Acta Astronautica 69 (2011) 667–675

Contents lists available at ScienceDirect

Acta Astronautica

journal homepage: www.elsevier.com/locate/actaastro

Effectiveness of the long-term program of scientific and applied experiments on the ISS Russian segment ☆

Konstantin Elkin, Alexander Ivanov, George Karabadzhak, Gennady Raykunov, Boris Zagreev *

TSNIIMASH, Korolyov, Russia

ARTICLE INFO

Article history:
Received 31 January 2011
Accepted 18 May 2011
Available online 15 June 2011

Keywords:
Effectiveness evaluation of research programs
Long-term program of scientific and applied experiments
ISS Russian segment
Planning of research programs
Decision support systems

ABSTRACT

The analysis and effectiveness evaluation of the Russian long-term program of scientific and applied experiments on the ISS RS have been done on the basis of adopted indicators and statistics accumulated for the entire period of manned flight of ISS. The planned and actual implementation of experiments, results of comparison of the Russian and foreign programs, as well as resources and capacities of the ISS for experimental research are presented. The requirements and criteria for more in-depth analysis of this program, assessment of the effectiveness of its implementation, the procedure for the most priority experiments selection are suggested. The analysis of problems and bottlenecks identified during the implementation of program in the period 2001–2009, as well as the forecast of long-term program realization has been done. Joint experimental programs are proposed, which leads to more efficient use of ISS resources for partners.

1. Introduction

At present, the International Space Station (ISS) is regarded primarily as a multi-purpose research laboratory for a wide range of scientific and technical research connected with the further exploration of the Solar system and development of technologies for the terrestrial applications [1]. Operations of the ISS as a whole and the Russian segment (RS) as an integral part were recently extended until 2020.

On the basis of analysis of the capabilities and resources of the ISS and results of the past research it is necessary to develop research programs (RP) and to build a mechanism for selection of the most important and significant experiments for priority implementation.

2. Research capabilities of ISS RS

Currently, Russian scientists conduct experiments on the service module (SM) and small research modules 1 and 2. There are 127 units of scientific equipment onboard for the time being. More than 3600 equipment and material units were delivered to the Russian segment of the total weight more than 2 t. The total weight of the space experiment (SE) results returned to Earth is about 0.6 t. Recently launched modules provide additional R&D capabilities, especially given the fact that, unlike Service Module, they carry universal workstations equipped with various scientific equipment both outside and inside pressurized compartments.

In late 2011 or early 2012 the Russian multi-purpose laboratory module (MLM) should be launched to contribute significantly in the ISS RS research capabilities. According to the preliminary estimation, after MLM introduction it will support approximately 40% of the total amount of experiment planned for the ISS RS until 2015 as well as provide some additional service functions.

☆ This paper was presented during the 61st IAC in Prague.

* Corresponding author. Fax: +7 495 5134884.
E-mail addresses: elkin@tsniimash.ru (K. Elkin), iai@tsniimash.ru (A. Ivanov), gfk@tsniimash.ru (G. Karabadzhak), corp@tsniimash.ru (G. Raykunov), zbv@tsniimash.ru (B. Zagreev).

0094-5765/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.actaastro.2011.05.018

MLM opportunities for R&D are comparable with the international partners' capabilities onboard.

By 2015, it is also planned to deploy two scientific and power supply modules of about 15 kW each.

Also, planned commissioning of the data relay system based on Luch satellites will increase the ISS RS information transmission capabilities.

In total the plans call for 8 modules of the ISS RS by 2015, with total power capability of 30 kW and the payload pressurized volume about 40 cubic meters.

3. Main directions of R&D and peculiarities of the ISS RS

Developing a program of research on the ISS, one should take into account the characteristics of ISS RS and opportunity of its use as an experimental laboratory for research, including its comparison with specialized research satellites.

3.1. ISS orbit and orientation

Orbital altitude of ISS allows effective observations along the whole bandwidth. It is also worth to mention that the orbital altitude corresponds to the maximum level of ionosphere ionization allowing the effective ionosphere plasma research. ISS orbit and nadir orientation meet Earth remote sensing requirements, however, the orbit inclination prevents monitoring of the significant part of the Russia territory.

The ISS orbit is also ill-suited for astrophysics researches, because at any given moment most of the celestial sphere is unavailable for observations; due to frequent sunrises and sunsets there are harsh conditions for thermal stabilization needed to ensure stability of high-precision optical systems.

Nadir orientation might be satisfactory for some scanning overview observation experiments, but for long-term monitoring of specific objects there is a need for the independent system of stabilization (preferably a separate 3-axis stabilized platform).

3.2. Conditions for carrying out experiments on the ISS RS

ISS is subject to a wide range of vibrations varying both in frequency and amplitude. The dynamic behavior of the station imposes constraints on the precision and stability of the sensors' pointing, which is essential for a number of astronomical experiments. It also makes impossible to reach microgravity level below 10^{-5} g for a number of gravitation sensitive experiments (material science, biological and others).

