On the Maximization of the Science Output of Space Missions

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Abstract Managing science-driven projects involve important differences with respect to other types of space missions. The main one is the character of science, exploring the unknown, that establishes how the final output is evaluated and thus the tools used to maximize it. For space missions supporting market-driven applications, the assessment of performance is clearly defined by the quality of the service provided and its added value. For space science missions, success is evaluated in terms of the advance of scientific knowledge, based on new discoveries and the tests of the laws of nature. The output can be facilitated but not fully predicted. Thus, performance has to consider initial science goals and the engineering requirements to achieve them but also, and most important, the preservation and maximization of the potential for unknown discoveries. The key indicator of the success of a space science mission is the quality and quantity of achieved scientific breakthroughs and discoveries. To optimize them, we need to consider the full mission lifecycle, from the mission definition through the development and its operations. In this paper, we discuss some management considerations to ensure and maximize the science output of a space mission over its whole lifecycle, from planning to operations. Specific elements are proposed to evaluate the results.

Keywords Space science · Full value chain management · Science output evaluation

1 Introduction

Science missions differ significantly from other types of space missions. First, space science missions, from the beginning to the end of their lifetime, are driven by scientific objectives that are more difficult to quantify than service missions driven by specific customer’s needs.
In fact, for the cases of telecommunications, TV broadcasting, navigation, weather forecast, or the monitoring of the Earth surface, success is given by performance in following well-defined requirements. Second, from a purely technical point of view, spacecraft and payloads are usually different for each mission. Space science missions are defined to go to new places or do new things, in other words, they are expected to explore the unknown and do what has never been done before. Therefore, the use of recurrent systems is severely limited, there will always be different engineering requirements from one mission to another due to changing needs with time of the measurements, observations and experiments to be done. They will continuously change to stay at the “bleeding-edge” of technology. Because of this, to ensure and maximize the science output of a mission it is necessary to pay attention to all the phases of its lifecycle, preserving the potential for new science, that shall not be jeopardized or suffer any loss. The management through all phases of a science mission, from selection to exploitation, is referred to as the full-value chain management and is the central idea in this paper.

By output of a science mission, we consider the main points in evaluating its success or failure. The first one is of course new curiosity-driven science as a result of breakthroughs and discoveries. Nevertheless, we have to be aware though that space missions involve large amounts of public investment, in money and effort, so that additional output has to be accounted. Science missions, by their very nature, are a key factor for innovation in space technologies and applications, an excellent tool to build bridges for international cooperation, they fascinate and inspire society, and motivate new generations to develop their interest in science and technology. In this paper though, only science for the benefit of new knowledge is considered. A proper analysis of any other benefit of space science should be discussed separately.

The lifecycle of a space science mission begins with the identification of the science frontiers, the big scientific questions to be addressed, and the strategic planning to answer them with specific space tools. In order to collect the best ideas from the scientific community, missions shall be selected out of open calls for proposals, retaining only the brightest in terms of the expected science impact. Potential science missions should then go through detailed assessment and study phases, looking into the scientific requirements and how the science output could be maximized, including the needs for technology developments that make the scientific goals both feasible and affordable within the constraints of the call. The approved mission will be subjected to the development phase, followed by its launch and the operations, when science is finally delivered. An evaluation of the actual science output will be needed, not only to ensure that the expectations were achieved, even superseded, but also to substantiate the need for mission operation extensions, or a new mission. At the end, an evaluation of the complete science achievements, in comparison with the initial expectations, should be done together with a summary of lessons learnt, i.e. an assessment of the impact on the final science of the decisions taken along the design, development and operational phases. Moreover, the scientific data produced and archived by a science mission is always open to the worldwide community. Any science output from the use of these archives is part of the post operational phase of the mission. Figure 1 shows the different phases and milestones in the lifecycle of a space science mission.

