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Evaluation of Development of Advanced Remote Technologies for Sensing the Earth and Near Space Objects

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***Abstract* – The article studies current trends of global digitalization of all spheres of society, including economic activities. The author analyzes and substantiates the significant contribution of space technologies and knowledge to the development of the world economy. Information obtained from the space helps solve pressing business problems. It is necessary to apply objective methods for evaluating and forecasting the effectiveness of using space information. It has been proven that a new scientific problem is prediction of the influence of promising space services on the efficiency of economic processes and economic growth. A model for assessing the economic efficiency of advanced space technologies, products and services in the context of resource constraints was built.**

Keywords – knowledge economy; digital economy; digital Earth; mathematical methods; world economy; space technologies.

I. Introduction

Currently, the global and Russian economies are acquiring features of knowledge and digital economies. The Government of the Russian Federation approved the program of the Digital Economy of the Russian Federation aimed at creating a domestic digital platform for collecting, processing, storing and distributing Earth remote sensing data that meets the needs of citizens, businesses and government (the Digital Earth program) [1]. The important results of space activities (navigation, communication, use of space energy, redistribution of sunlight, etc.) were not included in the Digital Earth project. The results of space activities and their intellectual processing using methods of fundamental mathematics and computer science can become a basis for the digital economy. It is necessary to have a theory for managing economic processes based on space information, including models describing the influence of space information on economic processes, as well as theoretical and practical fundamentals for using the results of space activities to solve economic problems.

The digital economy offers ample opportunities for the development of the system of management of economic processes at the level of the enterprise, industry and state. Modern technologies can be used to create an environment of the high-tech digital economy management platform which will minimize the human factor, corruption and errors, automate the collection of statistical, tax and other data, ensure decision-making based on the analysis of actual situations. The tool for automated decision-making can be intelligent control systems and intelligent algorithms embedded in various devices and machines. The main resource that ensures operation of intelligent systems and “intelligence of things” is big data, visual observations and measurements (RSD, GLONASS / GPS navigation information, data exchange via communication channels, etc.), knowledge of the global information space. By processing big data using artificial intelligence methods, creating self-learning neural networks, information is endowed with a specific economic meaning. The digital economy and space information penetrate into all areas of traditional business increasing productivity and decreasing costs. The convergence of space information from various sources and data from the global information space will result in economic knowledge and conclusions for the automated management of economic processes in various sectors of the national economy.

One of the most important areas of development of the Russian Federation is space exploration. Its development is a key issue of national security [2]. However, high cost of space programs and limited resources determine the urgent need to find ways to apply the results of space activities. One of these areas is creation of intelligent space systems that are competitive in the global and domestic markets. They are aimed at solving specific problems in various sectors of the economy [3]. The widespread use of intelligent systems in solving economic problems will transform industry-specific business processes and enhance their efficiency.

II. Development of Intellectual Space Systems

As a result of the evolution of the economic system, the volume of material production does not decrease, but properties of goods change. As a result of a new transformation of the economic system, goods will have properties of "smart" things that can integrate into economic systems (smart homes, smart cities) [4]. Big data will be a basis of smart things. Big data include visual observations and measurements (remote sensing data, GLONASS / GPS, meteorology, data exchange via communication channels, etc.), knowledge of the global information space. After processed using modern mathematical methods, they are transformed into knowledge used for managing economic processes. This is confirmed today by the trends observed in the space services market. The Earth remote sensing market is characterized by the following features:

1. Growing involvement of remote sensing data in civilian traffic and increased competition (Chinese, Korean, Japanese and other data) reduce prices of data and cause the need to use to more complex types of data delivery and processing in the form of information services [5].

2. The emergence of a huge number of small spacecraft devices (capable to shoot in a daily mode with a high ultra-high resolution) increases the volume of remote sensing data which requires data storage, processing, and provision in cloud systems, and data processing automation.