Because of the complex spatial structure of the ISS, a large part of the celestial sphere is overlaid by solar panels and other structures. On the other hand, the current ISS configuration allows simultaneous measurements in the spaced locations.

The ISS own atmosphere may hinder some experiments that require ultra-high vacuum. Thermal conditions on the surface are characterized by an abrupt change of luminance and periodic heating/cooling conditions.

ISS has long operation period (20+ years), which allows solving monitoring tasks like "space weather" observations, accumulating the long-term statistics on various space processes, as well as long-term exposing of samples.

3.3. The crew presence

The crew presence allows a gradual upgrade of experimental base, replacement of equipment or components, assembling of large structures part-by-part. Of course, the study of peculiarity of human life and work in space remains a major task of scientific program.

All above supports the conclusion that the ISS should be seen primarily as a multi-purpose research laboratory addressing a broad range of scientific and technical problems in basic research area, in research aimed at further exploration of the Solar system, as well as at innovations tailored to the Earth needs. Accordingly the ISS should be provided with a wide range of versatile equipment for each research area. Also, it is reasonable to assume that the subject field experts with the corresponding training should carry out the dedicated experiment sets in space.

There is a need for detailed analysis and comparison of research capabilities provided by the ISS and unmanned satellites taking into account the ISS characteristics described above as well as the cost considerations.

All in all, the study on manned space complexes and unmanned spacecraft are mutually complementary, although plans for such research are not yet sufficiently coordinated. In future the development of space systems naturally combining the advantages of both approaches is possible and necessary. In Russia for the past few years the project of OKA-T unmanned spacecraft served during periodical dockings with the ISS is developed. Partially this idea has already been implemented during the prolonged autonomous research flights of Progress-M transport spacecrafts after undocking from the ISS.

4. Results of the implementation of the research program on the ISS RS

4.1. Long-term program of scientific and applied experiments on the ISS RS

Research and experiments aboard the Russian segment of the ISS are conducted within the framework of the Long-term program of scientific and applied experiments on the Russian Segment of ISS [2]. Prior to 2008, the work was carried out under the program approved by Rosaviakosmos and Russian Academy of Sciences in 1999, which included a lot of experiments (345, including ones added in process) in spite of the budget shortages as compared with the planned initial resources and configuration of the ISS. As a result, many of SE have become irrelevant or unrealizable. All this required a revision of the Long-term program (LTP).

A new version of program was adopted by Scientific and Technical Advisory Council [3] in late 2008. In comparison with previous version the new program was significantly reduced. The main part of the program consisted initially of 156 experiments (currently 189). The part of experiments was known to be unrealizable for different reasons (lost scientific relevance, broken cooperation ties, lost technologies, etc.) and was withdrawn from the program. At present only experiments that were implemented or actively prepared remain in the program.

Experiments in the program are grouped into thematic categories or areas of scientific and technological research as follows:

Physical and chemical processes and space material science (*PCM*): Purpose of research in this area is a study of various physical and chemical processes, as well as material science research under microgravity conditions.

Geophysics and the near-Earth space (*GPH*): The aim of space research and experiments in this area is a study of geophysical processes from outer space, including the processes occurring in the upper atmosphere of the Earth and near-Earth space environment.

Medical and biological research (*MBR*): The main objectives of the program of medical and biological researches at this stage are:

- improving health care of the long flights on the Russian segment of the ISS; biomedical experiments for future flights to the other planets,
- elucidation of mechanisms of adaptation of biological objects, including humans, to unusual space flight conditions (weightlessness, cosmic radiation, and artificial habitat in the spacecraft).

Earth remote sensing (*ERS*): It was already mentioned that the orbit and the conditions of the Earth observation on the ISS are not optimal comparing with unmanned satellites for regular high-precision Earth remote sensing, particularly for Russian national territory. However, the ISS is suitable for development and testing of new methods and tools for the Earth remote sensing from space. In particular, there is a specific set of experiments aimed at developing a scientific basis of disasters forecasting. The proposals on the equipment of specialized spacecraft are prepared for the particular remote sensing tasks.

Solar system investigations (*SSI*): Purpose of research in this area is a study of the Sun, planets and small Solar system bodies. There are planned experiments in the following areas of research:

- Study of the Sun.
- Study of the interplanetary matter on board the ISS by contact methods (mass spectrometric, physical and chemical methods of analysis of near-Earth space dust).
- Planetary and small solar system bodies investigations.

Space biotechnology (*BTH*): The aim of experiments in this area is a study of the influence of space flight factors on biological and biotechnological processes, investigation and improvement of basic technologies for manufacturing of biological products under microgravity conditions.

Technical studies and experiments (*THN*): The aim of technical research and experiments is the development and improvement of space techniques and technologies, the use of new space technologies to increase the efficiency of research on ISS RS.