The management of each phase of a science mission must be driven by the achievement of its objectives and the maximization of the expected output, not only the traditional cost and schedule control. This implies appropriate policies for decision-making along all phases of the mission and the implementation of adequate protective measures. Based on the analysis of the management of each phase, this paper indicates some of the necessary and feasible measures required, proposing how to conduct the evaluation of the output as the key tool for the full-value chain management, with specific criteria.
2 Planning

Before the actual lifecycle of a given space science mission starts, a strategic planning of the program, i.e. the framework for the selection and implementation of individual missions, must be established. This is necessary to ensure the stability of calls and missions, required to maintain scientific skills and expertise in the community, as well as an adequate balance between the different science disciplines. In addition, the long-term planning allows for the allocation of the necessary funding, the coordination with international partners and the definition of the infrastructures needed for the program to be sustainable.

A space science program is established, and funded, to enable the scientific community to achieve and sustain excellence through cutting-edge projects, meeting the challenges of worldwide research. The strategic program planning is in fact to set up an appropriate program to address the most important scientific challenges, balancing the number and cadence of missions to better serve a broad community of scientists. This planning is usually carried out by a governmental agency (hereafter referred to as “the Agency”) assigned to manage space science missions and receiving the funds to implement them. The involvement of the scientific community in such a strategic planning is essential to ensure the best possible science output. Establishing priorities, or the tools to select and implement specific missions, must involve the potential users, i.e. the scientists relying on space platforms to advance in their research fields.

The plan will generally contain two main types of mission. First, there will be scientific frontiers requiring large flagship or strategic missions, requiring high budgets and long time for technology developments. Their definition, technology development needs and final approval will require concerted efforts and time at different levels, but it will not be possible to retain proposals of the scientific community for all science domains in a given planning cycle. These missions will thus need a full consensus of the scientific community about the priorities, what should the agency do and when, within realistic estimations of cost and other boundary conditions. Decisions on choices will be driven by science excellence and breakthrough opportunities but also by a comprehensive involvement of the relevant communities.
The second type of missions provides flexibility in response to excellent and innovative scientific ideas, with shorter time-scales. Opportunities must be provided by the establishment of budget allocations for a reasonable number, or cadence, of missions to be selected with fully competitive processes and no preselected science goal. Stability is the key element to sustain an excellent science output and, of course, these medium-type missions must be chosen through open calls for mission proposals.

Additional elements of the space science program are smaller, and faster, missions to respond to the need of specific science questions, with more restricted budgets but allowing for leaner management and higher risks. They have to be selected also in full competition in response to open calls but can service new scientific communities entering space science or those needing very specific monitoring capabilities, not available with infrastructures devoted to satisfy larger communities. We should also mention here the importance of considering that bigger risks, linked to innovative technologies, can generally be better assumed with smaller missions, while large and expensive missions can better serve a wide science community with a comprehensive approach. Finally, most agencies consider missions of opportunity. These are small contributions to missions lead by another agency enabling the access of their scientists to new science or technology opportunities.

2.1 Space Science Planning in the US and Europe

The National Administration for Space and Aeronautics (NASA) is responsible for the planning and implementation of US space science missions through its Science Mission Directorate. For planning activities, NASA supports the so-called Decadal Surveys, organized for each area of space science. These surveys involve the scientific community at large and the National Academy of Sciences (NAS), through its Space Studies Board (SSB), is responsible for organizing the planning activities with studies and discussions on each discipline of space sciences approximately once a decade. The findings are published in The National Academies of Sciences Engineering Medicine (2019), and present major science goals, ranking the priorities of research/mission proposals. NASA takes the recommendations of the Decadal Surveys as the driving input when implementing science missions, including strategic missions as well as fully competed medium and smaller missions.

