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SPACE VEHICLES, SYSTEMS, AND PROGRAMS OF IEC

Small Satellites in Remote Sensing of the Earth

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Abstract—We consider the innovative technical solutions that have led to the development of small satellites (SS's) and new possibilities for organizing remote sensing based on constellations of SS's that make it possible to satisfy the need for a systematic continuous survey with a minimal time interval between the views of any area at reasonable costs. This paper is aimed at studying the possibilities, as well as the limitations, associated with the use of SS's in the field of remote sensing; analyzing the problems of the design, deployment, and operation of SS constellations; and providing users with operational information.

Keywords: small satellites, orbital constellations, remote sensing of the Earth, use of small satellites

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INTRODUCTION

Satellites in low Earth orbits have opened up the possibility of imaging any part of the planet or objects on its surface and to observe the land, ocean, atmosphere, and cryosphere in the interests of Earth sciences. Remote sensing of the Earth was primarily required by imagery intelligence, which presented requirements for space imagery for detailed resolution on the ground and accurate referencing.

IKONOS, the first commercial Earth remote sensing (ERS) satellite (manufactured by Lockheed Martin), had a panchromatic channel resolution of 0.81 m and an active lifetime of 16 years (1999–2015).

Interested in attracting commercial spacecraft resources to solve the problems of imagery intelligence, the Department of Geospatial Intelligence NGA (National Geospatial-Intelligence Agency) started funding the creation and launch of commercial second-generation remote sensing satellites. The third-generation satellites, World View-3 launched into sun-synchronous orbit (SSO) in August 2014 and World View-4 (formerly GeoEye-2) launched in November 2016, had a 30-cm spatial resolution.

Imaging systems and service equipment were improved by increasing the mass of the satellites: the IKONOS satellite weighed 726 kg and the mass of World View-3 increased to 2800 kg. The increase in mass led to a sharp rise in the cost of projects: the total cost of the super-detailed observation satellite World View-4 with allowance for the launch and insurance costs reached $235 million. Like the World View satellite, the World View-4 equipment has a terrain resolution of 0.31 m in the panchromatic range and 1.24 m in multispectral channels. The general task of these satellites is to collect survey information on regions and objects to plan for shooting with equipment for a more detailed observation of military spacecraft of the Evolved Enhanced Crystal class with a spatial resolution of about 0.15 m in the perigee section of the orbit at an altitude of 270 km.

The dominance of geodata in the global market from companies focused primarily on the demands of imagery intelligence explains the origins of the problems of modern interfaces such as Virtual Earth:

(i) the duration of the full coverage of the survey in several days limits the possibility of its systematic updating using images of a sufficiently high resolution, and they do not cover all regions of the Earth;

(ii) the different timing of shooting leads to inconsistencies and incompatibility of images due to the variability of the terrain and differences in the characteristics of the shooting systems;

(iii) if an operational assessment of the situation and information support for emergency rescue operations in places of natural disasters or a natural and technical situation of a dangerous nature are required, a view of any area of the Earth with a minimal time interval is not provided.

CHANGES IN SPACE OPERATIONS RELATED TO THE USE OF SMALL SATELLITES

In one of the first monographs on SS's (Helvajan and Janson, 2009), small spacecrafts are defined as satellites of low mass and size, usually weighing no more than 500 kg. It is noted that SS's such as pico-satellites, nano-satellites, and CubeSats are used as platforms, the low weight of which allows them to be launched into space at a cost of several million dollars, which opens up low-cost access to space for countries without a space program, companies, and educational institutions.

There are several different options for classifying SS's. According to the classification of the German Space Agency (DLR), satellites with a mass of 1000 kg and more are considered large, miniaturized satellites include SS's with a mass of 200 to 1000 kg, microsatellites include satellites with a mass of 50 to 200 kg, nanosatellites occupy a range from 5 to 50 kg, and picosatellites occupy a range of up to 5 kg. A more widespread classification is that medium-sized satellites include satellites with a mass of 500 to 1000 kg, minisatellites are in the mass range from 100 to 500 kg, microsatellites occupy the interval from 10 to 100 kg, nanosatellites have a mass from 1 to 10 kg, and picosatellites are those that are lighter than 1 kg. The last three subclasses, micro, nano, and pico, with the same mass differences, are considered in (Kashirin and Glebanova, 2016). Femtosatellites with a mass of less than 0.1 kg and picosatellites with a mass between 0.1 and 1 kg are mentioned in (Kostev et al., 2016).

