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POSSIBILITY OF USING GLM DATA FOR STUDYING PLASMA PHENOMENA

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Abstract. The article deals with scientific and technical problems associated with the functionality of the geostationary lightning mapper, which is currently used for meteorological monitoring. Results of the study into the Schumann resonance phenomenon and the technical parameters of the mapper were analyzed simultaneously. A hypothesis is offered which suggests that there are pulsations in the time dependences of the radiation power of lightning activity at frequencies corresponding to Schumann resonance. A new application of the geostationary lightning mapper for studying plasma phenomena is proposed. Adding to the mapper an acousto-optic filter and a camera, which has the functions of switching the resolution/frame rate parameters, is shown to be useful for both meteorological and plasma studies.

Keywords: geostationary lightning mapper, Schumann resonance, acousto-optical filter, high-speed shooting.

INTRODUCTION

In order to effectively use "new large experimental facilities that have not been developed in our country in the past 35–40 years, complexes of instruments with advanced capabilities for measurements and experiments" [Zherebtsov, 2020], it is necessary, even at the final stages of development of these complexes, to not only promptly install modern sensors but also take full advantage of their potential. In the last decade there has been a revolution in the technology for manufacturing microchip elements, which has markedly improved performance and increased the number of elements in optical sensors. CMOS photodetectors (CMOS is a complementary metal-oxide semiconductor) of space qualifications can flexibly change characteristics of lightning detectors: increase the frame rate and reduce the conventional binning multiplicity [Kvitka, 2020]. Photodetectors of this type fit the concept "device on crystal" and provide better weight-size characteristics as compared to traditional CCD photodetectors [Romanov, Tyulin, 2017; Gektin, 2019]. The main purpose of this work is to determine untapped capabilities of the Geostationary Lightning Detectors (GLD) under development, which can be used to study underexplored plasma phenomena, as well as to substantiate the technical solutions necessary for the effective functioning of GLD.

OPTEKS, Branch of Space Rocket Center Progress, plans to equip GLD with a sensor of present-day modification. The Geostationary Lightning Mapper (GLM) [Goodman et al., 2013] installed by NASA in the GOES-16 satellite was chosen as a prototype during development of GLD [Kvitka et al., 2019]. GLD and GLM transmit a map of thunderstorm activity from geostationary orbit to investigate meteorological phenomena and forecast the weather.

GLM uses a camera with a CCD sensor of 1372×1300 pixels and 500 fps [https://www.nasa.gov/feature/goddard/2017/flashy-first-images-arrive-from-noaa-s-goes-16-lightning-mapper]. In GLD, it is supposed to adopt a CMOS sensor of 1102×1102 pixels with a frame rate of 1000 fps, which is maximum for this resolution [Kvitka et al., 2019]. In space instruments, data is usually pre-processed to reduce the amount of data transmitted to Earth. Such processing, developed for GLD of the International Space Station, is partially described in [Kvitka, Korkh, 2018]. The publicly available data obtained using GLM has a low frame rate compared to the 500 fps frame rate of the detector camera [https://www.nasa.gov/feature/goddard/2017/flashy-first-images-arrive-from-noaa-s-goes-16-lightning-mapper]. For example, in the video frame of thunderstorm activity over Missouri, obtained by GOES-16 on May 27, 2017 [https://www.youtube.com/watch?v=DIYtIg0Q89k], this parameter is 1 fps. According to the American Geophysical Union (AGU), such a temporal frame rate seems to be sufficient for meteorological research since research papers published by AGU suggest that the publicly available files with just this temporal frame rate should be processed [Bruning, et al., 2019].

Three orders of the detector's frame rate are seen to be uselessly lost onboard the mappers during preprocessing. Such a wasteful attitude to the valuable resource is due to lack of tasks for which it makes sense to change software solutions implemented taking into account parameters of previous generation sensors with much lower frame rate. High-speed shooting data may be useful for investigating plasma phenomena.

RESULTS

When addressing the conceptual issue about the possibility of using a special-purpose space instrument to explore the phenomena unforeseen during its manufacture, it is most difficult to find and justify the physical problem. Analyze electromagnetic waves in a waveguide consisting of two conducting spheres: Earth and ionospheric D-region [Schumann, 1952]. The spectrum of these waves corresponds to the Schumann resonance (Schumann waves). Such waves continue to be actively studied, specifically by means of space-based detectors [Fernando, Pfaff, 2011, Prácser, Bozóki, 2022].