The European Space Agency (ESA) establishes the science program planning in cycles of 10–20 years, following the advice of a special Senior Committees with external scientists and the involvement of ESA’s science advisory structure, led by the Space Science Advisory Committee (SSAC). This bottom-up process allows publishing long-term plans driving the implementation of the science program of ESA. The first long-term planning, Horizon 2000, was published in 1985 (European Space Agency 1984) and included the European space science missions to be launched in the following 20 years. It was a discipline-balanced plan that focused on key science frontiers and European research strengths. It was continued by a 10-year plan, Horizon 2000+, published in 1995 (European Space Agency 1995) with an extended framework up to 2015. The current Cosmic Vision, ESA’s new space science plan for a further decade was conducted and published in 2005 (European Space Agency 2005), covering research themes up to the year 2025 which was later extended without changing the identified ambitions and challenges. Now, a new programmatic discussion is being held with the scientific community aiming at defining the long-term planning for a period up to 2050, and thus called Voyage 2050. ESA’s science missions fall into three classes: large (L), previously called corner-stones, or ESA-led flagship missions; medium (M), and small/faster (F) missions, previously S-missions, providing flexibility to respond to new challenges. In addition, there is a continued contribution to non-ESA missions through the category of missions of opportunity involving intensive international cooperation.
The American and European strategic planning have two aspects in common: on one hand, they both engage the science community in the discussions, following bottom-up initiatives and reaching a consensus on the basis of science excellence. Besides, they aim at major science frontiers in space science disciplines and the development of innovative technologies. The United States and Europe, however, have different strategic planning structures, each with its own characteristics. For example, the former is more flexible to adapt to changing goals but less stable in the long-term planning and budgetary commitments. In contrast, the European program is less flexible to include new ideas in a fast way, but can be more systematic in solving fundamental questions, being more stable and thus better suited to international cooperative endeavors. Moreover, the US planning is done mostly independently for each space science discipline with a balance given by the initial budget allocation. In ESA, all disciplines are considered within the same planning and thus balance must be a result of science excellence among competing communities. Finally, the Science Mission Directorate of NASA includes Earth science missions and robotic exploration projects while, in ESA, the Earth Science Explorer missions are selected in a similar competitive way, but within an optional program for Earth observation called The Living Planet with the latest long-term planning published in 2015 (European Space Agency 2015). On the other hand, robotic exploration missions with Moon or Mars destinations are developed as part of the optional ESA program of Human and Robotic Exploration, in addition to the purely science-driven missions in the mandatory science program.

2.2 Space Science Planning in China

China is a new actor in the area of space science. After successfully implementing its first space science mission in 2004, Double Star with the cooperation of ESA, the Chinese Academy of Sciences (CAS) took the first steps for space science strategic planning in China. As a result, it has published Space Science & Technology in China: A Roadmap to 2050 (Guo and Wu 2009) and Calling Taikong: A Study Report on the Future Space Science Program in China (Wu 2016). In these publications, the science frontiers to be dealt with proposed Chinese space science missions are analyzed. In total, 23 science projects in different disciplines, were proposed. The missions being implemented by CAS under the frame of its Strategic Priority Program (SPP) on Space Science, are selected out of the projects proposed. China’s deep space exploration program is managed by CNSA (China National Space Administration). Manned space programs are managed by CMSA (China Manned Space Administration). These large space programs are at national level with large budgets approved by the central government with a top-down management process.

2.3 Planning in Other Space Countries

Japan is also one important space country with a significant space science program, mainly managed by ISAS (Institute of Space and Astronautical Science). ISAS is now a branch of JAXA (Japan Aerospace and Exploration Agency). The planning procedure is similar to what is done in the US and Europe, through a bottom up management process. Russia used to have many programs during the cold war period. In recent years, its science mission proposals are mainly from the Russian Academy of Sciences and Moscow University. They follow a 10-year period plan of a national development program. India’s space program is a very integrated, and centralized, program managed by ISRO (India Space Research Organization). In recent years, it has launched its Lunar and Mars missions plus one astronomical telescope mission.
2.4 Some Conclusions About Planning

Three important points can be drawn from the experience of space science planning mentioned above. First, science planning must aim at major science frontiers, i.e. should encourage scientists to propose new missions around frontiers and challenges, with promising significant output, ensuring science excellence and impact. Second, a broad consensus must be reached within the space science community to ensure the achievement of ambitious goals and science excellence while keeping a reasonable balance of disciplines. This is needed to guarantee the attraction of young talents, motivate high-quality science teams, and ensure the best possible exploitation of future missions, i.e. enabling a great science output. Third, the science planning should be reasonably flexible, so that identified adjustments can be introduced following changes in the science frontiers and challenges, or even responding to proposals coming from new, relatively small, space science communities. The key is to avoid missing any good idea or major opportunity for great breakthroughs in science. To maximize output, these three points must be considered as the key elements for the management of the planning exercise.