3. The global SRS market (Fig. 1) whose volume is estimated at $ 2.75 billion, continues on growing. In 2025, it will be $ 4.64 billion with a cumulative average annual growth of 7.9%. At the same time, the total earning potential in each segment will be:

• data: $ 13.67 billion;

• data processing: $ 6.92 billion;

• information products: $ 15.97 billion.

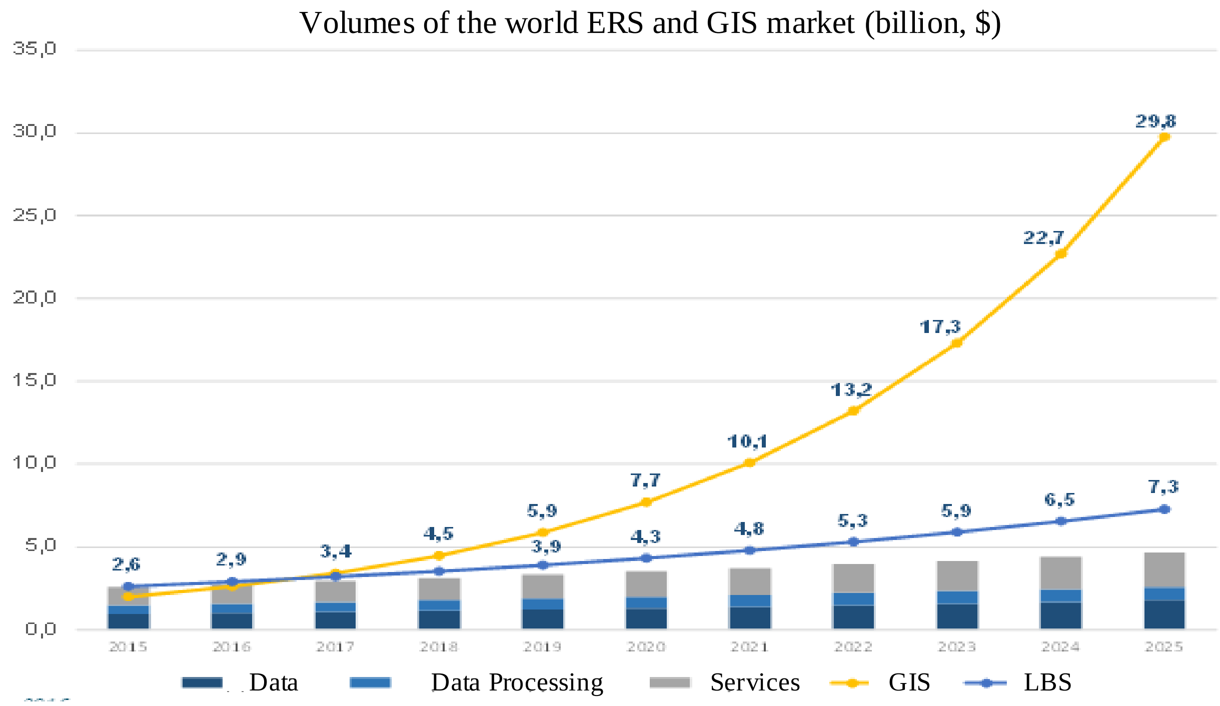

Fig. 1. Analysis of the global market for remote sensing data and services. Compiled by the author on the basis of [6].

4. The consistent decline in prices for raw Earth remote sensing data with the subsequent desire to make them free of charge. The volume of the data market is 1.7-2.0 billion US dollars, but the share and marginality of the largest players is decreasing.

5. The development of product lines through the development of services that use deep data processing, increasing value for the consumer, and added value for operators;

6. The development of combined and hybrid solutions (space + aerial photography, remote sensing + navigation + communication, remote sensing + geodesy and cartography);

7. The growing demand for technological remote sensing services supported by increased availability of communication channels, consumer devices, b2b, b2g, g2c interaction portals;

8. The development of new onboard equipment and ground infrastructure to enhance the quality of space information (multi-zone scanning devices for Earth remote sensing satellites which are the most complex optical-mechanical electronic systems for the newest Russian remote sensing satellites

Meteor, Okean, Obzor-O, Electro, and Arktika). Spacecraft devices receive images of the planet surface in several spectra, solving various tasks of climatic and environmental monitoring – from hydrometeorological observations to fire monitoring. One more example of new technologies is the DOZA-ELECTRON and DOZA-PROTON programs [7] which simulate the effects of electron and proton radiation from the outer space. The required accuracy of remote sensing can be achieved by applying technologies laser scanning and UAVs.

