Agence spatiale canadienne | Canadian Space Agency

Evaluation of Human Space Missions and International Space Station Utilization

Period from April 2013 to March 2018

Project No. 17/18-02-01

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Acronyms used in the report

AO	Announcement of Opportunity
ARC	Average Relative Citation
CSA	Canadian Space Agency
ESA	European Space Agency
EVAs	Extra-vehicular activities
FTE	Full-time equivalent
GBA+	Gender-based analysis plus
HQP	Highly Qualified Personnel
IGA	Intergovernmental Agreement
IIRB	Integrated Investment Review Board
INO	Institut national d'optique
ISECG	International Space Exploration Coordination Group
ISLSWG	International Space Life Science Working Group
ISS	International Space Station
JAXA	Japanese Aerospace Exploration Agency
LEO	Low Earth Orbit
MOU	Memoranda of Understanding
MSS	Mobile Servicing System
NASA	National Aeronautics and Space Administration
NFB	National Film Board of Canada
NPO	Non-profit organization
OECD	Organization for Economic Cooperation and Development
PM Strategy	Performance Measurement Strategy
R&D	Research and Development
SP	Sub-program
SSP	Sub-sub-program
STEM	Science, technology, engineering and mathematics
TB	Treasury Board of Canada
UNO	United Nations Organization

Summary

This report covers the findings of the evaluation of sub-program *1.2.3. Human Space Missions and Support* and sub-sub-program *1.2.1.2. International Space Station Utilization* (hereinafter called the "program"), implemented by the Canadian Space Agency (CSA) for the period from April 1, 2013 to March 31, 2018.

In 1985, the Canadian Space Station Program began when Prime Minister Brian Mulroney accepted the invitation by President of the United States Ronald Reagan to participate in the multilateral program to develop and build the International Space Station (ISS). The initial partners were the United States (leader), Canada, Europe (represented by the European Space Agency (ESA)) and Japan. An intergovernmental agreement (IGA agreement[1]) was signed in 1988, and updated to include Russia in 1998. Assembly in orbit began in 1998 and was completed in 2011. Canada contributed in the form of robotic infrastructure equipment, the Mobile Servicing System (MSS), for which Canada must support operation, provide training for team members to operate it, and pay its part of the common operating costs of the systems. From the beginning of the ISS to 2017, Canada has contributed approximately $2.2 billion in operating and development costs.

During the evaluation period, the following activities were conducted:

- 10 separate scientific research projects were in development or had been completed during the evaluation period;
- 10 separate scientific instruments were in development or had been completed during the evaluation period;
- Astronaut Chris Hadfield's mission was carried out from December 19, 2012, to May 14, 2013;
- The astronaut recruitment campaign that took place from June 2016 to August 2017 led to the hiring of two astronauts, Jennifer Sidey and Joshua Kutryk.

A variety of communication activities were carried out, such as videos produced by Chris Hadfield during his mission on board the ISS, presentations by astronauts and participation in school events in association with scientific projects, in particular those created by Let's Talk Science intended to raise awareness among young people about the importance of STEM (science, technology, engineering and mathematics) in their lives.

During the period evaluated, program expenses reached $56 million, mainly in financial support for external entities (54%) and salaries (33%). The other expenses (13%) were dedicated to the ongoing

[1] IGA (1998). *Agreement among the Government of Canada, Governments of Member States of the European Space Agency, the Government of Japan, the Government of the Russian Federation, and the Government of the United States of America concerning Cooperation on the Civil International Space Station*, January 1998, [https://aerospace.org/sites/default/files/policy_archives/Space%20Station%20Intergovernmental%20Agreement%20Jan98.pdf]

management of the program, including operating and maintenance costs. The human resources assigned to the program were, on average, 35 full-time equivalents (FTE) per year; that number was up during the last two years of the period (2016–2017 and 2017–2018) owing to the reassignment of resources to Astronaut David Saint-Jacques's mission, the astronaut recruitment campaign and the updating of the program's capacity to support an increase in scientific activities on board the ISS beginning in 2019.

The evaluation covers the relevance, performance, efficiency and comparative gender-based analysis plus (GBA+) of Human space missions and ISS Utilization (sub-program 1.2.3 and sub-sub-program 1.2.1.2), and various data collection methods were used: a comparative study and review of the literature, document review, 52 interviews, four case studies and an internal data analysis. The limitations encountered during the evaluation were as follows: 1) some performance data were not available; 2) most interview respondents had a direct interest in the program; and 3) it was too early to quantify and evaluate the results of certain projects. The evaluation reduced these limitations by using secondary data, adding qualitative information from case studies and asking respondents in interviews to provide examples to back up their opinions.

Evaluation findings

Overall, the evaluation paints a positive picture with regard to the relevance of the program, achievement of results and efficiency.

Relevance

Canada invested $2.2 billion from the start of the ISS to 2017 to participate in its construction and maintenance. This investment gives it the right to carry out scientific research on board the ISS using up to 2.3% of the available resources of the international portion (facilities, crew time and associated services, such as the transportation of research equipment and supplies). Human space missions and ISS Utilization are Canada's return on investment in the Mobile Servicing System.[2] Also, the document review demonstrates the interest that Canadians have in the importance of space exploration, an opinion that is shared both by the general public and the Canadian space sector. The five specific needs, identified in the program performance measurement strategy, were deemed relevant and are still in keeping with the new Canadian Space Strategy launched in March 2019: 1) to position Canada at the forefront of science and technology; 2) to recruit, train and secure flight opportunities for astronauts; 3) to identify, understand, reduce and eliminate the risks to the health of astronauts; 4) to design, build, launch and operate space hardware to conduct life sciences experiments and support the health of astronauts; and 5) to create new jobs in fields such as engineering, science, manufacturing and administration.

Since 2013, needs have not changed significantly, but the context has, and the program was adapted to remain relevant. In 2012, the program decided to focus on certain research priorities in the field of health and life sciences: fields with the potential to resolve health-related problems on Earth. In terms of

[2] Canada must also compensate NASA for 2.3% of common operating costs of ISS systems. These systems represent the costs related to the overall operation of the ISS.

astronauts, new selection criteria were used during the last recruitment campaign to adapt to the increased duration of missions from approximately two weeks to over six months. For example, considering that long space missions have become the norm, the CSA tightened the requirements related to the physical, psychological and social health of the candidates to support the profile of these missions. The CSA sought out individuals who were able to work well on a team for long periods in a confined environment.

In addition to the five needs identified by the program, the evaluation did not identify other needs not covered by the program, but some interview respondents said that public awareness of Human space missions and ISS Utilization was not clearly represented in the five needs, although this is a key element of the program.

The delivery model is deemed sufficient and the new Space Strategy allows to position the program for the future. Regarding human resources, interview respondents indicated that some positions were very specialized and unique, thus posing a risk of not achieving the results (loss of expertise in the event of an employee departure), but the small size of the team also allows to be agile.

Regarding governmental priorities, the activities undertaken through the program are in keeping with the Canadian strategy to use innovation as a lever for economic development. Space exploration missions require the development of state of the art technology, including applications that bring together space and Earth needs. The recruitment of new astronauts and the announcement in February 2019 of Canadian participation in the Lunar Gateway project demonstrate Canada's long-term commitment in this field.

Concerning the CSA's legitimacy to intervene through the program, it is clear that the CSA plays a unique role that could not be taken on by others, whether in the public, private or academic sector. There is no other program in Canada that is pursuing the same objectives or producing the same results. Through its enabling legislation, the CSA is a federal agency whose task is "to collaborate with space agencies, or organizations working in a related field, from other countries on the peaceful use and exploration of space."

Results

Overall, the outputs and results targeted by the program were achieved and surpassed. Canadian researchers and astronauts are recognized by the international community and garner the interest of the general public. Canada's allocation of time to use the ISS is 2.3%, which represents approximately 20 hours of crew time per six months. When partners cannot fully use all of their own allocation, the other partners may use the remaining time. As a result, the utilization target of 100% of the time per year was surpassed, except in 2015–2016, when 87% of the allocated time was used. According to an interview respondent, the CSA has practically doubled this allocation by collaborating with ISS partners for some research (e.g., using the same sample for different research). The international partners also acknowledged the excellence of Canadian astronauts by assigning them to critical duties and leadership roles during their mission. For example, Chris Hadfield was commander of the ISS for expeditions 34/35; Jeremy Hansen is currently responsible for the new class of astronauts at NASA; and before 2013, Dave Williams and Steve MacLean held important management positions at NASA. During the interviews, respondents, including ISS partners and external stakeholders, stated that the Canadian astronauts are highly qualified and able to perform well under pressure.

The lead researchers working on research projects that receive funding from the Agency employed highly qualified personnel (HQP) (58 per year on average) and students (13 per year on average) to help them with their work, thus contributing to the development of a highly specialized labour force in Canada and ultimately positioning Canada at the forefront of science and technology. Each year, on average, five Canadian university establishments (universities and teaching hospitals) participated in one or two research projects during the period evaluated, and, on average, six Canadian businesses participated in a research project.

Some projects led to use on Earth and re-use in space. For example, research studies funded by the CSA, which were begun in 1998, led to the development of the OSTEO instrument. Since then, this instrument has been used in a number of missions on the space shuttle, in particular with NASA in 2015 and the ESA in 2018. Also, Carré Technologies launched a commercial version of the bio-monitor called AstroSkin in the form of a line of intelligent clothing that can be used for research purposes in health, aerospace, security, defence and pharmaceuticals.

During the evaluation period, from 2013 to 2018, 47 peer-reviewed publications resulting from program funding were published. These publications were cited 254 times in other scientific articles, 5.4 times each on average, and 58% of them were an international collaboration with 10 countries, involving co-authors from 26 foreign teaching and research institutions and four foreign space agencies.

The results demonstrate a considerable collaboration both with Canadian and foreign universities and with the Canadian industry. This collaboration benefits Canada's profile abroad and allows for the advancement of knowledge about the ability of humans to live in space. Also, certain projects leading to re-use in space or use on Earth contribute to the Canadian economy and to other social benefits. The evaluation did not identify any unexpected negative or positive impacts.

Efficiency and economy

The evaluation focused on the qualitative aspects of efficiency given the absence of a comparable program and the varied nature of the program activities. The international cooperation required for projects as large and expensive as the ISS allows Canada to participate in scientific breakthroughs and the resulting technology. Also, Canada helped to advance the state of the art technology industry (in the fields of aerospace and robotics) by getting involved with the ISS. On a national level, the program collaborated with a number of partners, other government departments and agencies, the research industry and academia, leading to discoveries and innovative ways of treating illnesses, the creation of technology and discovery of new advances in life sciences and health.

It was mentioned during the interviews that the memoranda of understanding (MOUs) underlying the IGA agreement and the governance of multiple committees and working groups between partners are efficient and well established. The document review and interviews conducted as part of this evaluation nonetheless identified two factors that would contribute to improving the program's efficiency in the long term: increasing flight opportunities and having more collaborations with foreign partners. Canada is the smallest ISS partner,[3] which does not prevent it from making very large accomplishments. Also, Canada ranks well internationally with regard to the space field, whether for its contribution in science and robotics, its effectiveness, its efficiency or the quality of its collaboration. The human resources working on the program are deemed competent, but the small size of the group is also an issue for employee development and career opportunities. In interviews, some people said that the introduction of a new approval process in recent years had created additional pressure on human resources. However, interview respondents agreed that the process, which was more demanding than before in terms of preparation remains nonetheless more rigorous.

Impacts of the program on GBA+ groups

In March 2017, the CSA adopted its own directive for GBA+, which allows us to operationalize this requirement within the specific context of the Agency. The CSA directly integrated GBA+ considerations into its recruitment campaign for two new astronauts, and into studies on bed rest and isolation conducted in collaboration with the ESA. For example, during the latest recruitment campaign that led to the hiring of Jennifer Sidey-Gibbons and Joshua Kutryk, the following activities were undertaken: training on GBA+ taken by recruitment committee members before carrying out their mandate, a campaign that directly targeted women and visible minorities, and efforts made to engage northern communities and Indigenous peoples.

Conclusion

The evaluation demonstrated that the program is relevant, and that it achieves the targeted results while remaining efficient. It allows Canada to continue to play a key role in human space missions and also in research in health and life sciences in space.