3 Mission Identification and First Analysis

3.1 Call for Mission Proposals

The first milestone in the lifecycle of a space science mission is the call for missions to the scientific community. In fact, it is very useful to start the long-term planning described above with a call for ideas, or themes. This allows the identification of the most promising science goals to be pursued by the program. Selected topics may either develop into strategic flagship missions (priorities in NASA’s decadal surveys, or L missions in ESA's science program), driving the required technology efforts, or be the reference of open calls for mission proposals. The selection processes involved in both cases are obviously critical to the full value chain management of the program and it must be carried out within a peer-reviewed “bottom-up” approach.

The call for ideas, with no actual commitment for flight opportunities, does not only identify strategic science goals and priorities, but also the cadence and scope of the open calls needed by the scientific community to achieve the proposed science. In the case of strategic missions, where specific science goals or themes have already been identified in the long-term plan, a specific call may still be needed, after the necessary technology developments are in place, to ensure a positive response from the best possible science team. In all other cases, the agency issues a call for mission proposals open to all ideas, sometimes restricted per discipline (depending on budgetary opportunities), and generally limited in cost estimates (size of the mission). The “bottom-up” approach for the identification and selection of missions is therefore continued after the strategic planning was drafted. This approach is considered essential for the management of space science missions, not only to achieve and maintain science excellence, but also to ensure the full support of the scientific community to the program. For this purpose, it is very important to maintain a stable cadence of calls, so that non-successful science domains or proposers, keep on improving their ideas and advance in the preparation of future opportunities. The philosophy behind the “bottom-up” approach is that the agency develops the tools that the user needs. A “top-down” approach asks the scientists to make their best possible use of tools developed for
different, non-science reasons, and obtain scientific added value. This leads to some dis-
advantages: first, the decision-makers choosing the mission are not the users of the data;
second, the scientists, are passive participants, leading to compromised quantity and quality
of the output. To ensure a science output maximization, the commitment and enthusiasm of
the scientists must be ensured by means of a bottom-up rather than a top-down approach.

3.2 Selection of Mission Proposals

The number of proposals received is always far larger than the budget available. This is not
only the case in the US and Europe, Japan, but also in Russia, China and other countries.
Of course, it is always far better to have more ideas than money, rather than the opposite.
Selection is therefore a necessary process to invest on those missions with better potential
for a great science output, large impact and the involvement of a motivated community.
A limited ratio of successful missions, despite leading to a significant number of unhappy
scientists, shows a really competitive selection process, ensures world-class science, and
makes the program sustainable.

After the call is issued, the agency shall make the selection of the best candidates out
of the submitted proposals. This is a very important step in the lifecycle management and
the agency acts as the guardian of science excellence, ensuring an open, fair, and unbiased
competition. However, before the selection aiming at their scientific importance, a first round
of technical feasibility studies should be carried out by the management agency, a technical
screening, to avoid unnecessary efforts on technically non-feasible projects or well outside
the budgetary scope of the call.

Selection criteria shall be released beforehand to let all proposers being aware of them.
No matter which agency issues the call, there are two main criteria.

(a) The impact and ambitions of the scientific objectives, i.e. whether a mission aims at
major science challenges, and the potential breakthroughs can fundamentally change
human’s understanding of natural laws;
(b) The involvement of excellent science teams in achieving those goals, i.e. whether a mis-
sion is support by a significant number of high-quality researchers involved in analyzing
the data and using the scientific observation and experiment capacity of the platform,
thus producing large amounts of good science.