Astrophysics and fundamental physical problems (*AST*): Purpose of research in this area is to study the structure of the Universe and processes outside the Solar system as well as associated fundamental physical problems.

At the ISS these experiments do not require high precision orientation and stabilization and too low level of electromagnetic interference. The examples are observations in the short-wave bandwidth (gamma, X-ray) and observation of primary cosmic rays

Study of the physical conditions in space on the ISS orbit (*PCO*): Purpose of research in this area is to obtain data on radiation, electromagnetic and other physical conditions in the ISS orbit and its impact on the safety of the crew, space equipment and materials.

Education and promotion of space research achievements (*EDU*): The aim of this activity is to carry out scientific experiments and "Lessons from space" for education and popularization of space research and exploration as well as for promotion of the cosmonautics achievements.

4.2. Analysis of quantitative indicators of the long-term program

Simple assessment of a Long-term program can be obtained on the basis of statistics of performed experiments. 39 experiments of the program are already completed, 64 are being realized on-board the ISS RS and 86 in pre-flight preparation. The average percent of realization is 54.5%.

Fig. 1 represents LTP data as well as the data on the SE implemented on ISS RS in 2001–2010.

One may note that the SE for biomedical (MBR), biotechnology (BTH) and technical (THN) research form the bulk of the research program.

At the same time for MBR the percent of realized SE is much higher than for other research categories in LTP. For PCM, SSI and AST it is necessary to increase the percentage of SE in the research programs for the following years. For other research areas the balance approximately corresponds to LTP.

In average the duration of experiment starting from its inclusion into the Long-term program is few years with dozen of runs in flight phase.

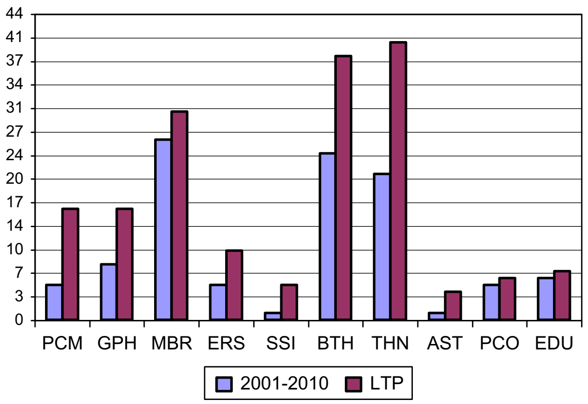

Fig. 1. Distribution of SE in LTP and SE implemented in 2001–2010 on the research category.

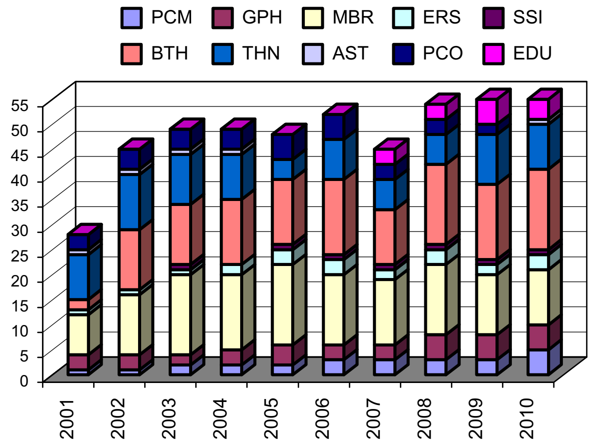

Fig. 2. Number of SE of different categories from 2001 to 2010.

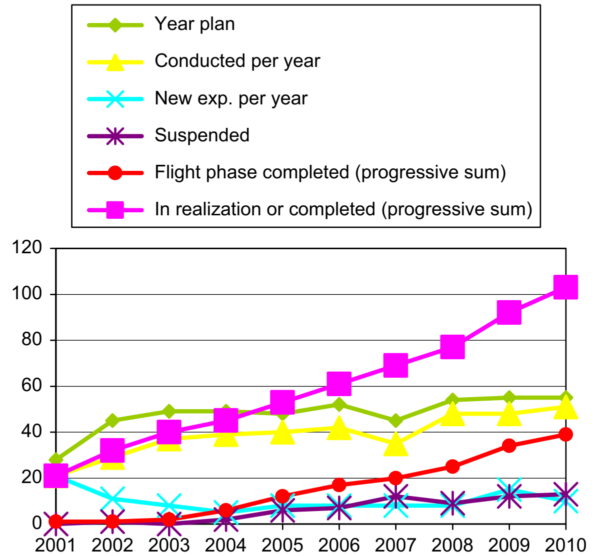

Fig. 3. Total number of SE planned and implemented in the period from 2001 to 2009. Figure shows also the number of new, completed and suspended SE.

The time series of the research program is shown in Fig. 2, which represents the number of the experiments for all increments in 2001–2010 in each research area.