The growth of the space services market is due to the expansion of the number of services in different areas of service utilization through economic analytics.

Services are being transformed into new services based on space information - intelligent space systems – which integrates technical capabilities of space services and capabilities of machine learning and artificial intelligence for data processing. As a result, we have a new paradigm of the space industry. Due to the integration of space and data mining technologies, a product with high-quality technical and economic characteristics that has a high added value was produced.

Intellectual space systems solve a number of urgent problems. In particular, objective systems for analyzing and monitoring projects automate processes and reduce the human factor. This approach reduces complexity of the processes and cost of implementation. Moreover, automatic systems for obtaining economic recommendations reduce the number of bureaucratic and logistical procedures, and enhance economic efficiency.

Thus, intelligent space systems solve the following tasks:

- increase the added value of space services;
- reduce the complexity of project support works;
- increase objectivity of cost estimates;
- reduce the number of bureaucratic and logistic processes;
- reduce the corruption component;
- improve the effectiveness of decisions.

Services capable of solving specific economic problems based on remote sensing data and their subsequent processing using artificial intelligence methods can be integrated into a digital platform for collecting, processing, storing and distributing Earth remote sensing data.

III. CONVERGENCE OF SPACE INFORMATION

The traditional sectors of the economy are changing. In many countries, automatic agricultural machines are used in fields. Their spatial coordinate positioning is carried out through the use of navigation systems (GLONASS, GPS). Irrigation, fertilization, pest treatment are controlled by real-time automated intelligent systems using remote sensing data.

The mechanisms for managing and controlling economic activities should be oriented towards the use of results of large state-scale projects aimed at ensuring economic growth and social development of Russia. Examples are as follows: a project involving the launch of more than 600 small communication satellites and remote sensing of the Earth ("Sphere"), a project aimed at creating a local system for improving the accuracy of geolocation (pseudo-satellites). The commercial success of these projects is due to the effective use of the results for solving economic problems.

The integrated application of the results of space activities and intellectual processing methods will become a basis for a new paradigm of economic process management and a new source of economic growth. Management of economic processes will be built on intelligent digital cloud platforms with open interfaces for machine-machine interaction. They will expand interaction of economic entities by creating their own applications based on this platform (with mandatory safety and compliance certification). The development of intelligent information systems used for real-time remote control and management of business processes will allow for the implementation of models and systems that can effectively plan and manage all types of resources. This system is a dynamic feedback system. The intelligent system will track production fact-plans across the industry, build accurate forecasts based on inventory and logistics, and respond to deviations and optimize daily, monthly, annual and other plans taking into account changing needs.

In addition to remote sensing technologies and economic analysis of objects, new sources of economic growth are technologies of deep space development. Some countries are forming the legal basis for commercial development of both near-Earth space and deep space objects. In 2015, the United States adopted the Commercial Space Launch Competitiveness Act" [8] which regulates various aspects of participation of the American private sector in the national space activities, including launch services and operations for controlling remote sensing satellites, and reduces administrative barriers to the implementation of private projects in the Earth orbit. This law allows the US citizens to engage in the development of planets and asteroids, own and manage the resources obtained, including water and minerals. The adoption of these laws speaks for the great interest of the United States in obtaining exclusive access to deep space resources. In 2019, SpaceX, a private aerospace company, conducted the first fire tests of the Raptor engine for the Starship spacecraft for interplanetary flights. According to SpaceX forecasts, by 2030 the engine will allow for traveling to the Moon and the Mars.