A separate place in SS formation is occupied by the CubeSat standard with a standard size of 10 × 10 × 10 cm and a mass of about 1 kg, which was proposed by Robert Twiggs, professor at Stanford University (Palo Alto, California, United States), meaning that everyone can create their own nanosatellite. The cost of creating a CubeSat was estimated at $50000, which includes the target equipment and launch as a part of additional cargo. Andrew E. Kalman, founder of Pumpkin Inc. and a consultant at the university, helped Twiggs reduce the time it takes to make a CubeSat to a few months in line with the curriculum.

Pumpkin Inc. has launched a generic CubeSatKit for assembling CubeSats. The kit consists of an aluminum case, a module with a motherboard, memory, standard electronics, software using the Space Plug-and-Play Architecture (SPA-1) protocols, and processors that were tested on a vibration stand and in a thermal and pressure chamber. The cost of the set is $7500. In 2010, Pumpkin Inc. began producing the CubeSat-Kit 3U for nano satellites with a size of 10 × 10 × 34 cm and a weight of 4.5 kg. Models 1U–3U are satellites that fall in between picosatellites (up to 1 kg) and microsatellites (from 10 to 100 kg) in international classifications.

Standardization made it possible to reduce the development time of the spacecraft from concept to launch readiness and production costs. Leaving out space components and switching to electronics from catalogs (off-the-shelf components), as well as the use of programmable logic integrated circuits (FPGAs), led to a decrease in the cost of the CubeSat model 1U to 65000–80000 dollars, about half of which is launch services. Upon transitioning from large spacecraft (with a mass exceeding 1000 kg) to nanosatellites, costs per kilogram of mass decrease from $3.16 to $0.4 million (Kashirin and Glebanova, 2016). The multifold reductions in costs—when compared with the price tag of large satellites—throughout the entirety of the project, including the cost of development, manufacturing, testing, and launch, have made the mass production of SS's possible. Modern possibilities of designing and developing these SS's were achieved due to technological barriers being overcome and the creation of microelectronics and microsystems (Verhoevenet al., 2011; Sevastyanov et al., 2009).

Flight tests of SS's and their development are carried out much more quickly than with large spacecrafts. The launch of many of the same type of spacecrafts at once makes it possible to identify an entire range of concerns, so flight design tests are in the forefront in the effort to eliminate shortcomings and miscalculations. The search for the optimal design occurs due to the rapid implementation of new solutions and their verification in orbit. The low cost of producing SS's and delivering them into orbit allows them to be used for testing and obtaining flight qualifications for new elements of spacecrafts and systems and for demonstrating promising technologies.

ISRO, the Indian space agency, has developed a versatile nanosatellite platform to accommodate various experimental payloads in demonstration missions lasting from six months to a year, and a 5-kg platform can carry a payload of up to 5 kg. Launched in the SSO orbit on February 15, 2017, by the PSLV-XL C37 carrier along with other payloads, the Indian INS-1B nanosatellite, weighing 9.7 kg, with scientific equipment for measuring the amount of neutral atomic hydrogen in the Earth's exosphere, also carries an experimental camera with origami optics. The origami lens was developed at the University of California at San Diego (United States). It has a diameter of 6 cm and thickness of only 5 mm and gives a high-quality image comparable to that obtained with a 38-mm large-aperture photo lens. The lens collects light passing along the outer edge with a narrow annular area, then the rays are reflected several times in the thickness of the calcium fluoride crystal and are collected in the central part, where the photosensitive matrix is located. The lens surface facing the subject (except for the ring) is a flat mirror, and the back surface consists of annular aspherical reflectors.