From the diagram in Fig. 2 one can see that the proportion of experiments of different categories is so far relatively stable, however, as it was shown previously, the ratio does not match the corresponding ratio in LTP. Total number of SE for the year can be also seen from the charts in Fig. 3, where the summary data for all experiments is provided. One can see that the number of experiments planned per year on ISS RS gradually increased and reached a level of approx. 55. Also the number of experiments carried out during the year is shown in Fig. 3. One can see the percentage of failure is about 10%.

Cumulative number of experiments with completed flight phase, the total number of conducted or completed experiments, the number of suspended experiments, as well as the number of new SEs is provided too. One can see that the number of imposed new experiments per year averages about 10.

To date, there are 103 conducted or completed SE. Therefore 86 of 189 experiments are not launched yet. Thus, on average 8.6 new SE per year accounts for the remaining 10 years of ISS life, which corresponds to the present rate of program update. This suggests that by 2020 all SE from LTP will be at least launched.

However, flight phase of only 39 experiments is completed so far. To fulfill LTP by 2020 successfully the rate of experiment's completion must be considerably higher.

4.3. Bibliometric analysis of the results of the long-term program

One of the most important metrics of the long-term research program is the number of publications. From 2000 to 2009 the results of the research on ISS RS were published in 609 articles and papers at various conferences. The distribution of these publications on research categories is shown in Fig. 4.

From a comparison of the experiments distributions and the number of publications one can see that in some areas (physical and chemical processes and materials, geophysics and near-Earth space, remote sensing) the number of publications per experiment is increased, while in others is relatively smaller (medicine and biology, biotechnology, education).

Distribution of the number of articles and reports on time is shown in Fig. 5. One can see that the proportion of publications in some areas is stable, while in other areas it changes significantly. For example, the proportion of publications on biomedical issues was large enough in 2003 and then began to decline, which clearly does not reflect the proportion of these experiments in the research program. In contrast, the proportion of publications on remote sensing sharply increased in recent years. One can also see that publications on biotechnology start only since 2004. This is because experiments in this area were started only in 2002.

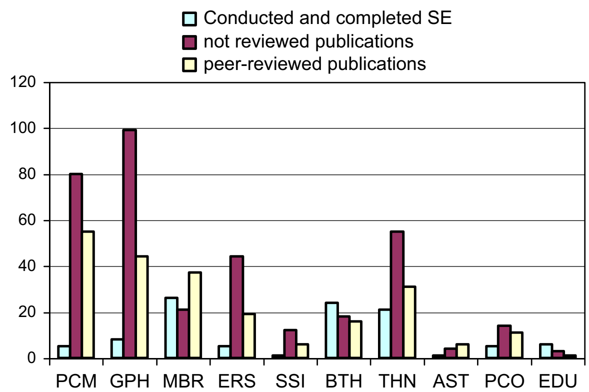

Fig. 4. Distribution of experiments and publications on research categories.

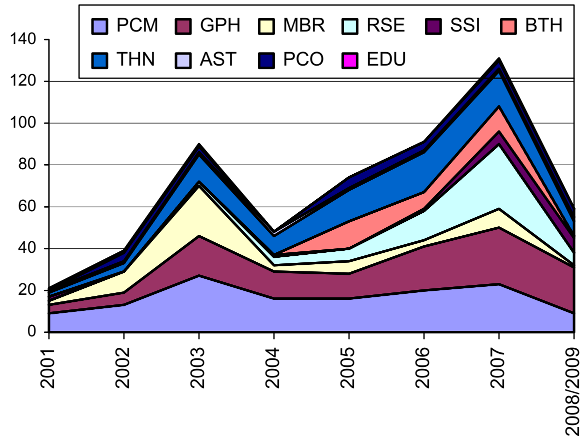

Fig. 5. Distribution of number of publications in time for the various disciplines.

In general there are two obvious peaks of publications in 2003 and 2007. The additional analysis is needed for the explanation. We may just have incomplete information on the latest publications. Now the international database of publications on research on ISS is being developed. More detailed bibliometric analysis (citation index, etc.) will be possible after it commissioning.

4.4. *Applications of results obtained in the Russian segment of the ISS.*

At present, the most significant applied results are obtained from the experiments in the following fields:

(1) Experiments to obtain high-quality proteins in microgravity. Crystallizer experiment holds a record for the data accuracy on the structure of the gene-technological human insulin, which in 2008 contributed to the International Data Bank of proteins. Corresponding investment project has been prepared based on the results of the experiment.
(2) In the field of biotechnology the special medicines against AIDS (SE Vaccine-K), hepatitis B (SE Antigen) cancer (SE Interleukin-k) as well as effective immunomodulators (SE Mimetik-K) were derived. Remedies and stimulators of plant growth (growth hormone, Micefit) have been developed. The effective strains for oil biodegradation (SE Bioecology) are obtained. In 2007 there was a pilot use of the "space" strains at the treatment plant. In order to expand the further use of these results, a number of investment projects have been prepared.
(3) Monitoring of ocean bioproductivity for research and fishing needs. (SE Diatomia, Seiner)
(4) In addition to the space applications used on Earth, a significant number of SE aims to improve efficiency and safety of space exploration:
    - New methods and technologies to find leaks, disruptions, corrosion points, protection against radiation and other negative factors of space.
    - Medical research to preserve the health of astronauts in long-term space flights which are also applicable in clinical practice on Earth.

