel will be connected to a V-shape passive dipole-like antenna with length 2 m of each probe. The antenna was mounted at the bottom of the platform. Initial footprint of the antenna will be around 2300 km along longitude and latitude, or h_{max} ~ 68° from the plumb line at the equatorial region. Specification of the RFA instrument is provided in the Table 2.

The Scientific Data Accumulation System (SDAS) contains 16 Gb of space qualified flash memory. Each record is triggered (see above) and has an adjustable pretrigger/post-trigger records. Position of the trigger in a frame could be varied.

The SDAS is capable of retriggering a new record within several microseconds after the end of the previous one. The S- and X-band downlink transmitters should provide a flexible high-speed downlink solution for Chibis missions, offering rates between 2.0 Mbps (S-band) and 20 Mbps (X-band). To manage data downlink and mission control tracking headquarters were organized on the basis of the Space Research Institute of RAS. The scientific data downlinks should occur at different stations up to several downloads per day.

3. VHF INTERFEROMETER «KITE» ONBOARD ISS

As it was mentioned above data provided by one-point measurement (made by one satellite) could not resolve the question about location of RF and gamma-ray emitter in the Earth atmosphere. As a result, it seems impossible to evaluate the luminosity function of the emitter. A great achievement would be working together ground lightning detection network (NLDN, WWLN, etc.), as well as more sensitive scientific instruments on the Earth's orbit. In order to solve the puzzle, we would like to propose for consideration "Kite" experiment onboard ISS.

It is well known that TIPPs/CIDs processes produce a broad and continuous spectrum of RF radiation, e.g. [*Dolgonosov et al.*, 2015]. If the radiation over a certain broad frequency band, say, from several tens to a few hundred MHz, is from the same source, the broad band signal could then be used to locate the radiation source. By recording over the entire bandwidth, different frequencies at a fixed separation of two antennas are equivalent to many baselines with respect to a narrow band interferometer. Lower frequencies correspond to shorter baselines and higher to longer baselines.

Figure 3. Installation points of "Kite" antennas is indicated by red arrows.

The phase differences at different frequencies can then be computed after Fourier integration of the time series data from the two antennas, which are then used to resolve the angle of arrival of the radiation source.

So, a broad band system requires fewer antennas than a narrow band system to achieve equivalent angular resolution. In addition, frequency dependent location of the radio emissions can be extracted for a more detailed look at the lightning breakdown processes. In the proposed «Kite» project it should be installed a set of up to 4 broadband VHF receivers in the range 20-50 MHz, similar to that used in the "Chibis-AI". Each radio channel will be connected to a passive dipole-like antenna (2 m long rod). The relative distance between antennas is estimated to be more than 8 m. The signals received by the antenna are transmitted through cables to the electronics. The cables for antennas are semirigid coaxial cables with the same length for tolerance to the exposed space environment. Expected «Kite» antennas positions on ISS surface are shown in Figure 3 by red arrows.

The project is in Phase A as of 2017. The expected launch of the project is 2020.

CONCLUSION

The «Chibis-AI» and «Kite» missions will be conducted on the ISS to observe global distributions of lightning and lightning-associated TGFs by combining observations with radio and gamma-ray sensors. This paper focuses on the payload devoted for investigation of high energetic processes (CIDs and TGFs) of the missions (i.e., RFA and NGS instruments) and serves as an initial overview. The «Kite» VHF receivers is a set of up to 4 of VHF broadband antennas and electronics to record VHF waveforms from lightning and lightning-associated discharges. It is designed to estimate the direction-of-arrival with about 10-km resolution, which is equivalent to the scale of a thundercloud. This means that the «Kite» is able to monitor thunderclouds with global lightning activity and effectively locate position of the emitter in the terrestrial atmosphere. Comprehensive analyses on the «Kite» and «Chibis-AI» observations during their campaigns are expected to provide us with new scientific insights and understanding.

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