Small satellites firmly occupy their niche in the field of remote sensing. One hundred and fifty SS's, of which 59 were remote sensing satellites, were launched into orbits in 2016; 106 nanoclass devices (1–10 kg), among of which 45 are equipped with remote sensing equipment, predominate. There are 44 SS's of micro, mini, and medium size; 15 of them have optical-electronic imaging equipment on board (Summary table..., 2018).

The Planet constellation, with the mission to receive images of the entire surface of the Earth with a resolution of at least 5 m every day, consists of more than 200 operating Dove (Flock) satellites and 13 SkySat satellites and is under the control of the RapidEye global agricultural monitoring system managed by the Planet company (Lebedev and Gansvind, 2010).

The Flock and SkySat SS's are based on the CubeSat standard. The Flock nanosatellite, a 3U CubeSat, has dimensions of 10 × 10 × 32 cm and a mass of 5–6 kg at launch. The target equipment, an optoelectronic system with a Maksutov-Cassegrain telescope with an aperture diameter of 91 mm and a focal length of 11460 mm, occupies 11/12 of the nanosatellite volume (over 21%). Service systems, which include control of movement and orientation, power supply, control of the onboard complex, and interaction with ground infrastructure, occupy a volume of 0.25 L. The record layout density was achieved due to the microminiaturization of components, electronics, and MEMS (microelectromechanical systems), as well as circuit solutions: sharing resources (processors, FPGAs) by various systems in the absence of an onboard cable network as such. The shooting equipment is designed to obtain images in four spectral channels with a resolution of 3.5 m (at an altitude of 400 km): red (610–700 nm), green (500–590 nm), and blue (420–530 nm), as well as in the near IR (770–900 nm).

The survey is carried out continuously when flying over the land with a frequency of once per second. The detector is located at a distance of 320 mm from the meniscus and is placed in a cylindrical "attachment" on the side opposite to the antenna. Optoelectronic conversion is performed by a single CCD with a Bayer filter and accumulation time delay. The file format after ground processing is GeoTIFF. The matrix has a capacity of 29 megapixel. Radiometric resolution is 12 bit. Georeferencing accuracy is about 20 m.

The control of satellites in the VHF and S-bands and the reception of images in the X-band are carried out at receiving stations with antennas with a diameter of 5 m located in Europe, the United States, Australia, and New Zealand. Cloud-based imaging runs on Amazon Service servers, providing remote client access to data via online channels with less than a day's delay after capture. The volume of actually downloaded data from satellites reached 4.5 TB per day by the spring of 2017. The need to process updated images led to a new approach to working with geodata, combining the capabilities of aerospace, geoinformation, and network technologies with geoportals and interfaces. A project was created in which satellite and aerial images of the entire surface of the Earth, Google, and Google Earth maps are put on the Internet using a three-dimensional model with the Direct X and Open GL interface.

The mass-geometric characteristics of CubeSats with a small load on the midsection at an arbitrary orientation of the satellite that is unstable in the incoming flow lead to significant aerodynamic drag at the altitude of the ISS orbit, where they are delivered by the Cygnus automatic cargo spacecraft for further launch. So that it slows down less, the satellite must be oriented by the end of the body and the edge of the solar array to the flow. Flock satellites are not equipped with a propulsion system, so, in order to maintain the structure of the constellation, a technique for modulating the aerodynamic drag of the satellite by changing its orientation was created and tested in flight. The separation of 28 satellites in the in phase took 35 days, while the value of the aerodynamic drag coefficients was refined (Foster et al, 2016). The period of the ballistic existence of the majority of SS's launched from the ISS do not exceed a year. For example, 51 satellites were successfully launched from the ISS in 2014. However, 28 Flock-1a satellites ceased to exist by the end of the year due to the braking in the atmosphere. In 2015, 50 small spacecraft were launched from the ISS by five groups, but only 38 of them survived at this altitude (Summary table..., 2017).

The standard for the CubeSat form factor, which has arisen due to the development of microminiaturization and nanotechnology, made it possible to dramatically simplify and reduce the cost of manufacturing nano and some micro SS's. The standard interface to the launch satellite made it possible to simultaneously launch a significant number of CubeSats.