The needs identified at the start of the program are still present and current. The ISS partnership model provides Canada with the opportunity to benefit from the use of a unique research laboratory in space and the resulting scientific and technological opportunities, in addition to producing significant benefits on Earth for the entire Canadian population. The immediate results of the program were not only achieved, but in the case of HQP and students, the established targets were greatly surpassed. The

[3] The initial partners are the United States (leader), Canada, Europe (represented by the ESA) and Japan. Russia has been a partner of the ISS since 1998. Currently, the ISS is made up of two sections: the Russian section and the international section, which is under the supervision of the United States. Within the latter, the allocation of partners is as follows: 76.6% for NASA, 14.4% for JAXA, 8.3% for the ESA and 2.3% for the CSA. In exchange for its contribution, Canada has the right to use 2.3% of the research facilities of the ISS, it has 2.3% of the time allocated to crew in orbit to use these facilities, and it is required to compensate NASA for 2.3% of the common operating costs of the ISS systems. These represent the costs related to the overall operation of the ISS.

intermediate results were mostly surpassed and the final results demonstrate that the program achieves the expected results, especially with regard to the quality of the science and the promotion of Canada internationally. Lastly, the delivery model is considered effective and efficient despite the small size of the CSA. The personnel assigned to the program, including the astronauts, is deemed competent and have a good reputation nationally and internationally. Also, the report highlights the significant leverage effect of partnerships between the CSA and the other ISS member space agencies that are coordinating their research efforts.

For these reasons, the report does not contain any recommendations and no management action plan is required.

1 Introduction

This report covers the findings of the evaluation of sub-program *1.2.3. Human Space Missions and Support* and sub-sub-program *1.2.1.2. International Space Station Utilization* (hereinafter called the "program"), implemented by the Canadian Space Agency (CSA). This is the first evaluation of this program, and it was conducted by the CSA's Audit and Evaluation Directorate from June 2018 to September 2019.

The evaluation covers a period of five years, from April 1, 2013, to March 31, 2018, and discusses the issues of relevance, effectiveness and efficiency of the following sub-sub-programs,[4] which apply to the Space Exploration program: *1.2.3.1. Astronaut Training and Missions*, *1.2.3.2. Operational Space Medicine*, *1.2.3.3. Health and Life Sciences*, and *1.2.1.1. International Space Station Utilization*. The last two sub-sub-programs contribute to the overall grants and contributions program in support of research, awareness and education in science and space technology. In addition to the sub-programs evaluated, the overall Space Exploration program includes the sub-sub-program *1.2.1.1. International Space Station (ISS) Assembly and Maintenance Operation*, which was the subject of an evaluation in 2016.[5]

This evaluation is included in the CSA's five-year evaluation plan and was conducted in accordance with the Treasury Board of Canada's Policy on Results (2016) (formerly Policy on Evaluation (2009)).[6]

2 Description of the program

This section of the report includes a description of the program and the general context in which it is implemented. The key components of the program are discussed: the logic model, main stakeholders and partners, governance structure and human and financial resources.

2.1 General context of the program

In 1974, NASA asked for Canadian expertise to develop a robotic arm: the Canadarm. This invitation marked the beginning of a close collaboration between Canada and the United States in the field of human space flights. Then, NASA invited a Canadian astronaut to participate in a space mission, which led to an initial corps of Canadian astronauts in 1983. In 1985, the Canadian Space Station Program was

[4] Since April 1, 2018, these sub-programs have been replaced by the Space Exploration Program.

[5] CSA (2016). *Evaluation of the Canadian Space Agency's International Space Station Assembly and Maintenance Operations Program – March 2008 to 2015*, *February* 2016, p. 15, [https://asc-csa.gc.ca/eng/publications/er-1415-0201.asp].

[6] The Policy on Results and the Policy on Evaluation define all the evaluation issues to consider when evaluating programs: relevance, effectiveness and efficiency.

started when Prime Minister Brian Mulroney accepted the invitation by United States President Ronald Reagan to participate in the multilateral program to develop and build the ISS.

The initial partners were the United States (leader), Canada, Europe (represented by the European Space Agency (ESA)) and Japan. An intergovernmental agreement ("IGA Agreement"[7]) was signed in 1988, then updated to include Russia in 1998. Assembly in orbit began in 1998 and was completed in 2011. The ISS has been occupied at all times since 2000 and can accommodate a crew of three to six people (six people since 2009). As of September 2019, 239 people from nine countries had visited the ISS. The ISS represents the combined effort of five space agencies representing 15 countries and remains the largest structure built by humans in orbit around the Earth. The ISS is a research laboratory that is orbiting the Earth at an altitude of 400 kilometres at 28,000 km/hour. Participation in the ISS mission gives Canada advantages, such as the development of industrial capacities, the advancement of knowledge, the strengthening of international partnerships, a better understanding of human health, the consolidation of national pride, and incentive for Canadians to make their careers in the science, technology, engineering and mathematics (STEM) sector. In addition to the IGA Agreement, NASA also signed memoranda of understanding[8] with each space agency. Russia, Japan and the United States operate space vessels for the transportation of cargo to the ISS. Crew transportation was provided by NASA's Space Shuttle program until 2011. Since then, the only option for the transportation of astronauts is the Russian vessel Soyouz.

Canada's contribution to the ISS took the form of robotic infrastructure equipment: the Mobile Servicing System (MSS). The main components of the MSS are the space station manipulator system (the robotic arm Canadarm2 launched in 2001), the mobile base transporting Canadian robots and components of the ISS across the length of the ISS truss (launched in 2002), and the special purpose dextrous manipulator (Dextre, launched in 2008). In accordance with the IGA Agreement, Canada must support the operation of the MSS, provide training for crew members to operate it, and pay its part of the common operation costs of the systems. From the start of the ISS to 2017, Canada spent $2.2 billion in operating and development costs. In exchange for its contribution, Canada has the right to use 2.3% of the research facilities at the station and 2.3% of the time allotted for crew in orbit to use these facilities (calculated based on the international portion of the ISS). According to the IGA Agreement, Canada is accumulating time credits in space for flights by Canadian astronauts. Canada therefore established a program to select its astronauts, ensure their medical monitoring and prepare them for flights to the

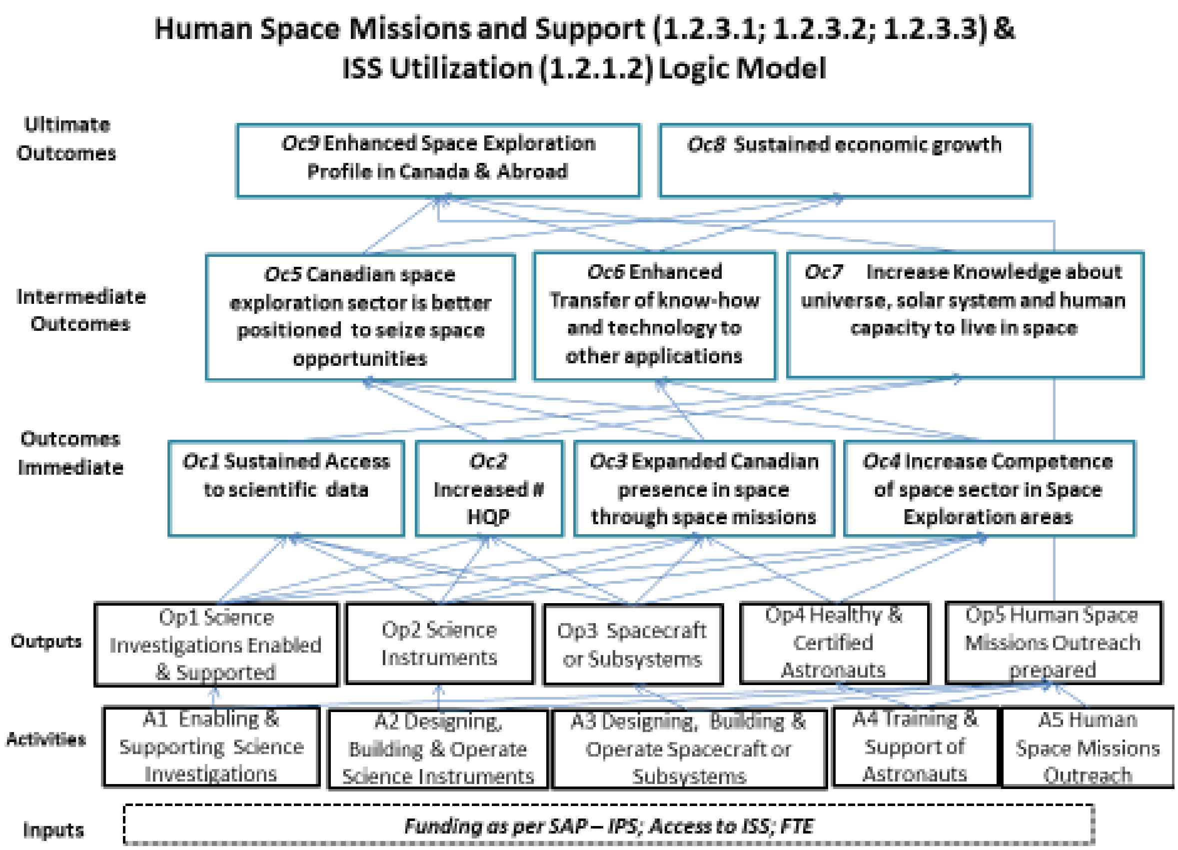
[7] IGA (1998). Agreement among the Government of Canada, Governments of Member States of the European Space Agency, the Government of Japan, the Government of the Russian Federation, and the Government of the United States of America concerning Cooperation on the Civil International Space Station, January 1998, [https://aerospace.org/sites/default/files/policy_archives/Space%20Station%20Intergovernmental%20Agreement%20Jan98.pdf]

[8] CSA and NASA (1998). Memorandum of Understanding between NASA and CSA concerning cooperation on the ISS, January 1998, [https://www.nasa.gov/mission_pages/station/structure/elements/nasa_csa.html]

station to which Canada has a right. It also participates in the overall management of the ISS program and has an equal vote with the five ISS partners.

2.2 Program logic model, activities, clients and partners

The logic model, described in the program performance measurement strategy,[9] introduces ties between the various elements of the program, from inputs and activities to the final results.



Generally, the life cycle of scientific instrument research and development initiatives includes a number of phases, including preliminary studies, definition, implementation and operations. Since some research takes place over an extended period (the life cycle is generally approximately five to seven years), the work carried out as part of the program can be related to projects that were started a long time ago. Training and support for astronauts is ensured by program specialists and through agreements

[9] CSA (2017). Performance Measurement Strategy for Human Space Missions and Support and International Space Station (PM Strategy), p. 18.

and contracts with partners and private businesses and astronaut missions are planned and negotiated according to the parameters of the IGA Agreement.[10]

Specifically, the program conducts the following types of activities:

- Financial support: the program gives financial support to partners and external stakeholders. For scientific research, most of the time, announcements of opportunity (AO) are issued and grants and contributions are given to researchers, and contracts are concluded following requests for proposals (RFP) to businesses or organizations. For the design and construction of scientific instruments, space vehicles and sub-systems, contracts are issued as well as grants and contributions. Memoranda of understanding are also concluded with other Canadian and international government entities for various services, such as the training of astronauts at NASA.
- Support for managers and program specialists: the personnel assigned to the program contributes to overall operations (planning, grant management, contributions, contracts and memoranda of understanding, general administration), participates with ISS partners on a number of multilateral bodies (councils, committees and scientific and operational working groups) and collaborates with external stakeholders, such as federal departments and agencies, international partners (other space agencies or nations in addition to ISS partners), the Canadian and international scientific community, universities and associations.