Schumann put forward a formula for resonant frequencies of such a waveguide

$$f_n = \sqrt{(n(n+1))}V_{\text{cp}} / L_3 \approx 6.0\sqrt{n(n+1)}, \qquad (1)$$

where n is the harmonic number of a Schumann resonant frequency; V_{av} is the average propagation velocity of an electromagnetic wave calculated in [Sentman et al., 1995]; L_{E} is the circumference of Earth. Experimental investigations show [Schlegel, Füllekrug, 2002] that the main resonant frequency is ~7.8 Hz and the whole spectrum of Schumann waves is within 5–60 Hz. One of the shells of the Schumann resonator is the ionosphere (plasma), so Schumann waves fully fit the above definition of plasma phenomena.

When solving the problem for eigenoscillations of the Earth—ionosphere system, Schumann and his followers did not consider the source of energy of these oscillations. The direction finding of lightning discharges [Füllekrug, Constable, 2000] through Schumann wave triangulation makes it clear that these phenomena are interrelated. While lightnings constantly occur in one or another part of the globe, there are time intervals between decay and sharp increase in the amplitude of Schumann waves. About 700 000 lightning discharges are recorded on Earth every day [Holzworth, et al., 2021], but only a few initiate the increase in amplitude and hence in energy of Schumann waves necessary for triangulation. Investigating plasma phenomena in regions where such lightning discharges are recorded is therefore of interest to fundamental science.

Schlegel, Füllekrug [2002] note that there is no information about the study into mechanisms of the relationship between lightnings and Schumann waves; Chowdhuri et al. in their review of lightning parameters [2005] indicate the absence of data on lightning radiation power fluctuations at the frequencies of Schumann resonance harmonics. I think that there is a trivial linear mechanism for redistributing the 5–60 Hz lightning radiation energy to Schumann waves through interference, but it is most likely not unique. In an unknown part of the range, as in the optical range of GLD detection, we cannot rule out the existence of nonlinearity that can increase the amplitude of Schumann waves and the beating in time dependences of the optical radiation power of lightning activity zones at frequencies corresponding to the Schumann resonance. Moreover, the linear mechanism does not explain the sharp increase in Schumann wave energy, which is rare as compared to the lightning rate.

Analyze the adequacy of GLD technical capabilities for studying lightning activity in the regions determined by triangulation. The typical sampling time for Schumann resonance measurements is 1/100 s [Schlegel, Fullekrug, 2002]. According to Kotelnikov's theorem, the frame rate necessary to reconstruct the characteristics of the time dependence of the phenomena should be at least twice the characteristic rate. Experiments have proved that the main portion of Schumann wave energy is in the range 5–60 Hz. Frame rates of GLM [https://www.nasa.gov/feature/goddard/2017/flashy-first-images-arrive-from-noaa-s-goes-16-lightning-mapper] and GLD [Kvitka et al., 2019] cameras are 500 and 1000 fps respectively. For the proposed research it is sufficient only to upgrade the GLD software, which will enable the joint transmission of meteorological data and measurement results in regions where an abnormal increase in the Schumann wave amplitude has been detected.

Due to the lack of technical capabilities, the task of studying characteristics of lightning activity in the regions determined by the triangulation method [Füllekrug, Constable, 2000] during a sharp increase in the Schumann wave amplitude has not been set until now. It is proposed that the data be saved with the accuracy required for investigating plasma phenomena in the zones after their coordinates have been determined. The proposed GLD software upgrade will make it possible to simultaneously monitor zones of increased lightning activity with the aid of GLD and several Schumann wave detectors whose number and location correspond to the implementation of triangulation. Detection of plasma phenomena after the GLD software upgrade may lead to a critical increase in the amount of information recorded in data storage media, will require deep onboard processing of images because the bandwidth of satellite radio lines is limited. An additional technical solution is therefore proposed — to keep the original images of a predetermined region on orbit until information about a sharp increase in the Schumann wave amplitude is received. The decision on whether there is a need to increase the performance of the onboard computer and the memory of the storage device, designed to store measuring results, can be made only after the time required to perform triangulation and to transfer information to orbit becomes known.