The experiment results are entered in the Roscosmos data bank and are available for the interested parties. They might be used both for further research (not only in space) and for practical applications.

5. Improving the effectiveness of the research program on the ISS RS

5.1. *The planning and realization of the research programs*

Now there are 4 types of research programs at the ISS RS corresponding to the various stages of SE preparation and realization:

- *Long-term program* (*LTP*): The structure of the program was discussed earlier. The program is actually a list of SE passed through scientific expertise and was approved by the Scientific and Technical Advisory Council of Roscosmos. Criteria for selection of experiments in this program are scientific and practical significance and relevance of the experiment, its technical feasibility, experience of researchers, the expediency of SE realization just on ISS RS. Long-term program is annually updated.
- *Medium-term program*: This program consists of experiments from the Long-term program for which the schedules of their preparation and realization have been prepared. Based on these plans a consolidated schedule of the program is prepared taking into account the resources and the intended funding of ISS research program. Selection of experiments in this program, as well as the terms of their preparation and implementation is determined on the basis of certain criteria. Apart from the scientific and practical significance of experiment they also include the availability of equipment for SE, availability of ISS RS resources and financial constraints. Proposed procedure for the selection and schedule will be described further.
  Medium-Term Program roughly corresponds to the Composite Utilization Plan (CUP) for the U.S. segment of the ISS. However, the Russian program is wider, because in addition to the plans of ISS use it also includes ground preparation plans for all SE. Central document of the program is the consolidated schedule of all works. The program is updated annually.
- *The annual program of preparation and realization of experiments on ISS RS*: Annual program for the SE realization is based on the annually updated medium-term program and is the basis for SE realization funding. In this program the schedule and SE programs are finally fixed. Selection criterion is the readiness of the experiment for launch and the availability of ISS RS resources.
- *Increment ISS RS program*: These programs are developed on the basis of the annual program and set up a detailed work plan for the upcoming increment.

The changes in the annual and increment programs are made exceptionally with special technical decision.

5.1.1. Core resources of the ISS RS and the procedure for the development of the medium-term research program

The main constraints on ISS RS are:

- ISS upmass/dowmass traffic;
- payload volumes in pressurized modules and number of external workstations;
- recourses for collection, storage and transfer of the service and scientific information;
- energy resources for payloads;
- crew time quota for research;
- financial resources.

With limited and expensive resources the combination of experiments that best corresponds to the goal (or goals) should be preferred.

To meet this challenge, as a rule, each goal corresponds to criterion function that is defined against the set of feasible (meeting the limitations) solutions, which is a measure of the goal achievement. One needs to allocate resources between experiments so that the criterion function reaches the maximum. Such optimization tasks are well known and in the simplest case, when the criterion function and the constraints on resources have the appearance of linear equations and inequalities are solving by means of linear programming methods [4]. It is possible if the program is just a simple list of independent SE competing for a pool of resources and such approach was implemented for short-term planning of experiments on ISS RS [5].

However, in this case the criterion function in general is nonlinear and nonadditive quantity and depends on the composition of the whole experimental program and the sequence of the experiments. Existing algorithms and software for planning, in principle, provide the balanced allocation of resources and work time, but the requirement on achieving the maximum of the criterion function makes the task very complicating. The global criterion function extreme in such tasks could be obtained with full reshuffling of schedule, in our case the experiments schedule within the framework of the Medium-Term Program.

But the complete reshuffling of existing plans and schedules for achieving the best solution would not be possible taking into account the large number of SE (189), a considerable amount of time (not just computer time) and work required for revision of the approved plans and contracts, need of concordance of all parameters and agreement between all the participants in each new version of such a timetable. Therefore, under the present procedure the schedules of new SE complement existing schedules which undergo rather minor changes. Only in rare cases, when a new experiment occurs, which is extremely important, or vice versa, the continuation of the ongoing experiment is considered extremely inexpedient, existing plans can be considerable changed.

At present the selection of priority SE and development of medium-term research program is performed as follows:

(1) The existing consolidated schedule of preparation and realization of SE combined with the baseline data on available resources are considered as the initial schedule.
(2) The experiments not meeting certain limiting criteria are rejected.
(3) The research category is determined with the lowest percentage of plan fulfillment.
(4) The highest priority experiment in this area is selected. Experiment priority is determined on the basis of both its scientific relevance and technical readiness. It should be mentioned that currently ranked lists of experiments rather than the experiments comparative weights are used. Thus, under the present algorithm the criterion function is not calculated.
(5) Resources for the first priority SEs are allocated. If we have not enough resources to do so, the next priority SE is selected of this category.
(6) The allocated resources are removed from the pool.
(7) Then the cycle is repeated starting from Step 3 and until there are not enough resources for any of the remaining experiments.