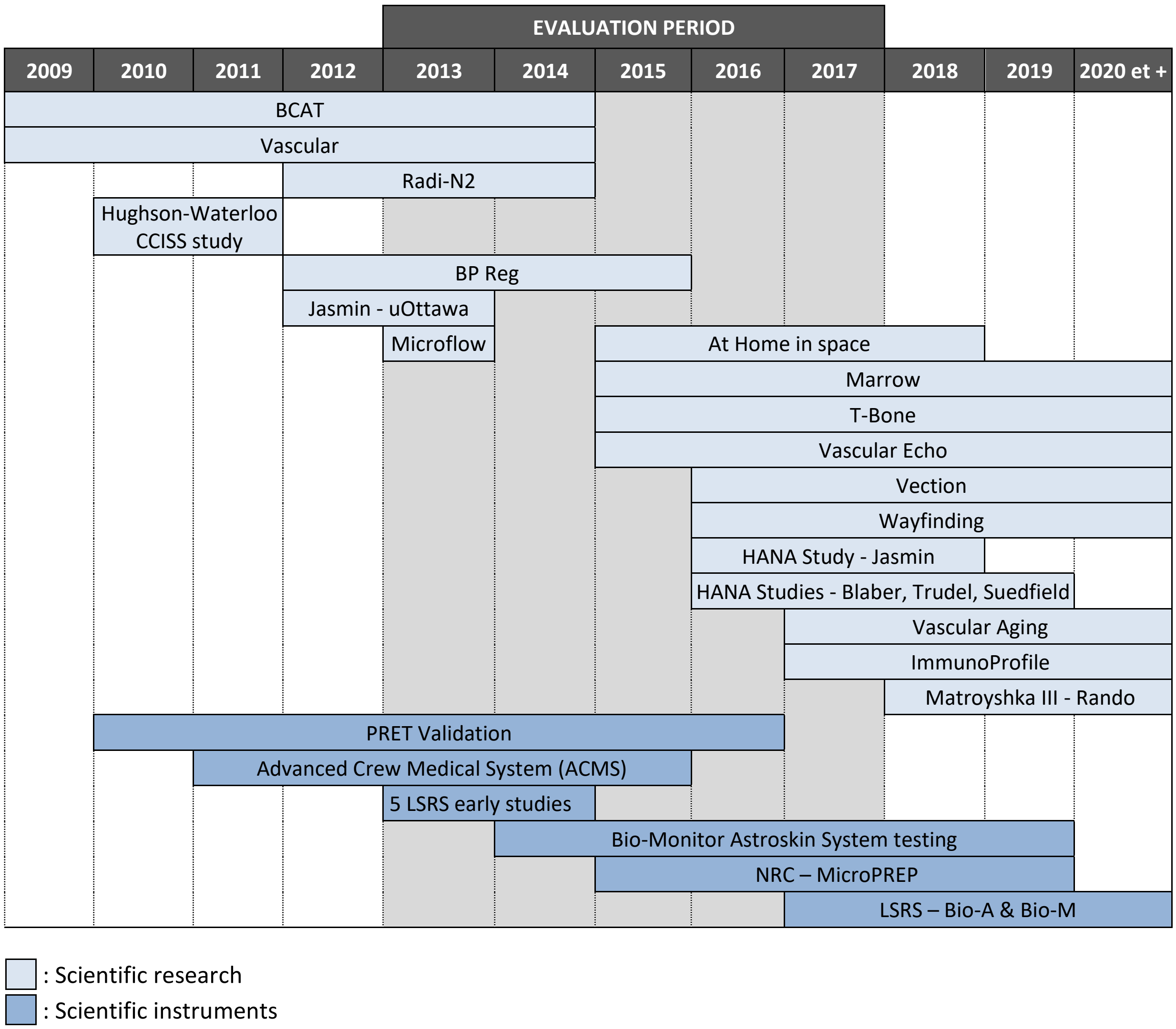
During the evaluation period, the program led the following activities:

- 10 separate scientific research projects were in development or completed during the evaluation period as illustrated in Table 6 (section 4.2 Outputs). The details of this research are outlined in Appendix A;
- 10 separate scientific instruments were in development or had been completed during the evaluation period as illustrated in Table 6 (section 4.2 Outputs). The details of these instruments are outlined in Appendix A;
- Astronaut Chris Hadfield's mission was carried out from December 19, 2012, to May 14, 2013;
- The astronaut recruitment campaign was held from June 2016 to August 2017 and led to the hiring of two astronauts, Jennifer Sidey and Joshua Kutryk;
- A variety of communication activities were carried out, such as videos produced by Chris Hadfield during his ISS mission, presentations by astronauts, and the program's participation in events such as tours in schools in association with scientific projects, such as a challenge organized by Let's Talk Science intended to raise awareness among young people about the importance of science, technology, engineering and mathematics (STEM) in their lives.

[10] IGA (1998). *Op cit*.

In figure 2 below, you can see the scope of the scientific research projects and instruments developed by the program. Details on each of these projects are outlined in Appendix A.

FIGURE 2. CHRONOLOGY OF THE CSA'S RESEARCH AND SCIENTIFIC INSTRUMENTS IN DEVELOPMENT AND IN OPERATION



To illustrate the results, four case studies were conducted as part of the evaluation and are outlined in the box below.

Four case studies

Microflow and the bio-analyzer (Bio-A)

Developed by the Institut national d'optique (INO) and then marketed, Microflow was the first tool that could be used to analyze biological samples on board the ISS. The experiment was successfully tested during Chris Hadfield's last mission, and the technology developed allowed us to generate new ideas that could potentially allow operational medicine communities in space or on Earth to provide the ability to analyze samples in situ. The Bio-A instument is also a system that allows us to analyze biological samples (blood, urine, saliva) in space, eliminating the need to freeze the samples and transfer them to Earth for analysis. At the time of the evaluation, it was imagined that this instrument would allow us to speed up scientific experiments carried out on board the ISS and could be useful for operational medicine on Earth and on the ISS. Businesses working on this project are planning to market this technology; for example, it would allow them to produce blood test results in less than five minutes.

Studies related to the cardiovascular system

Since 2007, six studies on the cardiovascular system have been carried out, including some that were still ongoing at the time of the evaluation. The various experiments concern the effects of flight on the health of astronauts. This research has direct applications on Earth, particularly with regard to aging and a sedentary lifestyle. Studies on the cardiovascular system were also conducted on bed rest to fill the lack of information on the physiolocial effects of long-term missions in space. Researchers from Canadian universities are leading these studies on the ISS and on the ground in collaboration with a number of international partners.

Chris Hadfield and expeditions 34 and 35

From December 19, 2012, to May 14, 2013, Canadian astronaut Chris Hadfield participated in his third mission in space, during which he became the first Canadian to be commander of the ISS. During his mission, he led scientific studies and tested new technology. His mission garnered the interest of Canadians and the entire world thanks to an extensive outreach campaign.

The last astronaut recruitment campaign

In 2016–2017, the CSA recruited two astronauts, Jennifer Sidey and Joshua Kutryk, during an extensive recruitment campaign intended to increase the number of Canadian astronauts, which was two active astronauts. The selection process mobilized a number of resources at the CSA and collaborations with other departments (e.g., National Defence contributed to the physical tests) and took place with a tight deadline. Considerations related to representation of minority groups were integrated into each step and the selection process was cited as an example by partners as having been rigorous.

Partners and target populations

Partners of Human Space Missions and ISS Utilization include:

- The partner space agencies of the ISS: NASA, main partner that plays a leading role in the ISS, is responsible for all management of the ISS and the integration of activities and equipment in the international section of the ISS. It is also responsible for the transportation of Canadian research equipment and supplies. The space agencies of the other ISS partners are Russia represented by Roscosmos, Japan represented by the Japan Aerospace Exploration Agency (JAXA) and Europe represented by the ESA. Canada is represented by the CSA.
- University institutions: the scientific community (scientists, doctors and engineers at universities and research centres and hospitals in Canada) developing and/or using instruments in space laboratories or carrying out experiments in laboratories on Earth concerning the risks to human health associated with human space missions.
- Private businesses: the working groups led by the industry, associations representing the industry and businesses involved in the development, construction and operation of instruments and software.
- Other federal departments and agencies that are collaborating on the achievement of horizontal objectives and that are consulted at the various stages of projects, planning and implementation.

ISS partners collaborate widely in scientific experiments, in the development of instruments and the documentation of results, in scientific publications and other media.

The target populations[11] include:

- University institutions and research centres involved in the research and development of space-related science and technology;
- Private businesses and not-for-profit organizations: small, medium and large enterprises, including not-for-profit organizations involved in the development of science and technology related to space exploration;
- Canadian citizens: young people and the general public.

[11] The target populations include "those intended to be influenced and benefit from the program" *A Guide to Developing Performance Measurement Strategies*, [https://www.canada.ca/en/treasury-board-secretariat/services/audit-evaluation/centre-excellence-evaluation/guide-developing-performance-measurement-strategies.html]

2.3 Program resources

During the five years covered by the evaluation, the CSA invested a total of $56.1 million in the program.

2.3.1 Financial resources

The data in Table 1 demonstrate that the majority of resources (87%) went to financial support for external entities (54%) (43% in contracts, 6% in memoranda of understanding and 5% in grants and contributions) and salaries (33%). The other expenses were for the ongoing management of the program through operating and maintenance costs.

TABLE 1: SUMMARY OF FINANCIAL RESOURCES ASSIGNED TO THE PROGRAM

SUB-SUB-PROGRAMS		2013–2014	2014–2015	2015–2016	2016–2017	2017–2018	TOTAL
ISS Utilization 1.2.1.2	Contracts	$2,080,197	$1,875,835	$1,639,787	$6,935,303	$8,463,804	$32,275,220
	Grants & contributions	$323,000	$271,331		$72,368	$274,796	
	Memoranda of understanding	$168,180	$100	$9,660	$1,550	$4,600	
	Salaries	$1,633,478	$1,627,316	$1,462,708	$1,402,501	$2,336,038	
	Operation and maintenance	$807,086	$433,619	$144,183	$121,178	$186,653	
Astronaut Training and Missions 1.2.3.1	Contracts	$244,143	$133,050	$181,251	$429,231	$768,347	$14,720,080
	Grants & contributions					$120,000	
	Memoranda of understanding	$100,659	$74,131	$153,108	$87,001	$375,458	
	Salaries	$1,231,158	$978,705	$783,519	$2,002,184	$2,301,788	
	Operation and maintenance	$843,586	$746,563	$937,276	$855,552	* $1,373,369	
Operational Space Medicine 1.2.3.2	Contracts	$196,199	$154,150	$239,625	$248,268	$213,849	$3,686,450
	Grants & contributions						
	Memoranda of understanding	$4,925	$85,250	$94,229	$82,114	$79,996	
	Salaries	$262,961	$432,501	$505,278	$211,059	$373,529	
	Operation and maintenance	$105,695	$72,068	$100,650	$54,852	$169,252	
Health and Life Sciences 1.2.3.3	Contracts	$62,786	$66,170	$1,000	$346,915	$10,800	$5,402,926
	Grants & contributions		$37,000	$497,034	$497,000	$498,001	
	Memoranda of understanding	$203,435	$341,838	$400,225	$330,000		
	Salaries	$286,410	$348,416	$495,178	$733,740	$7,255	
	Operation and maintenance	$39,493	$38,645	$32,765	$81,297	$50,521	
TOTAL		$8,590,390	$7,716,690	$7,677,475	$14,492,064	$17,608,056	$56,084,675

Source: CSA financial data.

* Note: the operating and maintenance costs also include costs related to special projects, such as the astronaut recruitment campaign and David Saint-Jacques's mission. These are expenses such as costs for travel, training of astronauts, activities and communications materials.

2.3.2 Human resources

The CSA personnel assigned to the program includes project managers, specialists (including one head doctor and one flight doctor), scientists and administrative support officers. Other CSA specialists also provide support for specific projects (matrix support).

In terms of human resources, on average, 35 full-time equivalents (FTE) were assigned annually to the program. Two elements emerge with regard to human resources (see Table 2): a small number of resources is assigned to two sub-sub-programs (*1.2.3.2. Operational Space Medicine* and *1.2.3.3. Health and Life Sciences*), on average 3-4 FTE, and an increasing gap should be noted for the sub-sub-program *1.2.3.1. Astronaut Training and Missions* in the past two years (2016–2017 and 2017–2018).