To supplement the thoroughly studied GLD upgrades necessary for investigating plasma phenomena in zones of increased lightning activity leading to a sharp increase in the Schumann wave amplitude, let us touch briefly on a possible hardware upgrade. The key elements of GLD and GLM are a wide-angle narrow-band light filter and a high-speed camera with a sensor that has nearly HD resolution. The light filter with a bandwidth of ≈2 nm is designed to identify the brightest lightning triplet of 777.19, 777.42, 777.54 nm against the sunlight reflected from clouds. On the NASA website [https://www.nasa.gov/feature/goddard/2017/flashy-first-images-arrive-from-noaa-s-goes-16-lightning-mapper], there is no information about the type of filter in use. Kvitka et al. [2019] suggest using an interference filter that at the ≈2 nm bandwidth works effectively only for the light flux incident at an angle of ~ ± 4.5° to the normal. Kvitka, Korkh [2018] plot the shift of the light filter bandwidth spectrum with $\Delta\lambda$=1.7 nm as a function of the light angle. Interference filters cannot cover the entire Earth surface, whose angular size is ~±8.7°, from the geostationary orbit.

Filatov et al. [2020] have shown the possibility of exploiting acousto-optic filters (AOF) in GLD, which have long been used in space research [Glenar et al., 1994, Pustovoit, Pozhar, 1999]. Korablev et al. [2016] have analyzed parameters of 11 acousto-optic space-based spectrometers. New trends in AOF designed for spacecraft are discussed in [Yushkova, et al., 2015]. Kozun et al [2020] plan to transfer the AOF based on the TeO_2 paratellurite crystal from a stratospheric balloon test platform to a low-orbit satellite and to use it for atmospheric remote sensing of aerosol and cloud properties. The declared parameters of the AOF are as follows: spectral range is 600–1500 nm; spectral resolution is 1.5, 2.2, 7.7 nm at wavelengths of 514, 633, 1152 nm respectively; optical aperture is 10×10 mm^2; angular aperture is 4°–6°; max RF power is <3 W.

The technical feasibility of developing AOF with an angular aperture of ≈±7° has been experimentally proved [Chang, 1974]. Since AOF, unlike an interference filter, has a limited spatial resolution, theoretical studies have been carried out [Voloshinov, Moskera, 2006; Mantsevich et al., 2020] in order to find conditions providing the highest angular resolution. As a result, tunable AOF were developed [Epikhin et al., 2013, Molchanov, et al., 2014]. The AOF [Perchik, 2013] designed for spectral monitoring of the ocean surface is considered to be perfectly adequate for wide-angle detection of lightning from geostationary orbit. In the 430–780 nm spectral range, the proposed filter provides a bandwidth of ≈2 nm, with spatial resolution of filtration being higher than that of the ≈800×800 photodetector matrix. Experimental measurements have shown that the angular aperture of this AOF is ~8° although preliminary theoretical calculations predicted it to be ~3°. AOF can form complex passband spectra [Filatov, 2021]. Filters of this type can be used for GLD hardware upgrade.

Technical descriptions of GLD and GLM contain no information whether these mappers exploit the capability of switching sensor resolution modes depending on the shooting speed. This capability is provided in commercial cameras such as 1920×1088 at 3500 fps and 1280×8 at 1008000 fps [https://evercam.ru/produktsiya/8/942]. Equipping GLD with a camera that has resolution/frame rate switching functions will enable optimization of spatial and temporal resolutions.

CONCLUSIONS

1. A hypothesis has first been put forward about pulsations in the time dependence of the optical radiation power of lightning activity zones at frequencies corresponding to the Schumann resonance.
2. We have proposed simultaneous monitoring of zones of increased lightning activity by the software-upgraded GLD capable of transmitting unmodified high-speed camera data from orbit and by several Schumann wave detectors whose number and location correspond to the implementation of triangulation. After determining through triangulation the time and coordinates of a thunderstorm leading to a sharp increase in the energy of Schumann waves, it is proposed to explore the features of this region, using the data transmitted from orbit or stored in GLD.
3. The GLD hardware upgrade with the aid of an acousto-optic filter and a camera having the capability of switching the resolution/frame rate parameters have been demonstrated to expand the functional capabilities of the device. The use of cameras based on CMOS photodetectors provides flexibility in selecting target parameters of GLD.

The work was carried out within the framework of the state task.

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