Any selected mission should meet either of the two criteria (Wu and Bonnet 2017), while
it will increase its priority if it meets both. In addition to the two above-mentioned selection
criteria, the agency also needs to balance the development of different space science disci-
plines and make sure that the best use of space and ground-based observatories is done in
a synergetic way. In the NASA system, priorities and calls are already distributed per disci-
pline, while in ESA all generally compete for the same opportunities. In this case, when a
discipline needs special support, the two criteria could be somehow less strict.

The agency shall insist upon two points in this process: first, to ensure that the mission
proposals are dealt with a “bottom-up” approach; second, to select out of them the best
ones according to the above-mentioned criteria. A priority list of the proposals must be
ranked by the science community through a peer-review selection process with no conflict
of interest, otherwise a fair and unbiased selection would be severely compromised. Though
a “top-down” selection may seem to strength the leadership of the relevant decision makers,
it leads to an unmanageable situation when implementing the mission, in the relations of
the scientists with the agency but, most important, the loss of reputation and credibility of
the programme in front of the scientific community and international partners. In a science-driven program, it is necessary to have fair and open selection mechanisms for all flight opportunities, as given in a bottom-up process.

From the first round of mission selection on, the proposing science teams have a key role in the preparation studies, as well as during further phases in the life-cycle of the mission, in case of final approval. The leader of the proposal is generally called the Principal Investigator (PI), though his/her role changes in different agencies and types of missions. In any case, the PI is the key contact point and reference in the scientific community for the development of the mission.

4 Mission Selection

A limited number of proposals, selected for further studies in the previous phase, constitute the basis for down-selection to those that will be finally implemented and launched. Before final approval, all candidate missions must go through detailed studies of the scientific objectives, the related engineering requirements and the needed technology to fulfill them. In this phase, the mission team studies the science objectives and the payload complement, including scope, risks, and feasibility issues together with alternative design options. This involves the discussion of the proposed mission concept, the analysis of payload elements, the evaluation of possible international cooperation, the identification of key technologies requiring further development, and the establishment of plans to ensure their availability.

The management of this study phase, in terms of science output maximization, includes two key points. First, is the monitoring of the study of the science objectives, in close cooperation with the PI, trying to make them closer to the two selection criteria mentioned in Sect. 2.2. For this purpose, further collaboration between scientists and engineers, looking for alternatives to enhance the science output of the mission, should be promoted. Second, is helping the establishment of international cooperation, on the basis of science excellence and mutual benefit. For this purpose, the organization of international forums and inter-agency discussions should be promoted, considering other initiatives around the world, scientific or technical, that could increase the science output of the mission.

The end point of the study phase is the down selection into the final candidates to be further defined and analyzed, entering formulation or preliminary design phase. A fair and open selection process is again essential for the bottom-up approach to be fully respected. Therefore, the involvement of the scientific community is needed to ensure that the best ones, those with a better science output perspective, are selected.

Missions that successfully passed the two previous rounds of selection should have science objectives aiming at a major science challenge, with a great involvement and support in the scientific community. However, further studies are necessary to check technical feasibility and budgetary affordability. In order to avoid major changes in the mission design, caused by changes in the scientific requirements, during the engineering development phase, the agency must develop studies on the science requirements, on the feasibility of the mission concept and about the necessary payload technologies. For this reason, the key technical risks and the total estimated cost of the mission have to be established, as well as their affordability by the overall science program, and evaluated in light of the constraints of the call. It should be reminded that a fair competition implies that the winner is not exempted of limitations imposed on the rest during the competitive process.

Once the selected missions have gone through these additional technical and budgetary feasibility studies, and following a successful preliminary design review, it is ready for approval. At this point, a project manager and a project scientist, or project PI, should be
appointed by the management agency. The project manager is responsible for the subsequent development phases until launch and commissioning. The project scientist/PI is the guardian of the scientific goals and continues to be key for the implementation of the mission with a science working team of the original proposal and the different payload elements as well as a number of independent mission scientists, ensuring a wide support of the scientific community.

