Determination of the main design parameters of cost-effective remote sensing satellite systems at the stage of preliminary design

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Abstract. This article surveys approaches to the selection of design parameters and modelling the functioning of the remote sensing satellite systems, taking into account the requirements and restrictions on customer resources. The objective of this research is to increase the efficiency of the use of space systems to solve urgent tasks of monitoring the earth's surface. Firstly, an analysis of the requirements for space imagery materials and consumer information support was carried out, secondly, mathematical models of remote sensing equipment and on-board systems of small spacecraft were developed, and finally, a database with the technical characteristics of the on-board systems and remote sensing equipment of spacecraft, launch vehicles and ground-based reception and processing information facilities was created. As a result, software to determine main design parameters and modelling the functioning of cost-effective remote sensing satellite systems was developed.

1. Introduction

Nowadays, a steady increase in the number of remote sensing satellites and surveillance systems, based on them, is characteristic of Earth observation. In [1-4] it is noted that from year to year the role of remote sensing of the Earth is constantly increasing. Experts believe that by 2026 there will be more than 1100 new remote sensing satellites in orbit. In addition, a constantly expanding market of space information has been formed. The analysis of the modern situation [5,6] highlights several key factors, affecting the progress of the market of remote Earth’s sensing performed with small satellites, namely:

- rapid progress in microelectronics, development of new materials;
- progress in remote sensing equipment;
- emergence of new launch opportunities, in particular, light and super-light rockets and flexible options for joint launches;
- active venture investment activity in the industry.

The main trends in global remote Earth’s sensing market in the segment of small satellites are deeply related to these factors. These trends include:

- small satellites are getting more capable to solve a broader range of tasks;
- serial production of satellites, based on standard platforms;
- decrease of the satellites’ weight with a simultaneous increase in operational capabilities (each year the mass of an average new satellite decreases by about 8%);
- rising interest in the satellite market from big industry companies;
deployment of large small satellite constellations able to solve various tasks, including remote sensing, with qualitatively new efficiency characteristics, such as productivity, the efficiency of information delivery, frequency of observation of Earth objects.

Considering the serious level of competition on the market of commercial Earth observation, the task of determining the economic indicators associated with the design parameters of the system at the preliminary design stage becomes ever so urgent. There are several well-known approaches towards the preliminary design of remote Earth sensing satellites [7-12]. However, these approaches do not factor in the new drivers and trends in Earth’s remote sensing development, that were listed above. The purpose of this research is to develop a means of automated designing and modeling of target functioning of Earth remote sensing monitoring system taking into account the requirements and limitations on the customer's resources.

2. Analysis of requirements to space imagery materials

Earth surface monitoring results are now being applied by many industries around the world. These include: agriculture; environmental management; forestry; water management; environmental monitoring; oil and gas; housing and communal services; construction; transport and logistics; cartography and state registration; emergencies, etc. Each of the sectors corresponds to one or several consumers (executive authority, subordinate structures and organizations, commercial contractors), which set requirements for the information product of remote sensing. In this study, the requirements for remote sensing information that can be used to solve problems in the above-mentioned domains have been analyzed. Table 1 presents the tasks of agriculture and environmental monitoring and the corresponding requirements for information on remote sensing of the Earth to solve them.

| Task                                                           | Industries                  | Spatial resolution | Temporal resolution | Spectral range                                              |
|---------------------------------------------------------------|-----------------------------|--------------------|---------------------|-------------------------------------------------------------|
| Clarification of the boundaries of agricultural fields         | Agriculture                 | Not worse than 20 meters | Once a year         | Panchromatic, blue, green, red and near infrared wavelengths |
| Clarification of crop boundaries                               | Agriculture                 | Not worse than 30 meters |                     | Blue, green, red and near infrared wavelengths; Hyperspectral information (for precision farming technologies); Short-wave IR range (for determination of moisture content) |
| Crop Assessment                                                | Agriculture                 | 1-10 meters         | Once a week         | Panchromatic, blue, green, red and near infrared wavelengths |
| Identification and monitoring of illegal landfill sites        | Environmental monitoring    | Not worse than 2 meters | Once a quarter      | Hyperspectral                                               |
| Industrial liquid sump monitoring                             | Environmental monitoring    | Not worse than 5 meters | Once a quarter      | Hyperspectral                                               |
| Earth spill monitoring                                         | Environmental monitoring    | Not worse than 30 meters | Once a quarter      | Hyperspectral                                               |

Thus, a link was established between the thematic tasks solved by the space monitoring system and the required characteristics of the information product: required image level and scale, spatial resolution and spectral range. Based on these data, it becomes possible to proceed to the determination of the design characteristics of the spacecraft sensing payloads. Similar dependencies were obtained for the following areas: “change monitoring”, “cartography”, “transport monitoring”, “oil and gas complex”, “nature management”, and “emergency situations”.

2
3. Mathematical models

Development of models of satellite platforms and payloads is necessary to determine the composition of on-board systems of spacecraft and their design characteristics, taking into account cost and time constraints. To model the characteristics of the power supply system, the thermal control system, and the system for transmitting the payload information, mathematical models proposed in [10-12] were used to determine the mass, size and cost of supporting systems of small spacecraft.