Regarding the increasing gap for 2016–2017 and 2017–2018, the gap between the actual and expected FTEs in the space exploration program for these years is mainly attributable to the reassignment of resources to astronaut David Saint-Jacques's mission, to the astronaut recruitment campaign and to new positions resulting from additional funding to support the ISS's activities until 2024–2025.[12]

TABLE 2. NUMBER OF FULL-TIME EQUIVALENTS, EXPECTED AND ACTUAL PER YEAR (2013–2014 TO 2017–2018)

	2013–2014		2014–2015		2015–2016		2016–2017		2017–2018	
SUB-SUB-PROGRAMS	FTE		FTE		FTE		FTE		FTE	
	Planned	Actual	Planned	Actual	Planned	Actual	Planned	Actual	Planned	Actual
1.2.3.1 Astronaut Training and Missions	10.3	11.4	9.5	9.4	8.1	7.0	7.0	18.0	16.2	24.0
1.2.3.2 Operational Space Medicine	5.1	2.2	1.3	3.1	2.9	3.6	3.5	2.0	1.2	3.0
1.2.3.3 Health and Life Science	4.1	2.7	2.8	3.0	2.7	4.2	3.5	8.0	0.0	1.0
1.2.1.2 ISS Utilization	15.0	14.1	15.6	13.5	18.1	13.0	16.6	12.0	14.2	19.0
TOTAL	**34.5**	**30.4**	**29.2**	**29.0**	**31.8**	**27.7**	**30.6**	**40.0**	**31.6**	**46.6**

Source: Financial data from CSA annual performance reports from 2013 to 2018.

2.3.3 Management structure

The General Director of space exploration assumes overall responsibility for the activities carried out as part of the program. He acts in accordance with all of the applicable policies from the Treasury Board of Canada as well as the Project Management Policy and the Integrated Governance and Monitoring Framework Directive adopted by the CSA.

The Director General of the program chairs the Space Exploration Management Committee to support the ongoing coordination of the program's activities, projects, finances and human resources.

[12] ASC. Departmental Performance Report 2016–2017.

3 Approach and evaluation methods

This section of the report describes the methodology used to carry out the evaluation of Human Space Missions and ISS Utilization. It is intended to outline the purpose and scope of the evaluation and describe the main evaluation questions and methods used to make the evaluation's conclusions. Moreover, it determines the limitations of the evaluation and the strategies used to mitigate them.

3.1 Purpose and scope

This report meets the commitment in the CSA's Departmental Evaluation Plan (2017–2018 to 2021–2022) to carry out an evaluation of Human Space Missions and ISS Utilization. It covers a period of five years, from 2013–2014 to 2017–2018, except for some case studies whose scope precedes the evaluation period given that some activities had started before April 1, 2013.

The evaluation covers relevance, performance, efficiency and gender-based analysis plus (GBA+) of Human Space Missions and ISS Utilization. Specifically, it answers the following 11 evaluation questions:

TABLE 3. EVALUATION QUESTIONS FOR HUMAN SPACE MISSIONS AND ISS UTILIZATION

Relevance	1. How did the program meet needs? 2. How are the program objectives in keeping with the priorities of the federal government? 3. What are the roles and responsibilities of the federal government in relation to the operation of the program?
Performance	4. How were the expected outputs achieved? 5. How were the expected immediate results achieved? 6. How were the expected intermediate results achieved? 7. How were the expected final program results achieved? 8. Did the implementation of the program have any unexpected negative or positive impacts?
Efficiency	9. Are there more profitable ways to implement the current program? 10. Were there any problems and facilitating factors during the various phases of the program life cycle?
GBA+	11. What are the program's impacts on GBA+ groups?

3.2 Methods

The evaluation data were collected using a number of research methods that are briefly outlined in this sub-section.

3.2.1 Comparative study and literature review

The program evaluation is based on a comparative study and review of the literature using CSA internal documents, public reports and national and international academic publications. These methods were intended to evaluate the collaboration between partners and the way in which the ISS was used to date in order to deepen knowledge related to space medicine and life sciences and investigate alternatives available to the ISS to carry out such research. Also, the comparative study and review of the literature included missions beyond low orbit and were intended to analyze the role that the CSA or the Canadian industry could play in such missions in the field of space medicine and life sciences. Lastly, the comparative study was also intended to learn more about the various ways in which astronauts from ISS member countries engage in public awareness activities.

3.2.2 Document review

The document review is varied and mainly concerns the relevance of the program. It includes various strategic documents, reports by expert groups, data, evaluations and statements by the Government of Canada. It also includes information provided by the CSA with regard to Human Space Missions and ISS Utilization, as well as documents identified or provided by other stakeholders, in particular as part of interviews conducted for the needs of this evaluation. The evaluation is also based on other evaluations carried out in recent years that cover topics common to Human Space Missions and ISS Utilization (e.g., Evaluation of the ISS Assembly and Maintenance Operations Program). Also, the document review covered activities carried out by other countries in the activities and scientific mission in which Canada participated. Lastly, a number of studies from external organizations were also reviewed, including the 2018 Evaluation of NASA, NASA's Management and Utilization of the International Space Station, a 2016 article from the OECD, New Trends in Space Innovation and another on the risks to human health from NASA in 2017, and Human Health and Performance due to in-Flight Medical Conditions.

3.2.3 Interviews with key informers

The interviews conducted with key informers helped to garner more in-depth knowledge of the activities of Human Space Missions and ISS Utilization, including the results obtained and challenges faced by key stakeholders. These interviews also corroborated, explained or clarified the findings of other sources of data. In total, 52 people from various groups of stakeholders were consulted as part of the individual and group interviews. The distribution of these interviews is outlined in Table 4.

TABLE 4. NUMBER OF INTERVIEWS AND RESPONDENTS BY CATEGORY

CATEGORIES OF RESPONDENTS	NUMBER OF INTERVIEWS	NUMBER OF RESPONDENTS
Program specialists – CSA	9	9
Corporate – CSA (communications, policy, human resources, programs and integrated planning, planning and explorations activities)	5	9
Senior management – CSA	3	3
Canadian astronauts (active and retired)	3	3
Senior management – External	7	7
Program specialists – External	6	6
Industry and academia	7	7
Non-Canadian astronauts	3	3
External organizations	5	5
TOTAL	**48**	**52**

The information gathered during these interviews is included throughout this report, as applicable.

3.2.4 Case studies

Four case studies were carried out based on a document review, analysis of internal and external data and interview data related to the selected cases. In order of priority, the following selection criteria were used to select the case studies:

- The representativeness of the diversity of program activities;
- The duration of the research theme;
- The amount of funding;
- The importance of international collaboration.

A brief description of each of the case studies can be found in section *2.2. Program logic model, activities, clients and partners* in the box. Also, throughout the report, various boxes related to the case studies discuss the evaluation questions.

3.2.5 Internal data

The internal data of the sub-program *Human Space Missions and Support* and the sub-sub-program *International Space Station Utilization* were reviewed to consider ongoing relevance. The internal data included reports on performance measurement, financial data, administrative data, the Performance Measurement Strategy (PM Strategy), bibliometric data and reports on plans and priorities.

3.3 Limitations

This section describes the limitations encountered during the evaluation and how they were approached.

1. **Some performance data are not available.** This is particularly true for the final results, which are difficult to measure: for example, the program's contribution to Canada's sustained economic growth. Having said that, the majority of data on performance for the evaluation were available and the information provided was reliable and valid even if some performance indicators were not measured as outlined in the PM Strategy.[13] The data collected from respondents in interviews as well as the more detailed results from the case studies mitigate this limitation by adding qualitative information related to the results.

2. **Most of the respondents have a direct interest in the program**. In addition to internal respondents with a direct interest in the program, external respondents were mostly researchers and businesses who had received support from the program or were ISS partners (e.g., NASA, other space agencies) who could also have a positive bias toward the program being evaluated. This limitation was mitigated by asking respondents to explain their points of view and to provide examples where appropriate. Concerning the report as a whole, the findings resulting from interviews with key respondents were cross-checked with findings from other data sources (i.e., document review, data from program performance and case studies).

3. **It is too soon to quantify/evaluate the results of some projects**. The life cycle of projects is generally approximately five to seven years, beginning with the Announcement of Opportunity / request for proposals until the end of the experiments and collection of scientific data. The first peer-reviewed publications are generated between six months and two years following the end of data collection, and other publications may also appear over the subsequent years. The more long-term impacts of major projects, such as some presented in this report, in particular the effect on Earth, can therefore take place a number of years after the end of the projects given their scientific nature. This is even more true for projects funded during the last two years of the evaluation period (2016–2017 to 2017–2018), which had not yet led to publications at the time of the evaluation. In order to mitigate this limitation, two case studies selected as part of this evaluation begin before the latter.

[13] Note that the PM Strategy was changed to the Performance Information Profile, approved by the CSA in December 2017 (in response to the new Policy on Results from July 2016).

4 Findings of the evaluation

This section of the report outlines the findings of the evaluation. First, the relevance of the program is discussed, and then the results and efficiency are outlined.

4.1 Relevance

This section covers three evaluation issues: 4.1.1 the response to needs identified at the start of the program; 4.1.2 consistency between the program objectives and the priorities of the federal government; and 4.1.3 the roles and responsibilities of the federal government in relation to the implementation of the program.

4.1.1 How did the program meet needs?

First, this section discusses the justification of the need at the beginning of the program. Second, it covers the evolution of needs, and third, the existence of other needs not covered by the program.

4.1.1.1 Justification of Human Space Missions and ISS Utilization

Finding: The program not only meets a demonstrated need by maximizing the return on investments made in the past (the complete use of the time allocated to Canada at the ISS), but it allows us to take advantage of the experience and reputation that the CSA has acquired over the years in research, space medicine and astronaut missions.

The general justification of Human Space Missions and ISS Utilization is determined by the use of major infrastructure, the ISS, which is part of the larger context of space exploration by humans. Also, the justification of the program can be broken down according to various specific needs of the program.

Maximize past investments

As outlined in section 2.1 of this report, Canada has invested $2.2 billion from the beginning of the ISS to 2017 to participate in its construction. This gives it the right to use the ISS research facilities and have allocated crew time of 2.3% (international portion). Human Space Missions and ISS Utilization allow us to use and maximize the return on past investments through the use of this allocation. The allocation of 2.3% of time is used for the flight of Canadian astronauts to the ISS and Canada's scientific experiments and technological demonstrations on board the ISS. Moreover, the 2012 budget extended Canada's participation at the ISS from 2016 until 2020, and the 2015 and 2016 budgets announced the maintenance of Canada's participation in the ISS mission. This reiterated Canada's commitment to contributing to the operation and maintenance of the Mobile Servicing System until December 2024, giving it crew time and transportation credits. As a result, Human Space Missions and ISS Utilization are part of the ongoing ISS construction project.

The program and the general context of space exploration

The needs identified in the Performance Measurement Strategy of Human Space Missions and ISS Utilization first establish the program in the larger context of space exploration. Space exploration contributes to knowledge development and the potential to contribute to new commercial opportunities: “The Space Exploration Program continues to serve the needs of Canada by producing innovations that have the potential to become commonplace products and services.”[14]

Various document review sources demonstrate Canadians’ interest in the importance of investing in space exploration. During consultations held with stakeholders from the field by the Space Advisory Board ordered by Canada’s Minister of Innovation, Science and Industry in 2016, it was recommended that space be considered a national strategic asset: “Designating space as a national strategic asset to ensure that the country (governments, industry, academia, and civil society) focuses on the importance of space to Canada’s economic and social growth.” Participants in the consultations noted that, in the past,

> Space capacity was generally considered by the governments as a national strategic asset capable of applying unique solutions to a large number of critical national problems. [...] Canadian space technology contributes in a special manner to the unification of the country [and] inspires Canadians as no other ability can (Canadarm, astronaut and space astronomy).[15]

This opinion is shared by the coalition Don’t Let Go Canada,[16] established by representatives of the space sector (industry and not-for-profit organizations), for whom it is essential that the government become more involved in the space sector.

In addition to stakeholders from the space sector for whom space exploration is important, an OECD article from 2016 states that some entrepreneurs and large private businesses are interested in human space exploration: “One major change, as compared to only a decade ago, is that such a vision is not only articulated by scientists in space agencies with more or less support from policy makers, but it is also an objective of some entrepreneurs and large commercial firms.”[17] According to this article, NASA is planning a significant role for the private sector in the “low Earth orbit economy” (“LEO economy”) for the development of activities related to crewed human space missions in the future.

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[14] CSA (2017). PM Strategy, *Op. cit*., p. 7.