At the Small Satellite Conference in Logan, Utah, in August 2018, the Aerospace Corporation proposed a new standard of micro-class SS's called the Launch Unit (Launch-U) with a weight from 60 to 80 kg and a size of 45 × 45 × 60 cm. The standard requirements relate to the location of the satellite's center of mass, the fundamental frequency of its elastic oscillations, and other characteristics and parameters necessary for the integration of payloads launched on a rocket (Afanas'ev, 2018).

The need for a systematic continuous survey of the Earth's surface with a minimal time interval between surveys of any area at an acceptable cost led to fundamental changes in the structure of ERS space SS's. The transition from the super-detailed resolution imaging of certain objects or territories with heavy satellites to systematic global imagery was ensured by multicomponent satellite constellations of SS's in low near-earth orbits while maintaining the structure of the placement of satellites in several orbital planes and replenishing the number after the expiration of the active life or deorbiting of the satellite.

A passing launch by medium-class missiles does not meet the requirement for fast and flexible access of SS's to orbits, since the timing of the launch of associated loads is determined by the main mission of the launch vehicle. The creation of a lightweight carrier will reduce the cost of launching a kilogram of mass and meet the growing demand for SS launch services. There is a steady downward trend in the mass of spacecraft. According to the Space Works forecast, about three thousand satellites with a mass of up to 50 kg will be launched by 2022, which is several times more than the expected number of large launches with a mass exceeding 1000 kg (Kostev et al., 2016).

SkySat satellites are located in four orbital planes; the separation of the satellites in phase in each of the planes and the maintenance of the constellation structure during operation is achieved using a CPS consisting of four microengines with a thrust of 1 N each and running on LMP-1035 "green" fuel. The satellite weight is about 110 kg, and its dimensions (in flight) are 0.6 × 0.6 × 0.95 m. The patented imaging equipment created by the SkyBox Imaging startup (later Terra Bella) makes it possible to obtain images in the panchromatic range of the spectrum with a resolution of 90 cm when shooting in nadir in four spectral channels with the standard arrangement of RGB and NIR (the ground resolution is 2 m). It is also possible to record video with a resolution of 1.1 m in a panchromatic channel with a frequency of 30 frames per second.

The payload mass is 23 kg, the telescope is made according to the Ritchey–Chrétien scheme and does not have spherical aberration and coma, the aperture diameter is 35 cm, and the focal length is 3.6 m. The telescope's hyperbolic mirrors are made of silicon carbide. The focal plane assembly consists of three detectors: Fairchild Imagin CIS2521F CMOS matrices with a size of 2560 × 2160 pixels. The pixel size is 6.5 μm. Matrices are staggered (with slight overlap). The upper half of each matrix is used for imaging in the panchromatic range, while the lower half is used for multispectral imaging; multiple overlapping shooting of targets (Pushframe technology) is carried out, as well as time delay with accumulation on high-speed matrices with subsequent processing, on the ground. The radiometric resolution is 11 bit. The width of the line capture is 8 km. Onboard image processing is carried out using the JPEG 2000 algorithm with further processing carried out on the ground (Khromov, 2014).

To calibrate images from the SkySat-1 satellite, the following was used:

(i) the site was a desert in Somali with a size of 10 × 10 km, which was filmed by Peliades-1A and SkySat-1;

(ii) a frame taken by Peliades with the overlay of images obtained from three SkySat matrices;

(iii) geospatial correction of images of each matrix carried out on a 17 × 17 point grid;

(iv) 1100 uniformly white images of clouds in polar regions were used to calibrate the signals of individual photodetectors;

(v) the NASA Stennis Space Center mire is used to take the frequency-contrast characteristic (Khromov, 2014).

The Planet constellation data are available to users through the PlanetPlatform online service. The Monitoring of Emergencies and Natural Disasters service allows one to do the following:

(i) determine the degree of damage and assess the ability of rapid response teams to access the necessary infrastructure;

(ii) take direct response measures based on the analysis of submeter resolution data;

(iii) plan recovery operations in the course of events.