Result of this procedure will be the list and schedule of priority experiments ensuring efficient use of the ISS RS resources. Generally speaking, the described procedure of the priority list and the sequence (schedule) of experiments definition does not provide a global optimal solution. This way one can find only good, but not necessarily the best solution, because, as it was already mentioned, the complete revision from scratch of the research program and schedule is impossible. In addition, such tough and unambiguous algorithm seems currently not suitable mean for multicriterial tasks solution. The following are the current approaches to address these challenges and prospects for their use in planning of research on the ISS RS.

5.2. Criteria for selecting the priority SEs and method of research effectiveness determining and optimal planning

To improve the efficiency of research at the ISS RS one needs to solve the task of comparative assessing, determination of efficiency of both separate experiments and the entire program.

5.2.1. SEs scientific and application significance indicators

There is no direct, objective and reliable metric for scientific work effectiveness and scientific knowledge volume. At the same time, research results have a number of easily counted features no one doubts about positive nature of. These indicators include: the number of related scientific articles and conference papers, citation indices, impact parameters of journals, economic indicators (development costs, actual or potential economic gain), etc.

The main difficulty when using these indicators directly for the SE selection is that they all are of a posteriori nature, that is, in relation to works already done, while the a priori estimation is needed for comparing the planned experiments. To certain degree, the a posteriori metrics related to the previous experiments of the certain research teams and/or institutions might be used to assess the skill of researchers and the relevance of the planned research.

It should be noted that these quantitative characteristics, like any performance metrics of the basic scientific research, are indirect indicators; however, nothing better has been suggested so far. Another common method for assessing the effectiveness and value of research and experimentation is a peer-review expertise for both planned experiments and achieved results. In doing so, the difference between basic and applied research should be taken into account.

For applied research, the criterion function is of eventually economic sense and is determined by the economic effect. It is not always possible to calculate the corresponded effect directly, but still, it should be considered a major fundamental metrics for this kind of research and experiments.

For basic research, the criterion function is fundamentally different in nature. The example of the effectiveness measure of new SE is the information obtained in this experiment per unit cost. In certain works [6] the information theory is suggested as the basis of quantitative measure of scientific significance for both already completed and only planned experiments by evaluating the new information obtained during the experiment.

For example, suppose there are an alternative hypotheses $y_1, y_2, \ldots, y_n$ with probabilities $p(y_1)$, $p(y2)$; … $p(y_n)$, respectively. At that $p(y_1)+p(y_2)+\ldots+p(y_n)=1$. Then, according to [6] the entropy of the current state of knowledge of the problem is a function of type:

$$H(y_1,y_2,\ldots,y_n) = -\sum p(y_i)\log(p(y_i))$$

The value of the experiment depends on this entropy decrease after the experiment. Thus, the value of the results of the experiment is more when, first, we obtained more unexpected result, and second, the more alternative hypotheses were rejected.

However, under such approach one cannot get rid of subjectivity, as the prior probability of the hypotheses $p(y_i)$ are determined interviewing the experts.

5.2.2. Definition of the criterion function for multi-purpose task

Suppose the value of an experiment in a certain research area can be determined, but how one can evaluate the research program consisting of experiments both of basic and applied character?

A number of different methods exist as described above of quantitative indicators (criteria), of value of already obtained or anticipated research outcome. Moreover, in addition to scientific significance there are indicators of technical readiness, skills and experience of researchers etc. To calculate the research efficiency on the ISS RS one has to define how to weight all these indicators and derive some combined indicator. In addition to the tasks of weighing indicators for one experiment, there is a task of summing of several experiments. The task is complicated by the fact that the total value of some experiments is not simply the arithmetic sum of the weights of each SE. For example, the value of two identical experiments is not more than the value of each of them separately (except for the situations when more statistics is necessary for certain conclusions). Thus, it is necessary to assess the efficiency of the program as an entire system.

Moreover, if in separate research areas it is still possible to rank and compare different experiments with expert evaluation, the task of comparing the relative importance of, say, medicine and astrophysics seems rather meaningless (for applied research, such a comparison can be done on the basis of actual or potential economic effects).

Thus, we have in general several criterion functions (corresponding for example different research areas) or one vector criterion function. In order to be able to compare and combine different indicators that are often of completely different physical nature, each of them is usually normalized to the maximum possible. The statistical and graphical techniques (charts) are widely used for such multivariate analysis.