The science working team supports the project scientist or PI, reviews the development of the project and prepares the exploitation phase of the mission. He or she should participate in all activities and reviews of the mission development milestones. As kind of science quality controller, he or she has a veto right on engineering decisions with a serious impact on the science output of the mission during the entire engineering development phase, but his or her primary function during these phases is to supervise rather than to lead.

5 Mission Development

Once a space science project is adopted and enters the engineering development phase, the major activities are the design, manufacturing, integration and validation of the spacecraft and the science payload, including all necessary tests. The goal is to meet all the science requirements and ensure a successful operation after launch. At this phase, besides the usual engineering issues in the development of any space mission, science-driven missions shall specifically focus on the design and development of the science payload. However, in many cases, the designers of the science payload, with a more academic background, may lack experience in space engineering and it is necessary for the payload team to closely communicate with the spacecraft engineering team, so as to work out the most efficient implementation scheme and avoid negative mutual impact. Again, the science working team has a key role in these discussions.

The project scientist/PI and the science working team, follows carefully the whole engineering development phase. Only decisions acknowledged by the project scientist/PI can ensure the optimization of the mission potential to deliver the best science output. Therefore, in this phase, the project scientist/PI of a space science mission must always be in the position of review and acceptance. Although the project scientist/PI could be in principle entitled to propose to stop the mission, if the science goals are seriously endangered, in fact, this will never happen for a well-managed space science mission. This implies, as mentioned above, that all actors play their due role through the whole phase with an open and fluent communication between the science and the project teams, i.e. between the project scientist/PI and the project manager.

6 Launch and Commissioning

Launch is of course a key milestone in the entire lifecycle of the mission. Before launch, it is possible for any problem in science, technology, or quality in the performance to be solved. Once launched, there will be no chance to make changes except via software updates or changes in operational modes. Therefore, prior to launch, the project scientist/PI must assess the potential risks for a science output below expectations and the agency, together with the engineering team, shall then establish the minimum conditions for launch.

Determining minimum launch conditions, is to work out action plans for any anomalies that might occur when a mission is being launched, considering scientific performance but
also the cost impact of possible risk mitigations. For example, in what circumstances can the launch go on without affecting the achievement of science objectives or must the launch be terminated, such as in case of an anomaly of payload hardware affecting key specifications. The determination of minimum launch conditions is a risk management tool to assess and ensure maximum scientific output in the case of non-nominal events.

When the spacecraft is in orbit, a two-step commissioning phase is required before delivering it to the users, the scientists. The first step is the internal commissioning of the spacecraft to make sure that all service systems, such as power, thermal control, attitude control, data management or telemetry, work properly. The second step is the payload commissioning by the science team to see whether their engineering parameters are nominal, to set the parameters in each observation and test mode, and to verify whether the scientific and technical specifications of the payload meet the science requirements.

When the commissioning of the mission is successfully completed, the project manager transfers the responsibility to the operations manager and the project scientist/PI takes a more active role, leading the science exploitation activities.

7 Mission Operations

At the operations phase, the key to maximize science output is to make the most effective use of science data, supported by a sound data policy. There are usually two types of science data policies: first, the PI-led team has the priority to access the data and exclusive access over a certain period of time; second, open share of the data with the entire scientific community so that any researcher interested has access to it. These policies encourage science output in two different ways.

The first policy focuses on encouraging the mission teams. The access priority and guaranteed rights are a reward for the team’s contribution over the years from the mission proposal to the operations in orbit, including the proposal of the core science of the project. In observatory missions, these guaranteed rights are extended for a limited time to scientists proposing specific targets in response to an AO for observing time. In general, researchers proposing science objectives and observation targets are the most eager to use the data, and the most likely to make major science discoveries. Furthermore, if the quality of the data is not good enough or not ready for an optimal use, the motivation of the people outside the core team will deteriorate, and the data utilization and the science output will be seriously compromised. Therefore, exclusive rights for a certain period of time not only helps protecting the enthusiasm of the mission teams, giving them time to improve both data quality and user-friendly tools for the analysis, but also maximizes the amount and quality of the science output of the mission.