Space programs of some countries involve the development of deep space as a priority. China is implementing a project on the study of the Moon. The Chinese lunar rover "Chang'e-4" automatically conducts experiments on planting cotton. The European Space Agency (ESA) announced that it is going to build a permanent lunar base "Moon Village". The Federal Space Program of Russia for 2016-2025 provides for the development of promising technologies and space systems to implement Moon and deep space exploration programs.

The results of large-scale projects indicate that in the near future space technologies will be involved in economic processes at a qualitatively new level. Let us consider economic aspects of rapid development of the outer space.

IV. Economic analysis and forecast of opportunities and difficulties of economic development of space

The emergence of new technologies allows us to begin commercial exploration of space. The emerging base for the economic assessment of reserves in the asteroid belt shows that the cost of space resources per inhabitant of the Earth is about $ 100 billion. [9] Technological accessibility and economic profitability of their extraction will eliminate the problem of resource limitations [10].

In addition to iron, nickel and magnesium, asteroids contain precious and rare earth metals (rhenium, iridium, etc.). Mining can be carried out in different ways: development of opencast deposits, mines, collection of metals from the surface using magnets, bio-mining, etc. The space development requires autonomous robotic stations for extracting metals and developing the space infrastructure. Orbital space factories will make it possible to locate “dirty” production beyond our planet.

On the asteroids which are the closest to the Earth, there are huge reserves of minerals: gold, cobalt, iron, manganese, molybdenum, nickel, osmium, palladium, platinum, rhenium, rhodium and ruthenium, etc. They are located on the surface.

Even the extraction of iron ore can be cost-effective. For example, the value of iron ore on (16) the Psyche is $ 10 trillion [9]. The NASA's research mission is planned for 2024.

Industrial development of the near-Earth space is required.

The deposits of rare earth metals are too scattered in their location which complicates mining.

Today, 95% of the global supply of rare earth metals belongs to China which significantly reduced their export due to the need to meet their own industry needs.

TABLE I. GENERAL RESERVES OF RARE-EARTH METALS

Country	**Reserves**	
	Million tons	***%***
China	55.0	42.3%
Russia	28.0	21.5%
Brazil	22.0	16.9%
USA	18.0	13.8%
India	3.1	2.4%
Australia	2.1	1.7%
Other countries	1.8	1.4%
Total	130	100%

Precious, rare and rare-earth metals which are essential for the development of high-tech industries are very expensive. In addition, with the reduced Chinese export quota, prices of rare earth metals are rising.

The payback of space mining projects can be achieved through the development of new technologies and competencies that can be used in solving other problems. However, since the demand for rare earth metals is growing, and their mining is associated with the need to address a number of issues, including geopolitical ones, it is necessary to develop technologies for obtaining them from the space.

More than 9000 near-Earth asteroids were discovered.

The diagram shows the dynamics of discoveries of near-earth asteroids over the last 20 years.