Most often, however, such tasks are reduced to the task with a sole scalar function (task of mathematical programming). There is a problem of choice of such functions to combine estimates of several indicators. The most common way to get an integrated indicator is additive or multiplicative weighting of indicators. Multiplicative weighting is applied when it is unacceptable to disregard any private indicator. This means that the task is actually multi-purpose and not achievement at least one of the goals is the failure of the program as a whole.

Additive weighting is applied when any member of the sum can be neglected in favor of another. For example, the value research program could be calculated as a weighted sum of values of each SE. The above examples in chapter IV of these indicators for program effectiveness measuring represent the simplest approach when the weights of all experiments are equal, and thus the effectiveness of program implementation is just a number of experiments as compared with plan level or the number of publications on these SE. This approach cannot be considered as satisfactory, as the SE have completely different scale, cost and scientific significance.

In addition, as mentioned earlier, the criterion function (value) of research program, generally speaking, is not an arithmetic sum of the values of every experiment and depends on the order of SE. There is a mutual influence of SE via criterion function and resource constraints. Accordingly, it is impossible to allocate resources for experiments independently. Therefore, the standard methods of optimization do not work in this case.

When a task is a multicriterial, i.e. there is no integral efficiency indicator of the program as a whole, often one preliminary selects variants of program that match Pareto-optimal conditions according to these criteria. I.e.

from the entire set of option programs those are rejected that are worse than any other option for all separate criteria simultaneously. If the result contains few Pareto-optimal options, you can choose the best solution among them with any other criteria (e.g., full use of resources) or with Decision Support Systems (DSS) [7,8]. In framework of such a system the preliminary results shall be regarded as recommendations for the person making the decision which he can either accept or not. The decision maker should clearly imagine what the main purpose of the planning is acceleration of work, resources savings or some compromise solution. With respect to the LTP the goal is to fulfill program in time with the most efficient use of ISS RS resources.

5.3. Collaborative research for efficient use of resources of the ISS

Space agencies are working within the framework of their national programs. The structure of these programs and scientific categories (disciplines) classification is also different significantly. Therefore, in [9] a comparative analysis of ISS partners programs was conducted according to the common classification of integrated research categories (see Fig. 6).

One can see that the structure of the research programs of all ISS partners is quite similar–the greatest attention is paid to the life sciences (medicine, biology, biotechnology).

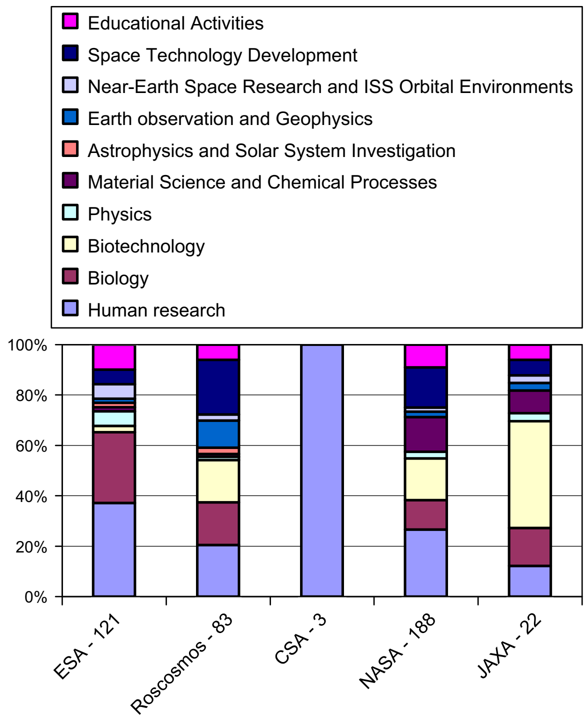

Fig. 6. Comparison of the ISS partners programs on the integrated categories (July 2009) [9].

NASA has the biggest research program. In this program (as in the program of Roscosmos and other agencies) the main area of research is human behavior under microgravity conditions. The second priority areas are biology and biotechnology. Considerable part of NASA research program is development of technologies. And finally, another important area of NASA research–Earth observation from space and educational activities.

It should be noted that at present there are several experiments–candidates for research collaboration onboard the ISS, but there are no NASA and Roscosmos joint experiments so far. At the same time, Roscosmos cooperation with the ESA and JAXA to conduct research on ISS expands. After the launch and commissioning of modules Columbus and Kibo, the number of experiments in national research programs of ESA and JAXA was increased significantly. They contain the experiments with liquids and gases on melting and solidification, which are always of interest to Russian scientists.

Analysis of partners' research programs and equipment indicates a considerable number of experiments that have similar aims and objectives of the on-board the ISS.

In framework of working groups on different research areas the joint research programs and experiments on ISS are developed.

Within the framework of the joint Russian–European research program on ISS were selected more than 20 SE. The top joint experiments, selected for primary realization are: Plasma crystal, Immuno, Matroshka, GTS-2, ATV reentry.