The second policy aims at enabling more people to access the data. It is more applicable for stable data flows produced by observatory missions in survey mode, with observing objects constantly changing and not subject to specific calls for observing time. They can continuously produce science data, like solar monitoring missions, astronomical surveys or rapidly changing objects. Because the subjects of the observations are changing, the science satellites produce a large amount of new data every day, which is beyond the processing capability of the mission team. If the data is accessible by more scientists, its benefits can be maximized, resulting in a larger amount of science output.

In general, data policies are tailored to specific science missions. Usually, the first policy is implemented for a period of time, such as half a year to one year, then it can be evaluated whether the second one shall be implemented. How long the data will be kept for exclusive
use only, is subject to the requirements of output maximization and the nature of the mission and its data as well as the response and evolution of the users community.

8 Output Evaluation

Output evaluation is the last but very important milestone in full-value chain management, and the key tool for science output maximization. It is also relevant because these outputs are the feedback for public investment in space science. Only with feedback can the value chain of the entire space science mission be completely connected. Positive feedback on the impact of the output must include not only the evaluation of the scientific community, but also the understanding and acceptance by the public, i.e. confirming that public money has a positive social effect, thus ensuring a sustainable development of space science.

When a space science mission comes to the end of its designed lifetime, there are two situations: either the mission still works well or the mission performs below expectations. If the mission is far from meeting the required performance, or even fails halfway, its lifetime extension will not be justified and the operations shall be terminated. For missions producing some science output, but less than expected, the ratio of their performance with respect to future additional costs should be assessed to decide whether to suspend them or not. In any case, a full assessment of what went wrong has to be produced; if the origin of the low output was due to poor technical performance, not well-enough prepared scientific goals, or even bad luck. All these evaluations and assessments require the involvement of the relevant scientific communities, so that lessons learnt can be applied to future missions.

In most cases the mission still works well at the end of their nominal operations. Output evaluation shall be conducted at this time. If the science objectives are achieved as expected, or even beyond expectations, the users will often put forward a request for extension of the operations. Extended operations of course mean extra costs, not initially planned. Therefore, the request for extra budget shall be submitted and justified along with that for extended operations. The evaluation of the performance of the mission during nominal operations has to include the following three elements:

1. The science output. This is of course the most important element. Major science output evaluation indicators are the research papers published in academic journals with a peer-review process. The quality of the papers has to be evaluated according to the impact of the journal as well as the citation rate, reflecting the reception of the output by other scientists in the field and how relevant is the mission for its evolution, but also how much attention got from the scientific community as a whole. The number of papers considers those based on the analysis of data produced during the nominal mission operations. A highly productive space science mission often leads to hundreds of papers per year. For example, the US Swift Gamma-ray Burst Explorer has produced more than 200 papers per year and the European XMM-Newton has produced well above 6000 papers in 20 years. The data obtained by the Hubble Space Telescope (HST) since its launch in 1990, led to more than 10,000 published papers. These results reflect that large numbers of science discoveries have been made. China’s space science is in its start-up stage, so it is reasonable to expect about 100 papers per year after a mission enters into stable operation. Nevertheless, it has to be understood that the number of papers published is also a function of the size of the scientific community involved and the nature of the mission, either as an open observatory or devoted to specific experiments. Numbers have no practical meaning when isolated from their context. For the science output
evaluation, and the success of the mission, the overall results of the mission need to be considered, not only individual experiments or group of scientists. The output evaluation actually involves the whole science team, and even the agency’s management, to see whether it has played the best role at each phase of the mission.

(2) The progress and transfer of new technology. Space science missions often use new technologies. Therefore, in addition to developing fundamental research and advancing science, investments in space science do hope to stimulate high-tech development. However, the transfer of technology knowledge used in space science missions is usually not the main concern of the science team. Therefore, the agency shall take it as its own responsibility and pay attention to the potential application of new technologies, including relevant patents, from the very beginning of the engineering development phase. At the end of the mission, the agency shall evaluate and summarize the innovative aspects and the transfer of knowledge of the new technologies. It should be noted that the evaluation should not focus only on technology transfer and innovation, ignoring science output. If a mission can only promote technology development, not science, it shall not be part of the space science programme. The advancement of science is the driving force of space science. New technologies may be needed for fundamental science research, but efforts in space science cannot be used for a different purpose than science.