[15] GOVERNMENT OF CANADA (2017). *Consultations on Canada’s future in space: What we heard*, August 2017, [https://www.ic.gc.ca/eic/site/082.nsf/eng/03996.html].

[16] The Don’t Let Go Canada campaign was initiated by the Aerospace Industries Association of Canada and MDA, Capada’s largest space company. More than 60 companies, associations and academic organizations from Canada’s space sector have joined the coalition. For more information: https://dontletgocanada.ca/faq.

[17] OECD (2016). *New Trends in Space Innovation*, October 27, 2016, p. 22, [https://read.oecd-ilibrary.org/science-and-technology/space-and-innovation/new-trends-in-space-innovation_9789264264014-3-en#page1].

The general Canadian public is also in favour of space exploration according to a survey of public opinion carried out in 2018 of approximately 1,600 Canadians age 18 and over: "Enthusiasm about space is stronger than in the past [...]. The Canadarm and Canada's astronauts are top-of-mind, and sources of pride. [...] Canadians support investment in the space sector and many reject the notion that Canada is too small a country to be active in space.[18]" However, this statement is qualified by another that states that expenses in the space sector are not the priority, since half of Canadians confirm that Canada should spend less on space in general: "Canada should spend less in the space sector because we have other greater priorities.[19]" Another survey carried out in 2019 of a virtual panel of 1,512 Canadians for Sun/Post Media revealed that 80% of Canadians are proud of the role played by Canada in space exploration and 63% confirm that the astronauts inspire them personally.[20] These data are also confirmed by CSA's high number of interactions on social media as outlined in the section on the final results (4.2.5).

According to an article prepared by the International Space Life Science Working Group (ISLSWG), the social advantages related to new knowledge and space technology are many and concern

> A large number of various aspects of daily life, from solar panels to implantable cardiac monitors, therapies to fight cancer with lightweight materials, water purification systems, improved computer systems and a worldwide system of search and rescue.[21]

Moreover, even if the nature of future advantages resulting from space exploration is unpredictable, current trends suggest that considerable advantages can be generated in fields such as new materials, health and medicine, transportation and information technology.[22]

Space exploration in the general sense is a current need according to various players in the space sector and the general Canadian public and allows us to produce innovations with economic, scientific and social benefits for Canadians.

<u>The specific needs identified in the PM Strategy Human Space Missions and ISS Utilization</u>

In the context of space exploration, the program specifically targets the following five needs identified in the program's performance measurement strategy, objectives that are still relevant and in keeping with the Space Strategy for Canada announced in March 2019:[23]

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[18] IPSOS (2018). *Canadian's Support and Enthousiasm for Development in the Space Sector is Taking Off*. September 20, 2019. [https://www.ipsos.com/en-ca/news-polls/space-sector-taking-off].

[19] *Ibid*.

[20] Majority of Canadians proud of country's space program: [https://toronto.citynews.ca/2019/07/21/canada-space-program-poll/].

[21] The International Space Life Science Working Group (ISLSWG) is a working group with the goal of coordinating strategic planning and implementing activities in life science in space. For more information: [https://www.nasa.gov/sites/default/files/atoms/files/islswg_charter_october_2015_signed.pdf].

[22] CSA (2016). *Evaluation of the ISS Assembly and Maintenance Operations Program*, *Op. cit*., p. 43.

[23] CSA (2019). *Space Strategy for Canada*, [https://lobbycanada.gc.ca/app/secure/ocl/lrs/do/advSrch?lang=eng].

1) To position Canada at the forefront of science and technology;
2) To recruit, train and secure flight opportunities for astronauts;
3) To identify, understand, reduce and eliminate the risks to the health of astronauts;
4) To design, build, launch and operate space hardware to conduct life science experiments and support the health of astronauts;
5) To create new jobs in fields such as engineering, science, manufacturing and administration.[24]

The evaluation focused on the relevance of each of these needs and on the manner in which the program responds to them.

1) TO POSITION CANADA AT THE FOREFRONT OF SCIENCE AND TECHNOLOGY

The need to position Canada at the forefront of science and technology is a common need in the sub-program Human Space Missions and Support (1.2.3) and the sub-sub-program ISS Utilization (1.2.1.2). The ISS is a laboratory that allows for scientific and technological development, and the *Canada Space Agency's Evaluation of the International Space Station Assembly and Maintenance Operations Program*[25] noted this unique potential use of the ISS in particular in scientific research and Earth observation.

> Research in human health on the ISS allows for a better understanding of human health, in particular aging, trauma, illnesses and the environment [...]. The ISS facilitates the observation of Earth to understand and resolve environmental issues [...]. Astronauts can make observations and take images in real time and provide information for personnel on the ground who program the automated Earth observation systems on the ISS.[26]

Since the beginning of the ISS, Canada has participated in 60 experiments and projects associated with science and health,[27] which has allowed it to position itself at the forefront in some specific areas, such as space medicine and cardiovascular health.

During the interviews, almost all of the internal respondents believed that the program contributed to positioning Canada at the forefront of science and technology. In their opinions, Canada is respected and recognized in the international community for its contribution and knowledge sharing in the fields of technology and health research. Respondents also mentioned that there is a true demand from our international partners in this regard. Also, many respondents indicated that the need to position Canada at the forefront of science and technology is still current and that this is

[24] CSA (2017). PM Strategy.
[25] CSA (2016). *Evaluation of the ISS Assembly and Maintenance Program*, *Op. cit*.
[26] *Ibid*., p. 44
[27] CSA (2019). Space Strategy for Canada, *Op. cit*., p. 3

reflected in the Agency's activities. More than once, it was stated that this need is intrinsically related to the Agency's mission. External respondents said that Canada's contribution is small in quantity, but large in quality. Almost all external respondents stated that life science and technology were going to become more important sectors with future missions to Mars and that Canada could increase its importance on the world stage if it continued its involvement in these areas.

The ISS provides Canada with opportunities to position itself at the forefront of science and technology and the program allows us to take advantage of these opportunities and to be recognized by the international community.

2) TO RECRUIT, TRAIN AND SECURE FLIGHT OPPORTUNITIES FOR ASTRONAUTS

The need to recruit, train and secure flight opportunities for astronauts is related to the sub-program *Space Missions and Support* (1.2.3). The maintenance of a corps of astronauts allows us to take advantage of flight opportunities allocated to Canada under the rights and obligations as per the agreement with ISS partners.[28] A number of interview respondents stressed the importance of maintaining a corps of astronauts in Canada. This is an essential activity of the program that is even more important in the context of future opportunities for commercial flights and the exploration of deep space. The program is the only one to recruit and look for flight opportunities in Canada, which makes it unique, and the Agency must ensure that the astronauts are qualified, healthy and sufficiently trained. In this regard, all stakeholders believe that the Agency is recruiting enough astronauts. With respect to training, most stakeholders think that the Agency is reaching its objective.

All respondents believe that by recruiting astronauts, the Agency should be able to guarantee them flight opportunities. A number of respondents believe that the program allows us to reach this objective. However, a quarter of respondents emphasized that Canada had not yet reached its full potential in this area. According to some, we should be able to guarantee more space flights. In section 4.3 on efficiency, the issue of increasing the frequency of flights is discussed.

3) TO IDENTIFY, UNDERSTAND, REDUCE AND ELIMINATE THE RISKS TO THE HEALTH OF ASTRONAUTS

The need to identify, understand, reduce and eliminate the risks to the health of astronauts is a need related to sub-program *Human Space Missions and Support* (1.2.3). It is a common need among ISS partners that must maintain the health of astronauts. The exploration of space exposes human beings to health risks that can compromise the mission or have long-term consequences. These risks are largely related to the space environment, in particular space radiation, variable gravity and the isolated, confined and extreme environment, but some risks are also related to the delivery of health care. The identified risks are described in detail in documents such as *Human Health and Performance*

[28] IGA (1998). *Op. cit*.

Risks of Space Exploration Missions[29] and *Risk of Adverse Health Outcomes and Decrements in Performance due to In-flight Medical Conditions.*[30] A summary of the risks was produced by the Multilateral Human Research Panel for Exploration (of which the CSA is a member) and is presented in table 5.[31]

TABLE 5 – HUMAN HEALTH AND PERFORMANCE RISKS SUMMARY

RISK CATEGORY	DESCRIPTION
Musculoskeletal	Reduced muscle strength and aerobic capacity, and increased bone fragility.
Sensorimotor	Sensory changes/dysfunctions reducing performance.
Ocular Syndrome	Microgravity-induced visual impairment and/or elevated intracranial pressure.
Nutrition	Inability to provide appropriate quantity, quality and variety of food to meet nutritional requirements and maintain morale.
Behavioural Health and Performance	Isolated environment, work/rest balance, stress, issues with team dynamics, human-system interface issues, risks associated with integration into post-space flight career phase.
Radiation Health	Impairment associated with radiation damage. Risk of carcinogenesis and degenerative tissue disease due to radiation exposure.
Hypogravity	Physiological adaptation during transit (i.e. long duration exposure to microgravity) and extra-vehicular activities (EVAs) on the Moon, asteroids, or Mars (vestibular and performance dysfunctions).
Environmental Stressors	Exposure to a toxic environment in the spacecraft, during EVAs or while on extraterrestrial bodies without adequate monitoring, warning systems or understanding of potential toxicity (planetary dust, chemicals, infectious agents, microbial contamination).
Autonomous Medical Care	Inability to provide adequate medical care throughout the mission (Includes onboard training, diagnosis, treatment, and presence/absence of onboard physician)

ISS partners have conducted a number of studies on Earth and on the ISS to understand the risks associated with space flights and find mitigation strategies to reduce their impact.[32] According to an auditing report by the American Office of Inspector General in February 2018, "Understanding and mitigating risks to astronaut health and performance for long-duration spaceflight has been a top priority for the Station since its inception."[33] This report provides an overview of the situation of all risks to the health of astronauts, demonstrating the scope of research that remains to be done for the development of countermeasures; there are at least eight risks to human health that need to be tested on the ISS until 2024 or after,

[29] NASA (2009). *Human Health and Performance Risks of Space Exploration Missions*, [https://humanresearchroadmap.nasa.gov/evidence/reports/EvidenceBook.pdf].

[30] NASA (2017). *Risk of Adverse Health Outcomes and Decrements in Performance due to In-Flight Medical Conditions*, [https://humanresearchroadmap.nasa.gov/evidence/reports/Medical.pdf].

[31] Health Research and Development for Space Exploration Plan, March 20, 2018, p. 4.

[32] For example, in 2014, NASA spent over $215 million on research on the risks on human health of space travel. NASA OFFICE OF INSPECTOR GENERAL (2015). *Nasa's Efforts to Manage Health and Human Performance Risks for Space Exploration*, p. 13, October 29, 2015.

[33] NASA (2018). *NASA's Management and Utilization of the International Space Station*, p. 7, [https://oig.nasa.gov/docs/IG-18-021.pdf].

including research into cognitive or behavioral conditions, inadequate food and nutrition, team performance decrements, spaceflight associated neuro-ocular syndrome, long-term storage of medication, sensorimotor altercations, altered immune responses, and host-microorganism interaction.[34]

A number of risks still need to be identified and countermeasures developed, even more so in the context of deep space travel for which the impact on human health is not all known and for which the countermeasures are limited.[35]

All of the people interviewed believed that identifying, understanding, reducing and eliminating risks to the health of astronauts was part of the Agency's major concerns. According to many, this is a need that is intrinsically tied to the previous need – recruiting, training and securing flight opportunities for astronauts (need no. 2) – in the sense that sending astronauts into space requires that we ensure their health. Also, it was said a number of times and by different stakeholders that the identification, understanding, reduction and elimination of risks to the health of astronauts would increase in importance with future moon and Mars missions, since these missions would be longer and could cause higher risks to the health of astronauts. According to several stakeholders, it is important to continue with scientific and medical research related to the impact of space flight on humans. In conclusion, the risks to the health of astronauts are still present and must be studied.