Within the framework of the joint Russian–Japanese program more than 10 SE were selected. Primary experiments proposed for the joint ISS realization include AQH, PADLES, PCGE.

As for Russian–Canadian cooperation, it is now proposed first joint experiment in the outer space called Epsilon. A scientific protocol is already signed. The experiment will be conducted aboard the Russian module MIM2.

Ukraine is not an ISS partner. However, the Ukrainian national space agency has its own national program of research and experimentation on the ISS with dozens of space experiments, as well as good facilities for production of scientific equipment for ISS. This is clearly of interest to researchers on ISS.

Since 14-th increment NASA includes in its increment program experiments of ISS partners. Every year ISS partners (except for Russia) develop Consolidated Operation and Utilization Plan (COUP). Similar (medium-term) program is currently being developed for the ISS RS. It is evident that international cooperation and coordination in these programs benefit all the ISS partners, could provide complementary investigations and leading to a synergistic effect, and making a more effective use of resources of ISS.

6. Conclusions

For the time being the Russian program of the basic and applied research on the International Space Station passes through the phase of evaluation of previous approaches and measures aimed at increasing of research efficiency.

1. At the stage of program development one has to match many parameters and constraints, reconcile balance sheets, select and assess various indicators. Known indicators and methods of efficiency measuring were analyzed for both already completed and planned researches. A system approach and well known techniques for efficient resources allocation give the framework for solution of this kind of tasks. However, a complex character of the ISS research programs requires the development of criteria and methods for assessing the efficiency of research as well as for selection of the most priority SE, because the ordinary resource allocation optimization algorithms are little applicable here. The existing method for primary experiments selection and adjusting of the schedule of research program has been described; its shortcomings and possible ways of improving were suggested on the basis of Decision Support Systems.
2. Analysis of the realization of the long-term research program at ISS RS has identified a number of weaknesses in its implementation. The analysis of program efficiency has been done based on the number of publications of articles in journals and presentations at conferences about results of SE. It is shown that for some areas of research there have been a relatively high number of publications per SE while for others the situation is opposite.

   There are certain application results in a number of experiments; however, the return of the ISS research could be increased. Separately, one need to consider those experiments, which exceeded the status of pure research and the question is how to transform them in order to use these methods, and results in practice permanently. To do this the regulations of such kind activity are being developed now.

   For more effective implementation of the ISS research programs Scientific and Technical Advisory Council of Roscosmos keeps a continuous search for new ideas, expanding the pool of potential participants in the research program, suggests to actively interact with potential users and consumers of ISS research results.

   It was shown that in order to fulfill the LTP one has to accelerate implementation and especially completion of the SE. The main reason for delaying realization of experiments is inadequate preparation of appropriate scientific equipment. In this connection the Russian side would use the resources of ISS partners and of other countries interested in collaboration.
3. Currently the cooperation with ISS partners has been started due to the mutual interest to improve performance of research programs and efficient use of ISS resources. On the basis of the analysis of partners programs and resources the arrangements are suggested for such cooperation. Some joint experiments are already conducted; the other are being prepared to run.

References

[1] NASA, M. Dietel, B. Feuerbacher, V. Fortov, D. Hart, C. Kennel, O. Korablev, C. Mukai, A. Sawaoka, P. Suedfeld, S. Ting, P. Wolf, N. Buckley, C. Fuglesang, P. Johnosn-Green, G. Karabadzhak, T. Nakamura, D. Pettit, J. Robinson, T. Ruttley, I. Sorokin, T. Thumm, M. Urhan, M. Zell. The Era of International Space Station Utilization: Perspectives on Strategy From International Research Leaders. NASA/NP-2010-03-003-JSC.

[2] The long-term program of scientific and applied experiments on ISS RS (version 2008) 〈http://knts.tsniimash.ru/ru/src/Files/dp.pdf〉.

[3] Scientific and Technical Advisory Council 〈http://knts.tsniimash.ru/en/site/Default.aspx〉.

[4] A.Taha Hamdy, Operations Research: An Introduction, 7th Edition, 0-13-032374-8, 2002 Hardcover.

[5] M.Yu. Belyaev, D.N. Rulev, Optimization of planning the experiments to be carried out onboard orbital stations, Cosmic Research 45 (2007) 220–2273 45 (2007) 220–227.

[6] Bruce Knuteson: A Quantitative Measure of Experimental Scientific Merit 〈http://lanl.arxiv.org/abs/0712.3572〉.

[7] P.N. Finlay, Introducing Decision Support Systems, Blackwell Publishers, Oxford, UK Cambridge, Mass., NCC Blackwell, 1994.

[8] S.A. Piyavski, Methods of optimization and optimal control: tutorial, Samara, 2005

[9] V. Sorokin Igor, Comparative analysis of ISS international partners' research areas. IAC-09.B3.4.4, S.P.Korolev Rocket and Space Corporation Energia, Korolev, Moscow Region, Russia.