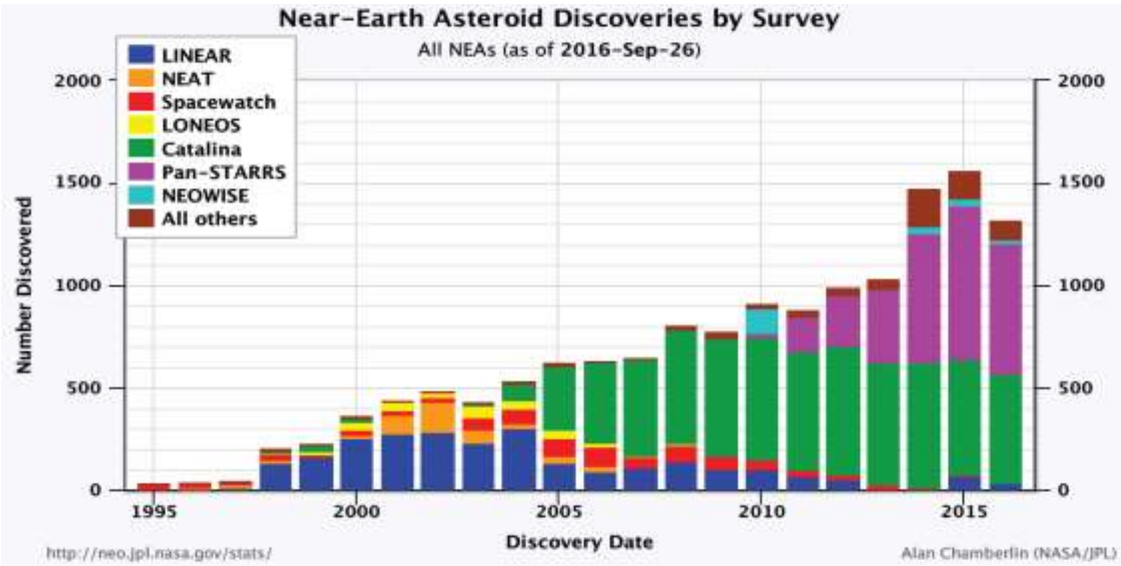

Fig. 2. Dynamics of discoveries of new near-Earth asteroids (Source: http://neo.jpl.nasa.gov/stats/)

Industrial development of extraterrestrial objects is a system of serious problems for the entire global economy:

- Technological problems. Development and implementation of mining programs for the near-Earth space.
- Legal problems. The world community needs to adopt rules for space mining.
- Economic problems. It is necessary to attract huge resources with a long payback period. Accurate calculation of project profitability is required.

To describe and predict the industrial development of the near-Earth space, it is necessary to develop theoretical economic models describing the economic growth under the influence of digitalization and redistribution of labor and financial resources to the new economic sector.

The difficulties of mathematical modeling of the economic component of the industrial development of near-Earth space are due to the vagueness of projects and the lack of basic data. However, using rough approximations, one can simulate economic processes.

It is obvious that in any world economic development scenarios, it is advisable to implement projects of exploration of the near-Earth space as early as possible. It is necessary to improve onboard measuring equipment and ground infrastructure of spacecraft, use the full range of remote sensing technologies, including laser scanning and UAVs.

Let us build the mathematical model for achieving the economic effect of implementation of new space technologies.

V. Model of Evaluation of Economic Efficiency of Advanced Space Technologies

Let us build a model of economic efficiency of advanced space technologies, products and services in the context of resource constraints.

Let us introduce the following notation:

$x(t) = (x_0(t), x_1(t), ..., x_n(t))$ is the vector-line of types of products and services produced using traditional and advanced space technologies for the t-th period where $x_0(t)$ is the volume of products for the t-th period, $\{x_1(t), ..., x_n(t)\}$ is the set of volumes of products and services produced and delivered using new technologies for the t-th period;

$p(t) = (p_0(t), p_1(t), ..., p_n(t))$ is the vector-line of prices of products and services produced and delivered for the t-th period ;

$w(t) = (w_0(t), w_1(t), ..., w_n(t))$ is the vector-line of prices of resources used for producing and delivering products or services in the t-th period within the interval $T = [1,\ 2, ..., N]$

Formal functions expressing the relationship between costs of economic resources and output can be presented as

$$X_l = F(x_l(t)),\ l = 0,1,...,n, \tag{1}$$

$\Pi(x_l(t))$ the gross profit for each type of product or service is

$$\Pi(x_l(t)) = p_l F(x_l(t)) - [w_l \cdot x_l(t) + c_0],\ l = 0,1,...,n, \tag{2}$$

where $TR(x_l(t), p_l) = p_l F(x_l(t))$ - monetary revenue, the volume of sales;

$TC(x_l(t), w_l) = w_l \cdot x_l(t) + c_0$ is the total cost of production of the lth product, including variable $w_l \cdot x_l(t)$ costs in the production of products and c_0 fixed. The total gross profit for N periods for all types of products (services) is

$$\Pi_\Sigma(x_l(t)) = \sum_{t=1}^{N} \sum_{l=0}^{n} \Pi(x_l(t)). \tag{3}$$

Intensity $q_l = \dfrac{dx_l(t)}{dp_l}$ of sales of basic products (services) and diversified products depending on the price is