4) TO DESIGN, BUILD, LAUNCH AND OPERATE SPACE HARDWARE TO CONDUCT LIFE SCIENCE EXPERIMENTS AND SUPPORT THE HEALTH OF ASTRONAUTS

The need to design, build, launch and operate space hardware to conduct life science experiments and support the health of astronauts is related to sub-sub-program *ISS Utilization* (1.2.1.2). Scientific and medical instruments are specifically built to maintain the health of astronauts. For over 20 years, Canada has developed expertise in instrument design such as the mini-laboratory OSTEO[36] and Microflow. These instruments, along with those developed as part of the Life Science Research System (LSRS) project, were and are used by the scientific community to support the identification, characterization and reduction of risks associated with human flights as discussed under the previous

[34] *Ibid*.

[35] NASA (2015). *Nasa's Efforts to Manage Health and Human Performance Risks for Space Exploration*, p. 13., 29 October 2015. See the introduction to the section entitled *What we Found*: "Long duration missions will likely expose crews to health and human performance risks for which NASA has limited effective countermeasures".

[36] The Canadian Space Agency supported Millenium Biologix in the design of the mini-laboratory OSTEO, which helped test the growth of bone cells using a synthetic biomaterial, Osteologic, also developed by Millenium. This biomaterial, which imitates bone structure, helped with the study of 192 bone cell samples, which had been previously developed. Now, a medical version of this material, Skelite, is used in Canada, the United States and in Europe to heal fractures. For more information: https://www.asc-csa.gc.ca/eng/sciences/osteo.asp.

need (need no. 3). In addition to helping to support the health of astronauts, the technology developed can be used for Earth applications in the field of health care,[37] particularly in telemedicine.

According to the *Report of the Expert Group on the Potential Canadian Healthcare and Biomedical Roles for Deep-Space Human Spaceflight*, "the Canadian medical technology industry comprises an estimated 2,000 companies spanning many areas of therapeutic focus and technological platforms,"[38] such as lab-on-chip diagnostics, artificial intelligence and digital health technology such as Hexoskin. This report recommends that we "invest significantly in deep-space autonomous healthcare, as a bold contribution to space exploration and a means to develop national capacity in virtual healthcare for the benefit of all Canadians."[39]

All interview respondents questioned on this topic believe that Canada is successfully designing, building, launching and operating space hardware to conduct live science experiments and support the health of astronauts. Moreover, a number of them said that this was at the centre of the Agency's mission. Some also indicated that the space hardware developed could also be re-used on Earth and that it could provide good visibility for Canadian expertise on the international stage. As a result, designing, building, launching and operating space hardware to conduct life science experiments and support the health of astronauts could also help improve and transform the remote delivery of healthcare and care for seniors.

[37] Bioanalysis technology could allow people who live in distant regions (e.g., the North) to be quickly tested for health problems such as infections, thus reducing healthcare costs and providing access to hospital-level tools to more Canadians. Bio-monitoring technology can be used to find telemedicine applications, for example in the mining sector and maritime environments, the Arctic and the military sector in distant areas and hostile environments. Telemedicine allows patients to get medical services quickly and efficiently in distant areas without needing to travel. This technology could also be used by seniors in the comfort of their home for the purposes of remote monitoring by doctors.

[38] CSA (2019). *Canadian Healthcare in Deep Space: Advancing our country's leadership in autonomous care in space and on Earth*, [https://www.asc-csa.gc.ca/eng/publications/canadian-healthcare-in-deep-space.asp].

[39] *Ibid*.

5) TO CREATE NEW JOBS IN FIELDS SUCH AS ENGINEERING, SCIENCE, MANUFACTURING AND ADMINISTRATION

The need to position Canada at the forefront of science and technology is a common need in the sub-program *Human Space Missions and Support* (1.2.3) and the sub-sub-program *ISS Utilization* (1.2.1.2). In 2017, personnel in the Canadian space sector included 9,942 people (in full-time equivalent (FTE)), including 4,085 highly qualified personnel (HQP)[40] and nearly 20% from universities and research centres (1,871 FTE).[41] A competitive and innovative space sector is critical in order to create jobs and establish the infrastructure necessary for a knowledge-based economy.

> ***Bioanalysis case study***
>
> *The bio-monitor was built by a Montreal start-up company and more than a dozen people worked on the project. Two other small Canadian businesses, including one that branched off of McGill University, in the field of biotechnology contributed to the development of sub-systems for the bio-monitor.*
>
> *According to a program lead, "it would have been very difficult for these businesses to have access to space without the program."*

The majority of interview respondents thought that it was important to create new jobs in the fields of engineering, science, manufacturing and administration. It was also said more than once that this need was intrinsically related to the Agency's mission and that it was still current. Moreover, a number of respondents think that the need to create new jobs in these fields will increase with the development of the industry and the greater involvement of commercial businesses in human space flights. To date, the commercial space markets are telecommunications, navigation and launchers (emerging market). The domestic market is very small (limited to the institutional market or government). Consequently, the sustainability of businesses working in the space exploration sector is related to activities based on Earth markets. Hence the importance, in the short and medium term, of relying on businesses that can co-develop Earth and space applications of the same technology to develop and preserve sustainable strategic space capacities.

It was also said more than once that meeting this need was relatively difficult considering that the space field is a particularly specific sector. A number of people believe that Canada has the potential to carve out a place in some fields related to the space sector, such as growing sectors like biomedical engineering. Developing autonomous systems and medical devices that can be used in extreme conditions can contribute both to needs in space and remote needs in distant regions of Canada.

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[40] CSA (2018). *State of the Canadian Space Sector Report 2018 (Facts and Figures 2017)*, p. 41, [https://www.asc-csa.gc.ca/eng/publications/2018-state-canadian-space-sector.asp].

[41] *Ibid*., p. 18.

General needs

In addition to the previous five needs, the program's activities contribute to general objectives, such as economic competitiveness, the improvement of healthcare for Canadians and the inspiration of Canadians to pursue their highest ambitions (i.e., astronauts' missions inspire young people to study and pursue careers in the fields of science and engineering).

However, other achievements of the ISS have as much to do with geopolitics as with science and innovation. Interview respondents said that the greatest achievement of the ISS program is as related to humans as technology. In addition to bringing together a number of launch vehicles, launch, operation, training, engineering and development facilities distributed across the world, communication networks and the international community, the ISS has housed multinational crews for nearly two decades, despite ongoing conflicts on Earth. Such an achievement led the ISS to be nominated for a Nobel Peace Prize in 2014 and to receive the Westphalia Peace Prize[42] the same year for its work on unity and peace in Europe. As ESA astronaut Alexander Gerst said on board the ISS:

> Today, the ISS is a striking example of how people can live and grow to work together for all of humanity. The ISS is the hallmark of international cooperation. A milestone in human history. Since it is only if we are together, if we consider ourselves a single and same society (we can see it clearly from space) that we can build a better future[43] [translation].

4.1.1.2 The progression of needs in the past five years (2013–2018)

Finding: Since 2013, needs have not really changed, but the context has evolved and the program has adapted itself to remain relevant. We decided to focus on certain research priorities. With respect to the astronauts, new selection criteria for recruitment were used during the last astronaut recruitment campaign.

The previously identified needs remain the same and are still current. However, the context of these needs has evolved over the 2013–2018 period. In fact, 1) the duration of human space missions is longer and longer; 2) astronauts have more time allocated to scientific research on board the ISS; 3) there was a reorientation of research priorities toward space exploration and longer missions; 4) new recruitment criteria for astronauts were applied; and 5) the availability of space vehicles (e.g. SpaceX) is increasing.

According to the information gathered during interviews and the document review, the evolution of the context can be explained by various factors. These factors are as follows: 1) the global economic slowdown

[42] The Westphalia Peace Prize is an award given to people or organizations that work to strengthen European and international peace. It has been awarded every two years since 1998, the year of the 350th anniversary of the Westphalia Peace Treaties (1648) that mark the end of the Thirty Years' War and the Eighty Years' War. For more information: https://www.réformés.ch/201403246850/6850-le-prix-de-la-paix-de-westphalie-est-decerne-dans-lespace.html (French only).

[43] ESA (2014).

that began in 2008 and that continues to affect the availability of funds from governments for space activities; 2) the end of the ISS assembly period in 2010; 3) the end of the NASA space shuttle program in 2011, which reduced space flight opportunities; and 4) the 2012 announcement of the extension of Canada's commitment to the ISS program until 2020. With the completion of the ISS, the CSA and its international partners have chosen to refocus their efforts on human space missions to the moon and Mars in the coming years. Former President of the United States Barack Obama announced the reorientation of NASA's activities in this direction in April 2010.[44] The Agency changed its strategic directions for the 2013–2018 period, adapting itself to macro-economic trends and changes in its international partners' direction.

Bearing in mind the factors that lead to a new context, the CSA is adapting its activities to meet the needs identified above. For example, interview respondents indicated that the research work related to the health of astronauts is increasingly focused on the psychological and psychosocial impacts of long missions.

1) Long space missions

Some interview respondents stated that there were fewer flight opportunities for astronauts since the decommissioning of the American space shuttle. Long space missions have become the norm and low-Earth orbit where the ISS orbits remain the only destination for human flights. These missions, which typically last six months, are the result of the unavailability of means of crew transportation other than the Soyouz and allow us to prepare for potential long trips to distant destinations.

Among the advantages of longer missions, a number of stakeholders indicated that long-term human presence allows us to conduct longer research experiments and to study the effect of longer space flight on human health. In the past, shuttle flights, lasting a maximum of two weeks, were rather limited since the experiments needed to be autonomous. It is now possible to carry out various research in the ISS (e.g. changes in fluids can be studied in humans over a period of six months). Also, one respondent indicated that the CSA could now conduct longer experiments.

There are some disadvantages to long flights in the Canadian context. Since Canada accumulates flight credits at a rate of 2.3% of the total available time, the longer the flight, the longer the wait for the next flight. According to some interview respondents, it may be preferable for Canada to have shorter flights so that Canadian astronauts can fly more frequently. Another disadvantage is that longer missions mean that the turnover rate of astronauts is lower and we have to wait longer to have a sufficient sample of subjects studied. That said, the objective of research work in the field of health in space is in fact to study

[44] CENTRE FOR PUBLIC MANAGEMENT INC. (2011). *Environmental Scan and Priorities in Life and Health Sciences: Final Report*, Canadian Space Agency, August 14, 2011.

the effect of longer flights in order to support distant space exploration projects. It is essential to continue these studies, although they are tedious to carry out.

2) Astronauts have more time allocated to the utilization of the ISS

The ISS is a laboratory in orbit around Earth. The first module of the ISS was launched in 1998 and it has been manned permanently since November 2000.[45] Since the end of the assembly period of the ISS in 2010, astronauts have been able to concentrate more of their effort on scientific and medical experiments, while using the ISS more. In other words, at the beginning of the ISS, crew time was used more for assembly and operations and less for laboratory use as is the case today. Now that construction is complete, a number of interviewed people indicated that the CSA is concentrating more on the use of the ISS laboratory and on space exploration in general.

3) Reorientation of research priorities

The 2013–2018 period marks the emergence of new research priorities, which are increasingly targeting human exploration in deep space using the ISS as a platform to prepare. Interview respondents indicated that research priorities have progressed during the 2013–2018 period, mainly because of the end of the assembly of the ISS, the extension of Canadian involvement until 2020 and the consideration of future opportunities related to space exploration (e.g. Lunar Gateway and Mars). The document review corroborates these statements. According to an environmental analysis intended to identify future scientific objectives and the key issues for an announcement of opportunity (AO) made in 2011,[46] the Agency's priorities have started to change to better align with issues related to long-term human exploration (e.g. medical architecture for exploration, study of health and the impacts of long-term isolation on crew members, and use of the ISS as an analogue for exploration vehicles).[47] These research priorities were also confirmed in 2016 during a wide national consultation on the future of space exploration coordinated by the CSA.[48] Moreover, the CSA collaborates with ISS partners (United States, Europe, Russia and Japan) and other space agencies in the International Space Exploration Coordination Group (ISECG) to discuss and prepare future collaboration opportunities, destinations for human exploration and the technology required to get there.

Interview respondents mentioned more than once that the CSA has gradually stopped its involvement in the physical sciences beginning in 2010 to concentrate on issues related to the health and well-being of astronauts. This decision to prioritize research related to life sciences and health is influenced by the desire to carry out long-term missions in the future. By prioritizing research related to life science and health, the CSA wishes to identify and resolve problems related to space exploration beyond low orbit,

[45] CSA (2016). *Evaluation of the CSA's ISS Assembly and Maintenance Program, Op. cit.,* p. 2.