The basis for the standardization of SS form-factors of micro and mini, which are used to create groups for the operational monitoring of rapid phenomena and the state of the environment, is the development of platforms carrying service systems to ensure the operation of target equipment of SS's of various classes. The SSTL (Surrey Satellite Technology Ltd), a UK leader in space activities, has developed a number of platforms. Based on the SSTL-300S1 platform with a mass of 218 kg, a constellation of Russian Kanopus satellites ERS with a mass of 465 kg was built, a constellation of Rapid Eye agricultural monitoring satellites with a mass of 154 kg was built on the SSTL MicroSat-150 platform, and the Carbonite-2 satellite with a mass of 100 kg was built on the SSTL-42 platform.

Together with UrtheCast, the SSTL is creating the Urthe Daily ERS satellite constellation, which is scheduled to launch in 2020 for obtaining high-resolution multispectral images intended for work in geoanalytics. SS constellations are created on the SSTL-250 platform. Spectral channels are selected to be comparable with images of the Landsat-8, Sentinel-2, Rapid-Eye, and Delmos-1 operating satellites.

The Black Sky Global project provides for the formation by 2020 of an orbital constellation of 60 Earth remote sensing satellites for global multispectral imagery and video with 1-m spatial resolution. The constellation will include two satellites in polar orbits and 58 SS's in eight planes in inclined orbits based on a maximal viewing frequency of up to 40–60 flights per day for regions with latitudes between 55° N and 55° S, where 90% of the world's population lives. The ground complex will have seventeen receiving and control stations. The first Black Sky Pathfinder-1 experimental satellite was developed based on the Sentry-400 platform with dimensions of 0.84 × 0.98 × 0.41 m.

Small remote sensing satellites retained a dual purpose. The American military is firmly convinced that all orbital constellations in the future will be built based exclusively on SS's and their total functionality will be higher than that of all existing Pentagon orbital constellations consisting of the latest generation large satellites in orbit now (Chernyi, 2018).

The main cost-based proposals of operators of low-orbit satellite constellations are associated with the provision of images of the Earth's surface, as well as communication services (telephony and broadband Internet). Loading pictures from satellites should take place in almost real time. In addition, there are restrictions on both the onboard storage of information and its reproduction. Therefore, a wide communication channel is needed to dump information and to communicate from SS's to ground points at any point of the orbit. Besides expanding the global network of ground stations, cloud platforms that integrate unused capacities of existing information receiving and processing points are being developed.

Space activities of Russia in the field of SS's has not yet reached a level that meets the interests of using the capabilities of SS's in areas such as

(i) preparing students for practical activities in the design, manufacture, testing, and flight control of scientific and educational satellites;

(ii) operational monitoring of land and ocean for control over emergency situations;

(iii) flight qualification of innovative service and target equipment using demonstration and technological satellites;

(iv) expanding high-speed Internet coverage over the territory of Russia;

(v) obtaining data for operational weather forecast;

(vi) space exploration.

Russia's need for SS's makes it necessary to develop a domestic standard for SS's, starting with unified platforms. As the SSTL experience shows, unified platforms for certain weight classes of SS's play the key role in SS technology. In Russia, based on a medium-sized spacecraft, the Progress Rocket Space Centre has created a platform with a mass of 330 kg for the Aist-2D ERS satellite with a mass of 530 kg launched in the SSO with a height of 490 km, a resolution of 1–2 m, and a swath of 39.6 km. A passing launch of SS's with medium-class missiles does not meet the requirement for fast and flexible access of SS's into space, since the timing of the launch of passing loads and the launch orbit are determined by the main mission of the launch vehicle.

Despite having the ability to create SS's for various applications and means to launch them into orbit, Russia is missing out on taking its place in the growing SS market.

Developing a domestic standard for SS's, standard platforms, and the creation of light-class launch vehicles of the Soyuz 1LK type would allow us to enter the global SS market and take our well-deserved place on it.

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