3.1. Model for the mass characteristics of the optoelectronic telescopic complex determination

To determine the mass characteristics of the optoelectronic telescopic complex, the following mathematical model is proposed, linking its mass with the performance characteristics:

\[ m_{\text{sensor}} = k_{\text{spec}} \cdot \pi \cdot k_D \cdot k_{\text{MM}} \cdot \frac{\Delta l_p}{2} \cdot B \left( \frac{k_D}{2} \cdot k_{\text{MM}} \right) \cdot \left( \frac{\Delta l_p B}{\Delta L} + \frac{\Delta l_p H}{\Delta L} \right) \]

where:
- \( k_{\text{spec}} \) – specific surface weight of the payload,
- \( k_D \) – overshoot ratio of the payload body diameter over the diameter of the main mirror,
- \( k_{\text{MM}} \) – overshoot ratio of the payload main mirror diameter over the photoreceiver,
- \( k_f \) – overshoot factor of the payload over its length,
- \( \Delta L \) – linear resolution on the ground,
- \( \Delta l_p \) – characteristic size of a photoreceiver element (linear pixel size),
- \( B \) – swath width,
- \( H \) – spacecraft altitude.

3.2. Models for the mass characteristics of on-board systems determination

As the first approximation, the mass of onboard systems is calculated as the percentage of the total weight of the spacecraft \( m_{SC} \) [10-12].

The weight of the power system depends on the type of current source. Currently, typical power supply systems utilize batteries, solar arrays, fuel cells, solar concentrators, and others. The relative mass of the power supply system for the spacecraft for remote sensing of the Earth with solar panels is 4...6% of the mass of the spacecraft. Thus, the mass of the power system in a first approximation can be calculated as follows:

\[ m_{PS} = (0.04...0.06) m_{SC} \]

The mass of the thermal control system depends on the heat emission of the equipment and spacecraft systems. The relative mass of the thermal control system is from 3 to 12% of the spacecraft mass according to statistics. The lower value refers to a small spacecraft with a low level of heat generation and the simplest, often passive, thermal control system. The upper value of the relative mass of the thermal control system corresponds with spacecraft with high heat generation and a complex thermal control system with liquid circuits, radiators, etc. Thus, the mass of the thermal control system can be calculated in the first approximation as follows:

\[ m_{TCS} = (0.3...0.12) m_{SC} \]

The mass of the attitude control system in a first approximation is calculated as follows:

\[ m_{MCS} = (0.050...0.100) m_{SC} \]

The approximate function for calculating the mass of the antenna-feeder device and the cable network, which are obtained by processing the results with statistical data are as follows:

- mass of antennas and feeder devices: \( m_{\text{AFD}} = (0.008...0.025) m_{SC} \);
- mass of cable network: \( m_{\text{CN}} = (0.06...0.10) m_{SC} \).

The absolute mass values of the radio link equipment for small spacecraft are: 1 ... 10 kg.
4. Results

As a result, an algorithm was developed that allows to determine the main design parameters and to perform modeling of the target functioning of the space monitoring system, taking into account the requirements and limitations of the customer's resources. The algorithm is the basis for software and for computer-aided design and simulation of the operation of a space monitoring system. The algorithm includes the following stages.

First, the characteristics of the optoelectronic telescopic complex (hereinafter referred to as payload) of the spacecraft are determined by successive selection of the thematic area of the problem, section, topic, name of the problem, thematic map (scheme), mapped layers and level of observation detail. As a result, a list of characteristics of suitable payloads that meet the requirements of the problem in terms of characteristics of scale, resolution and composition of spectral bands is formed. Figure 1 shows the software implementation of this stage.

Secondly, the composition of spacecraft on-board systems is being formed. For each block of on-board equipment parameters are either calculated using the developed mathematical models or selected from the appropriate databases of already developed products with known characteristics. Figure 2 shows the software implementation of this stage. For each block of on-board equipment and on-board system, the following parameters are transferred to the module for calculating the characteristics of the spacecraft: mass, density, volume, a moment of inertia, production cost, production time, as well as characteristic parameters such as memory capacity, swath width, resolution, etc.

Thirdly, the main characteristics of the designed spacecraft are calculated, including mass, dimensions, volume, a moment of inertia, energy consumption, cost and time of its production. In case of emerging discrepancy of the obtained characteristics to the required (set by the customer), there is a possibility of change of composition of on-board systems of the spacecraft and parameters of on-board equipment and the subsequent iterative recalculation of characteristics of the spacecraft. After each calculation iteration, a protocol is formed that reflects all the calculated and given characteristics of the on-board systems.
On the fourth step, the basic parameters of the space monitoring system are set, which include the number of spacecraft in the system, their active lifetime, the duration of payload operation on a single orbit pass, the minimum altitude of the Sun above the horizon during the sensing, the maximum allowable angle of deviation of the spacecraft during the operation, the time of image preparation for sending to the ground control complex and the required level of processing of the received images.