[46] Although the 2011 environmental analysis precedes the evaluation period, there is continuity with the program. As a result, the evaluation considered this study as well as some results of projects from after April 1, 2018.

[47] CENTRE FOR PUBLIC MANAGEMENT INC. (2011). *Op. cit.*

[48] CSA (2016). *Canadian Space Exploration. Science and Space Health for the Next Decade and Beyond*. p. 8

such as long-term space exploration and living in microgravity for long periods of time. This research concerns the life and health of astronauts, but also has the potential to resolve problems related to life and health on Earth.[49] Although the CSA has limited its intervention to health, it should be noted that there are still researchers in Canada who are carrying out research on the physical sciences related to space.

This remains in keeping with the recommendations of the advisory group that carried out the 2011 environmental analysis. This group had recommended seven priority areas of scientific research related to life sciences and health in space, for which Canada can or should develop international scientific leadership in the next 15 to 20 years. The areas are as follows: 1) muscle and bone atrophy; 2) neuroscience; 3) physiology and metabolism; 4) radiation; 5) space psychology; 6) maintenance of life in a closed system; and 7) remote diagnoses and treatments – remote care.[50] Although these research areas are not new and have already benefited from support in the past, the 2011 consultation workshops confirmed that they included key research areas for space exploration missions, including longer missions in microgravity conditions. These areas were selected for the importance of their ability to keep astronauts alive, healthy, and alert and encourage harmony between them so that they make an efficient team.

Moreover, the 2013–2018 period represents a transition step in the development of new technology (allowing for example remote diagnosis and treatment) that will allow us to support the health of astronauts during long missions beyond low orbit. Microflow was used for the first time on board the ISS by Chris Hadfield in 2013;[51] the bio-monitor was sent to the ISS in December 2018[52] so that David Saint-Jacques could use it first. It is also during this period that the bio-analyzer technology was developed and used for the first time in May 2019[53] by David Saint-Jacques. These contributions support the objective of the CSA to define and develop niches of expertise that will result in significant and unique contributions to major missions with space partners.

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[49] CENTRE FOR PUBLIC MANAGEMENT INC. (2011). *Op. cit.*

[50] *Ibid*.

[51] CSA (2019). *Microflow: Bringing Earth's lab technology to space*, [https://www.asc-csa.gc.ca/eng/sciences/microflow.asp].

[52] CSA (2019). B*io-monitor: Keeping an eye on astronauts' vital signs*, [https://www.asc-csa.gc.ca/eng/sciences/bio-monitor.asp].

[53] CSA (2019). *Bio-analyzer: Near-real-time biomedical results from space to Earth*, [https://www.asc-csa.gc.ca/eng/iss/bio-analyzer.asp].

4) Emergence of new recruitment criteria for astronauts

> ***The last astronaut recuitment campaign***
>
> *"Given that human space missions are expected to be increasingly long, it will be important for Canada and its partners to incorporate into the selection process more and more elements highlighting leadership, personality and teamwork." Interview with leaders of the last recruitment campaign*

Considering that long space missions have become the norm, the transition requires painstaking planning and a number of changes to the astronaut recruitment program. The criteria regarding the health of candidates – physical, psychological and social – were also tightened to support long missions. Interview respondents indicated that the CSA and other space agencies are progressively recruiting individuals with a speciality and who are able to work well in a team for long periods of time in a confined environment, which will be even more important in the future for missions in deep space. Also, interpersonal skills, such as ability to communicate and raise awareness, were evaluated in candidates during the last recruitment campaign.

5) Commercial space vehicles are increasingly used for equipment transportation

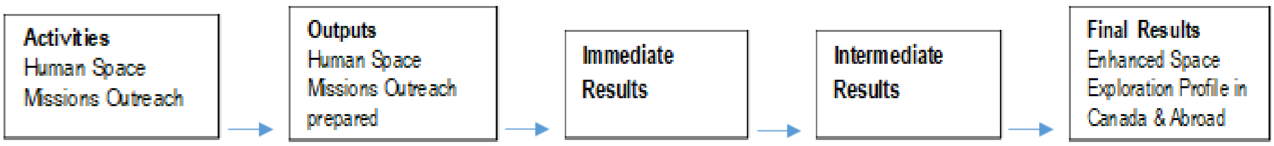
The decommissioning of the NASA space shuttle program in 2011 reduced the number of opportunities available for human space missions. The CSA currently collaborates with other space agencies to access space and the ISS, and the American private sector is developing the ability for space transportation. All of these changes affect Canada's access to and use of the ISS. Along those lines, interview respondents stated that the use of commercial space vehicles plays a significant role in the logistics related to cargo. It was said that the CSA plans to take advantage of the increased availability of transportation to the ISS once commercial vehicles are successfully tested. In order to maintain an active and highly competent corps of astronauts, the program identified a goal to establish more frequent space flight opportunities than the rate of the ISS crew allocation, by taking advantage of the imminent arrival of commercial crew transportation vessels in 2020 (SpaceX Crew Dragon and Boeing Starliner).

4.1.1.3 Other needs not covered by the program

Finding: The needs defined and that the program meets are exhaustive.

All interview respondents believed that the needs identified and those that the program meets are exhaustive. Although Canada decided to limit fields of research to health, in the past, the Agency has taken part in some studies related to physical science and botany research. Some internal respondents stated that the need to raise awareness among Canadians of space exploration was a key element of the program, especially in relation to astronauts, and that this need should be added to the program's five specific needs. Awareness is not represented in any of the links of the program logic model (see Figure 1, section 2.2 Program logic model, activities, clients and partners). According to the logic model, the program includes in its activities the planning of awareness products, which are outputs in the form of communication products and subsequent steps whose results are no longer directly related to awareness.

FIGURE 3. ELEMENTS OF THE LOGIC MODEL DEMONSTRATING THE RELATION OF AWARENESS ACTIVITIES TO THE FINAL RESULTS



The immediate and intermediate results do not reflect awareness and, as a result, there are no performance indicators. According to program leads, it is difficult to identify key indicators to measure results related to awareness, which explains why there are no elements represented at any levels of the logic chain. The logic chain was designed so as to have a jump from outputs to the final results, owing to this difficulty in determining results and appropriate indicators. At the time of the evaluation, work was under way to establish a departmental logic model integrating all programs to bring together the Agency's activities that contribute to raising the public's awareness. This could have an impact on CSA program performance information profiles (PIP). Moreover, for some program leads and other CSA stakeholders, the challenge is not whether awareness is represented in the logic of activities and intended results, but rather in determining how to measure the actual impact of this awareness among Canadians. The issues related to the measurement difficulties are discussed in section 4.2 Results.

4.1.1.4 The degree of consistency between activities, the distribution of funding and delivery model and needs

> **Finding**: The delivery is deemed adequate and the new space strategy allows us to position the program for the future. Some interview respondents indicated that limited human resources were a risk (loss of expertise in the event of an employee departure) but that the small size of the team nonetheless fostered agility.

In general, the program allows us to meet needs, taking into account the priorities of the federal government. However, a number of interview respondents, including some external respondents, were worried about the future of human space missions in the context of the potential end of funding for the ISS by the United States. These respondents stated that Canada was lacking strategic positioning for the future of space exploration. It is important to note that the interviews were conducted before the launch of the new space strategy. The Prime Minister's announcement on February 28, 2019, laid the foundation for Canada's commitment by ensuring the longevity of the program, in particular by confirming Canada's participation in the Lunar Gateway.

Program delivery model

The program delivery model is varied; research projects are carried out through the awarding of grants and contributions to universities or other public organizations, through the issuing of contracts to private companies that develop instruments, or by contracts and intergovernmental agreements for the purchase of services for astronauts (e.g. for training). Program specialists working at the Agency are coordinating various activities, such as research activity planning (e.g. announcements of opportunity), astronaut missions and the administrative management of the program. In terms of space medicine, the Agency employs a lead physician, flight physician and project leads who are responsible for nutrition and exercise for the astronauts. Given the modest size of the program, scientists, engineers and physicians have unique positions on the team, which increases the risk of not achieving the program results or meeting Canada's obligations as an ISS partner in the event of the loss of expertise owing to the departure of a resource. These resources are hard to replace given the specialized expertise required. The program has a human resources contingency plan to diversify the expertise of the resources in place and plan for the replacement of expected departures.

Also, project leads and specialists confirmed during interviews that in recent years they were faced with the issue of increased administrative requirements for project approval. In their opinion, the approval process requirements undermine the response to needs targeted by the program by creating long delays for project approval. In 2016, the evaluation of another CSA program had also described the approval process as being long: "the long decision-making process required for approval of missions limited CSA's ability to engage in proposed space missions and adapt to partner space agency deadlines."[54] A suggested improvement would be to better plan approvals and possibly increase efficiency by grouping required approvals for operational activities. This element is discussed further in section 4.3 on efficiency.

4.1.2 How are the program objectives in keeping with federal government priorities?

Finding: Program activities are in keeping with the Canadian strategy focused on innovation as a driver of economic development. Space exploration missions require the development of new state-of-the-art technology, including applications linking space and Earth. The recruitment of new astronauts and Canadian participation in the Lunar Gateway project demonstrate Canada's long-term commitment in this area.

In order to encourage Canada's economic growth, the federal government is specifically focused on innovation and resulting economic opportunities. In 2017, the unveiling of the Innovation and Skills Plan reflects this strategy, which includes fundamental and applied research, the development of new products and services and their marketing and positioning on Canadian and foreign markets.

Program activities are in line with this approach. Canada's participation in space exploration activities paves the way for an array of some of the most innovative research, development and marketing activities

[54] CSA (2016). *Evaluation of the Space Astronomy Missions and Planetary Missions Program*, p. 37.

with applications for both space and Earth. As was highlighted by stakeholders consulted as part of the evaluation, the program not only offers professional and economic opportunities to those who work to support space exploration missions, but it also helps position the whole of Canada as one of the nations that has worked on some of the most complex issues and challenges that exist.

The addition in 2017 of two new recruits to the CSA astronaut corps, and the unveiling of the new Space Strategy for Canada in March 2019, confirm a direct connection between the program and federal priorities. Through the program's activities, Canada will be able to maintain its participation in future ISS missions and the Lunar Gateway project.

4.1.3 What are the roles and responsibilities of the federal government in relation to the operation of the program?

Finding: The CSA plays a unique role that neither the public or private sector nor academia could take on.

The justification for public intervention in space exploration can be explained in part by the flaws of a market that introduces a number of obstacles to entry. These obstacles include the fact that the risk is too high to interest private investors, that the development of technology is long and that investments do not necessarily lead to commercial opportunities.

> In many cases, the investment in innovative space activity may not necessarily yield goods, services or industrial processes which can be reserved for the exclusive use of the innovator, even if it is a private entity. This is particularly true for space missions that may include many diverse actors, all benefiting in some ways.[55]

The Agency plays a unique role in human space missions in Canada and utilization of the ISS, and there is no other program in Canada pursuing the same results. The Agency is also a federal organization whose function is to "collaborate with space agencies, or organizations working in related fields, from other countries on the peaceful exploitation and use of space" (incorporating act).

The Agency benefits from a number of partnerships to implement the program, as outlined in section 4.3.1. These partnerships help to share resources and funding in order to achieve the targeted results. According to a program lead, the alignment of the priorities and the impact of the program could be strengthened by collaborating more with other departments.

[55] OECD (2016). *New Trends in Space Innovation*, October 27, 2016, p. 17, [https://read.oecd-ilibrary.org/science-and-technology/space-and-innovation/new-trends-in-space-innovation_9789264264014-3-en#page1].

4.2 Results

Finding: Overall, the outputs and results targeted by the program were achieved and surpassed. Canadian researchers and astronauts are recognized by the international community and garner the interest of the general public. Some projects led to uses on Earth and re-uses in space.

4.2.1 Data on performance

Availability and reliability of data on performance

Most of the data on performance were available for evaluation, and the information provided was reliable and valid. The overview of results allowed us to judge the program performance. Nonetheless, some performance indicators outlined in the performance measurement strategy were not collected: data from social media and the review of news clippings on Canada's involvement in space exploration. Also, data provided by communications did not cover all of the awareness activities carried out, in terms of activities, outputs and final results. As outlined in section 4.1.1.3, the results related to awareness are difficult to measure, and there was much fruitless effort to identify performance indicators and collection methods. The conclusion remains that the data available, such as the number of social media engagements, have significant limitations, and that awareness will be measured only among a portion of the public targeted by the program activities, such as youth by using data on youth participation in astronaut-related activities.