$$q_l = \frac{dx_l(t)}{dp_l}$$

$$q_l = q(x_l(t), p_l),\ l = 0,1,...,n, \tag{4}$$

The economic efficiency of new types of products (services) is associated with the condition

$$\Pi_\Sigma(T) \geq \Pi_*, \tag{5}$$

where Π_* is the minimum amount of gross profit in monetary terms, corresponding $x_l^0(t)$ to the break-even point of production, i.e. when $\Pi(x_l(t)) = 0$ and the company (industry) can operate within the interval $T = [1,\ 2, ..., N]$. The dimensionless value can be used as a criterion for assessing the level of economic efficiency of production based on advanced space technologies

$$\gamma = \frac{\Pi_\Sigma(T) - \Pi_*}{\Pi_*}. \tag{6}$$

At the same time, the economic efficiency of the output of products and services based on advanced space technologies will be evaluated in the following forms:

- new types of space products (services) are cost-effective, if $\gamma \geq 1$;

- new types of space products (services) have little effect on economic efficiency, if $\gamma \in [0, 1]$;

- new types of space products (services) are economically inefficient if $\gamma \leq 0$.

The efficiency of projects based on advanced space technologies will depend on the cost of delivery of required elements of the space infrastructure to the orbit, complexity of creation of the required infrastructure, projects implementation duration, etc. The choice of an optimal structure of existing and new products (services) in conditions of limited financial resources, taking into account demand functions q_l (1), will be reduced to a multicriteria vector optimization problem:

$$(\Pi(x_0(t)), \Pi(x_1(t)), ..., \Pi(x_n(t)) \rightarrow \max_{(x_0, x_1, ..., x_n)} \qquad (7)$$

under the following conditions:

a) gross profit should cover all costs

$$\sum_{t=1}^{N} \sum_{l=0}^{n} \Pi(x_l(t)) \geq \Pi_*, \qquad (8)$$

b) the costs for creation and sale of products (services) should not exceed C^* for period T

$$\sum_{t=1}^{N} \sum_{l=0}^{n} w_l x_l(t)) \leq C^*. \qquad (9)$$

The optimal solution of the problem (1) - (9) is the one under which the maximum economic efficiency is achieved using advanced space technologies.

VI. RESULTS AND CONCLUSION

1) The use of space information for managing economic processes solves complex business problems. It is necessary to develop objective methods for evaluating and predicting the effectiveness of using space information. It is necessary to consider a number of theoretical and fundamental issues that have practical application and are associated with the development of mathematical methods for predicting the effectiveness of the use of space services. Based on the simulation modeling using modern methods of artificial intelligence, it is necessary to solve complex issues (analysis of unstructured and heterogeneous information, creation of a stochastic simulation system that takes into account heterogeneous factors that ensure formation and evaluation of forecast scenarios). The use of space information for managing economic processes is of great importance. A new problem is prediction of the impact of promising space services on the efficiency of economic processes and economic growth.

Complexity and multidimensionality of the task of forecasting the development of methods for managing economic processes on the basis of space information determines an interdisciplinary approach to this problem. To develop new forecasting methods, it is necessary to develop and improve mathematical methods for analyzing the domain (space services), constructing forecast scenarios, and evaluating the effectiveness of their use and cost. After obtaining fundamental results in the mathematical construction of forecast scenarios, the problem of building information algorithms for implementing mathematical models arises. This task involves development and creation of new methods and algorithms for intelligent extraction, interpretation, presentation and analysis of data (Data Mining, Machine Learning), as well as implementation of artificial intelligence models.

2) Industrial development of the near-Earth space opens up great prospects for stable production of resources (minerals) located on asteroids. Using mathematical modeling, it becomes possible to identify optimal strategies for exploration of the near-Earth space and methods of international cooperation. It should be borne in mind that:

- the price of all earthly fossils will rise.
- the project implementation time is equal to the time when the price of minerals will be high.
- the main problem is of economic nature.
- the cost of these projects is equal to the cost of luxury goods, sports, military spending, etc.
- the first participant will be able to get a payback at the expense of the other ones.

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