On the fifth step, the launch vehicle is automatically selected according to the number of spacecraft, their mass and volume. The selection of the launch vehicle is performed with a simultaneous calculation of the number of required launches and their cost.

On the sixth step, geographic coordinates, equipment and cost of creation of ground complexes for receiving information from the space monitoring system are specified.

On the seventh step, geographic coordinates and names of observation objects of the space monitoring system are determined.

On the eighth step, the spacecraft orbit is selected from the list of available orbits, or a new orbit is created for which the following parameters should be specified: perigee altitude, apogee altitude, inclination, ascending node longitude, perigee argument and launch date. Figure 3 shows the choice of space system parameters.

Then, a simulation of the space monitoring system functioning is performed, as a result of which the following parameters are calculated: an average period of surveying of the selected objects, an average speed of information delivery to the ground point, total captured area of the Earth’s surface, number of transmitted images and time of the spacecraft stay in orbit. Figure 4 shows the simulation process.

Finally, the discount rate is set and the economic performance of the space monitoring system is calculated. The internal rate of return, discounted net income, payback period and cash flow are calculated. The cost of creation and/or lease of ground complexes of information reception, characteristics of the cost and time of spacecraft production, parameters of the system deployment are used as initial data for calculation of the system economic efficiency indicators. In case of detection of inconsistency of the calculated economic indicators with the required ones (set by the customer), there is an opportunity to return to any of the stages of selecting a thematic task, setting the characteristics of on-board systems of the spacecraft, selecting the parameters of the monitoring space system, the spacecraft orbit, and repeat the simulation modeling. After each stage of calculation of economic indicators of the space monitoring system, it is possible to form a protocol of results of calculation of
system characteristics. The resulting protocol serves as the basis for the tactical and technical specifications for the space monitoring system being created.

![Image](image_url)

**Figure 4.** Modeling the functioning of the space monitoring system.

5. **Conclusion**

The approach to the design of remote sensing systems is described, as well as, software to determine main design parameters and modelling the functioning of cost-effective remote sensing satellite systems is developed. The proposed approach allows determining the main design characteristics of a competitive remote sensing system, developed within the framework of commercial projects, by the formation of a list of thematic tasks and requirements for their solution. This approach will make it possible to increase the efficiency of attracting private and venture capital investments into promising projects on the creation of remote sensing systems. On the basis of the proposed approach, the main design characteristics can be chosen of a high resolution remote sensing small satellite that can be formed in order to solve relevant observation problems.

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7. **References**

[1] Baklanov A I 2018 New Horizons of Space Systems of Optical-Electronic Observation of High Resolution Earth *Rocket-Space Device Engineering and Information Systems* **3** 17-28

[2] Baklanov A I 2018 New Horizons of Space Systems of Optical-Electronic Observation of High Resolution Earth (Part II) *Rocket-Space Device Engineering and Information Systems* **4** 14-27.

[3] Skidanov R, Strelkov Y, Volotovsky S, Blank V, Ganchevskaya S, Podlipnov V, Ivliev N and Kazanskiy N 2020 Compact Imaging Systems Based on Annular Harmonic Lenses *Sensors* **20**(14) 3914 DOI: 10.3390/s20143914.

[4] Kazanskiy N, Ivliev N, Podlipnov V and Skidanov R 2020 An Airborne Offner Imaging Hyperspectrometer with Radially-Fastened Primary Elements *Sensors* **20**(12) 3411 DOI: 10.3390/s20123411.

[5] Belward A S and Skøien J O 2015 Who launched what, when and why; trends in global landcover observation capacity from civilian earth observation satellites *ISPRS Journal of Photogrammetry and Remote Sensing* **103** 115-128.

[6] Sweeting M N 2018 Modern Small Satellites-Changing the Economics of Space *Proceedings of the IEEE* **106** 343-361.
[7] Kirilin A, Akhmetov R, Kurenkov V, Stratilatov N, Abrashkin V, Kucherov A, Safronov S and Yakischik A 2015 Generation of Land Remote Sensing Satellites Conceptual Design Based on Regard to Required Efficiency Indices Procedia Engineering 104 65-75.

[8] Jafarsalehi A, Fazeley H R and Mirshams M 2016 Spacecraft mission design optimization under uncertainty Proceedings of the Institution of Mechanical Engineers 230 2872-2887.

[9] Kucherov A S, Kurenkov V I and Yakischik A A 2013 Spacecraft designing with the aid of problem-oriented system integrated with 3D design system Proceedings of 6th Conference on Recent Advances in Space Technologies 523-526.

[10] Kurenkov V I, Kucherov A S and Yakischik A A 2018 Developing statistical models of satellites onboard systems masses based on cluster analysis Izvestiya Samarskogo nauchnogo centra RAN 20 45-53.

[11] Kurenkov V, Shilov L, Kucherov A and Yakischik A 2018 Methodology of optimizing the angles of solar cell batteries installed in land-remote sensing satellites, considering their dynamics AIP Conference Proceedings 2046.

[12] V I Kurenkov and A S Kucherov 2019 Methodology and software for estimating target efficiency of land remote sensing satellites at the stage of design J. Phys.: Conf. Ser. 1368 042037.