(3) The impact of space science missions in the general public. Funding of space science programmes comes basically from public budgets, that is, taxpayers’ money. Therefore, the results of space science missions must be shared with the general public. Besides the science discoveries and breakthroughs of a given mission, and possible success in technology innovation transfer, it is necessary also to evaluate the public outreach activities. The science objectives or the development activities should be released to the public through the media from the approval of the mission, making the envisaged science knowledge accessible to the general public. This is especially important for the younger generations, that generally consider the fundamental science knowledge about the universe as a hot topic. Any science and technology advance in the area of space science is a great motivation for them to study science, technology, engineering and mathematics (STEM). Therefore, it is necessary to make use of the fascination of space science missions, to conduct public outreach activities. The pursuit of social benefits is a task of the agency as well as the mission development teams. Evaluating the social benefits and public impact, during and at the end of a mission, is an important part of its full-value chain management.

The above three points, in particular the first one, are considered the key performance indicators (KPI) of the success of a space science mission. If, after a proper evaluation, a mission is considered to have the potential for additional output, its lifetime extension request shall be approved. At the end of such mission extension, the evaluation of the output during this additional period of time will be carried out again until the mission finally ends. Then, the engineering development of the mission is summarized comprehensively with a review of all lessons learnt aiming at improvements for future missions.

9 Conclusions

Full value chain management of space science missions is the foundation of maximizing science output, and a powerful guarantee for the sustainable development of space science. Most funds for space science missions come from the government’s investments in scientific
research, coming from taxes, that is, from the general public. Whether the public will support space science missions depends on whether the missions will feedback social and economic development. Therefore, in the long run, for the sustainable development of space science, it is of the utmost importance to ensure the best possible output of space science missions, from selection to operations.

To maximize the output of space science missions, both the agency and the science community need to: (a) identify major science frontiers at the strategic planning phase; (b) adopt a “bottom-up” approach, following open and fair selection procedures, with selection criteria that guarantee large impact; (c) at study phases, optimize the mission concept, develop key payload technologies, and involve international cooperation; (d) before final approval, make sure that the technical feasibility and economic affordability of the mission are well studied with all risk properly identified and mitigation actions in place; (e) at engineering development phase, give priority to the scientific payload and the science objectives, making them the driving force during all steps and reviews, making the scientists responsibilities clear; (f) at the operation phase, adopt the appropriate data policy depending on the characteristics of the mission, with open access as a priority.

All agencies managing space science missions have experienced different issues and have tried to adopt different ways to proceed in order to maximize the science output of their missions. However, to reflect on the key factors through the full lifecycle of a space science mission with more general consideration is still necessary as a reference, not only to the management teams, but also for the scientific community. This will certainly help in further improving the management and output of space science missions, receiving greater support from the public, and to enable a healthy and sustainable development of the programme.

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References

European Space Agency, Horizon 2000. ESA-SP 1070 (1984)
European Space Agency, Horizon 2000 Plus. ESA-SP 1180 (1995)
European Space Agency, Cosmic Vision—Space Science for Europe 2015–2025. ESA-BR 247 (2005)
European Space Agency, The living Planet Programme. ESA-SP 1329 (2015)
H.D. Guo, J. Wu, Space Science & Technology in China: A Roadmap to 2050 (Science Press, Beijing, 2009)
The National Academies of Sciences Engineering Medicine, Decadal surveys (2019). http://sites.nationalacademies.org/ssb/ssb_052297
J. Wu, Calling Taikong: A Study Report on the Future Space Science Program in China (Science Press, Beijing, 2016)
J. Wu, R. Bonnet, Maximize the impacts of space science. Nature 551, 435–436 (2017)