Some interview respondents stressed that the data used to measure the research results do not capture the qualitative aspect of the results. For example, a research project may lead to publications and allow for the employment of HQP and students, but may also allow Canada to position itself at the forefront of the field, generate international collaborations in the research community and create new knowledge other than that in the publications. Also, some indicated that the result indicators are still not aligned with what the Agency is trying to achieve; for example, a project could generate a lot of HQP, but with less scientific merit, or fail to create value in a niche with potential. To remediate these issues, case studies provide the opportunity to deepen the available knowledge on projects and consider a number of aspects, such as scientific merit, collaborations and outreach.

Among the other issues related to data on performance, some data collected at the corporate level are not distributed at the program level. A survey is sent annually to all businesses in the space sector that work with the Agency to collect information on the number of employees, business revenue and spending in research and development (R&D). These data are not usable on the program level, since they concern all of the business's activities. The same issue applies to data on social media interactions, which cannot be distributed by program.

Use of data on program performance

The evaluation considered the use of data on performance to measure to what extent these data were used. Examples of use at various levels demonstrated that the data collected by the program are used for different purposes, acting as a common basis to communicate the results:

- On the Integrated Investment Review Board (IIRB), the data are presented to show the trends of past results and support investment decision-making.
- During the drafting of documents for the Treasury Board to request new investments (e.g. TB Submission, Memorandum to Cabinet), data on program performance were overlapped with a host of other data (e.g. economic data from the Policy Directorate) to supply the results section and demonstrate past results.

Data are used at a strategic and tactical level, and the fact that some indicators have been measured for a number of years, constituting series of longitudinal data, help demonstrate the relevance of past investments through the use of data.

Evolution of the measurement of program performance

Improvements have been made to the program performance measurement strategy since April 1, 2013, in particular a rationalization of the number of performance indicators. Since the implementation of the Policy on Results (July 1, 2016), a number of changes have been made, and the measurement of program performance continues to be rethought, both within the space exploration program and throughout the Agency thanks to a collaboration between various stakeholders responsible for data on results (Programs and Integrated Planning, Policy, and Audit and Evaluation directorates).

4.2.2 How were the expected outputs achieved?

From 2013 to 2018, the targeted outputs outlined in the performance measurement strategy were achieved or surpassed. Various scientific research and design of scientific instruments and space sub-systems were begun, under way or achieved from 2013 to 2018, surpassing the targets in the performance measurement strategy as outlined in table 6.

TABLE 6. RESEARCH/SCIENTIFIC INSTRUMENTS AND SPACE SUB-SYSTEMS BEGUN, UNDER WAY OR COMPLETED BETWEEN APRIL 1, 2013 AND MARCH 31, 2018

INDICATORS	TARGET	RESULTS
# of enabled Investigations (Op 1.1)	8	10
# of supported investigations under development (Op 1.2)	5	5
# of supported Investigations in operation (# of operational investigations performing according to requirements) (Op 1.3)	9	9
# of instruments under development (science or medical) (Op 2.1)	10	10
# of instruments delivering data on a regular basis (Op 2.2)	2	2
# of spacecraft or subsystem in operation (Op 3.2)	1	1

The list of research and scientific instruments is outlined in detail in Appendix A.

ISS utilization time

Canada's allocation of utilization time for the ISS is 2.3%, which represents approximately 20 hours of crew time per six months. When partners do not use all of their allocation, the other partners can use the remaining time. As a result, the target of 100% utilization of time per year was surpassed, except in 2015–2016, when 87% of the allocated time was used. According to an interview respondent, the CSA has practically doubled this allocation by collaborating with ISS partners for some research (e.g. by using a single sample for various research).

TABLE 7. ISS UTILIZATION TIME

INDICATOR	TARGET	RESULTS	DETAILS
Science Experiment Crew time planned vs allocation (Op 1.4)	100%	On average 116%	The target of 100% was surpassed each year except for 2015–2016, when 87% of the allocated time was used.

Astronaut missions and operational space medicine

For the 2013–2018 period, the output targets were almost all achieved, and the Canadian astronaut corps included four astronauts: two in training and two qualified and medically certified, ready for a space mission. A high proportion of all categories of interview respondents emphasized the high quality of Canadian astronauts. Although Canada has a small group of astronauts (the current astronaut corps consists of four people), respondents, including ISS partners and external stakeholders, believe that they are highly qualified and able to perform well under pressure. Canadian astronauts participate in a number of awareness activities and inspire the general public. The quality of Canadian astronauts was recognized and appreciated by international partners, which translated into leadership roles for those astronauts. For example, Chris Hadfield was commander of the ISS for expeditions 34/35; Jeremy Hansen is currently responsible for a new class of astronauts at NASA; and, in the past, Dave Williams and Steve MacLean held important management positions at NASA. Also, Chris Hadfield and David St-Jacques were co-pilots of the Soyouz vessel. In terms of awareness, from 2014 to 2018, approximately 350 presentations were given by Canadian astronauts and a number of communication activities were carried out, such as media interviews and presentations at scientific events.

The last astronaut recruitment campaign

The annoucement of two new astronauts had various effects in the media:

- The unveiling of two new astronauts at CSA headquarters generated a total of 488 mentions in the media between July 17 and 30, 2017;

- The CSA coordinated over 45 interviews with various media, such as The Canadian Press, CBC, GLOBAL, La Presse, etc.

- On July 5, 2017, the publication of the presentation of two new astronauts on Reddit led to a significant number of visits; it was the third publication in terms of visits since Chris Hadfield's return to Earth.

Canada has astronauts who are doctors, which is considered particularly useful, and will become more so during missions in deep space. NASA conducts long-term monitoring of the health of retired astronauts on a voluntary basis, which explains why the result for this indicator is a little below the target.

Chris Hadfield and expeditions 34 and 35

The CSA's and its partners' activities and events during expeditions 34 and 35 include:

- 33 live events from space (e.g. a live broadcast with Chris Hadfield, media interviews, the unveiling of the new five dollar bill by the Bank of Canada);

- 88 scientific videos were produced before and during the mission, and they were viewed by more than 42 million people and used across Canada by teachers to inspire students in science;

- 7,000 students from approximately 300 schools communicated and interacted with Chris Hadfield in space;

- there was a national scientific competition;

- 12,267 new items (e.g. radio, web, TV, press reviews) were mentioned between December 11, 2012, and June 12, 2013 (a number six times higher than the annual average for the CSA);

- the new technology on board the ISS was widely disseminated on social media, including Twitter, and Mr. Hadfield took part in a Reddit AMA (Ask me Anything);

- a virtual game allowing players to operate the Canadarm on the CSA website was visited over 10,000 times; and

- a partnership with the National Film Board of Canada (NFB) helped launch an interactive web learning platform on space intended for teachers and students (265 teachers engaged along with 20,000 students).

Also, interviews with internal and external stakeholders indicate that Mr. Hadfield's third mission is still considered as one of the greatest successes of the Canadian space program.

TABLE 8. RESULTS OF OUTPUT INDICATORS RELATED TO ASTRONAUTS

INDICATORS	TARGET	RESULTS	DETAILS OF RESULTS 2013–2018
% of active astronauts assignable to space missions (technically qualified and medically certified) (Op 4.1)	100%	100%	In 2013-2014, the three Canadian astronaut corps consisted of Chris Hadfield, Jeremy Hansen and David Saint-Jacques were qualified and medically certified. Chris Hadfield retired in July 2013.
Number of Canadian astronauts assigned to space missions (Op 4.2)	2	2	Canadian astronaut Chris Hadfield (C2) from Dec. 2012 to May 2013. Canadian astronaut David Saint-Jacques (C3) from Dec. 2018 to June 2019.
# of eligible astronauts participating in their long-term health monitoring (Op 4.3)	80% (target established since 2016–2017 only)	72%	Participation of retired astronauts in long-term health monitoring: - In 2013–2014: 5 of 7 retired astronauts - In 2014-2015: 5 of 7 retired astronauts - The following years: 6 of 8 retired astronauts

4.2.3 How were the expected immediate results achieved?

The immediate results were not only achieved, but, in the case of HQP and students, the established targets were largely surpassed.

TABLE 9. ACHIEVEMENT OF IMMEDIATE TARGETED RESULTS

INDICATOR	TARGET	RESULTS	DETAILS OF RESULTS 2013–2018
Number of HQP working with a lead researcher who had received funding	20 per year	58 per year on average	
Number of students (Bachelor's, Master's and Doctorate) and post-doctorates working on projects funded by the CSA	5 per year	13 per year on average	
Number of astronauts assigned as crew members (primary or back-up)	1 every 5 years	1	Chris Hadfield was commander of the ISS during his mission.
Number of space missions during which a vessel or Canadian space sub-system or instrument or scientific research was in operation	2 per year, or 10 in total	10 missions	10 separate missions: BCAT-1, BPReg, MVIS, Radi-N2, Vascular, AHiS, Marrow, Vascular Echo, Tbone, Wayfinding*

*See Appendix A for details on the scientific instruments and research.

The lead researchers working on research projects receiving funding from the Agency employed HQP and students to help with their work. On average, 71 people were assigned annually to these projects, contributing to the development of a highly qualified labour force in Canada and ultimately to the positioning of Canada at the forefront of science and technology.

4.2.4 How were the expected intermediate results achieved?

The intermediate results were surpassed for the most part, except for scientific publications, which were just slightly below the target. These results include the participation of universities and the industry, scientific publications, Earth re-uses or applications of instruments or vessels and sub-systems developed for space.

Results related to the participation of universities and the industry

- Each year, on average, five Canadian university establishments (universities and teaching hospitals) participated in one or two research projects over the evaluation period, surpassing the established annual target of three per year. The number of universities participating in missions is growing, going from two to three in 2013–2014 and 2014–2015 to six from 2015–2016 to 2016–2017 and finally eight in 2017–2018.

- Each year, on average, six Canadian businesses participated in research projects during the evaluation period, surpassing the annual target of three per year. The number of participating businesses increased, going from two on average during the first two years to eight per year for the following three years.
- Also, 17 research teams from university establishments or businesses asked the CSA for letters of support to participate in foreign missions, for the PerWaves and NASA HERO projects.

Microflow and the bio-analyzer system (Bio-A)

The Microflow project generated three peer-reviewed scientific publications that were cited about 12 times. Regarding the visibility of the program, multiple articles on Microflow were published on the NASA and CSA websites as well as in local media.

In 2019, Alentic Microsciences Inc. received $2.9 million from the Atlantic Canada Opportunities Agency in order to apply the bioanalysis technology on Earth and to promote it across the world, allowing users to get blood test results in less than five minutes, regardless of location, using just a small drop of blood. Key informers emphasized the potential to develop a bio-analysis and bio-monitoring sector in Canada.

<u>Earth applications and re-uses from results of funded projects</u>

- Scientific research funded by the CSA, begun in 1998, led to the development of the OSTEO instrument. This instrument participated in two missions on the space shuttle in 1998 and 2003, as e-OSTEO with the CSA and ESA on board a Russian FOTON-BION in 2007. More recently, NASA adapted ISS technology to OSTEO-4, which was used in 2015. In 2018, the ESA flew OSTEO technology on the ISS under the name InVitroBone. After the STS-107 mission, the materiel was managed by Calm Technologies.
- Bio-monitor: Carré Technologies launched a commercial version called AstroSkin (Hexoskin is the Earth product), as a line of advanced intelligent clothing that can be used by organizations for research purposes in health, aerospace, security, defence and pharmaceutical research.

Studies related to the cardiovascular system

Based on data provided by lead resarchers on six projects, these projects led to 62 presentations to the media and were presented at 50 conferences. Moreover, from 2008 to 2019, the various projects accumulated 29 years of research in total, employing, on average, six university employees and two other researchers. In total, funded projects on the cardiovascular system generated 10 non-peer-reviewed publications and 44 peer-reviewed publications (between 2007 and 2018), which were cited, on average, 16 times each.

<u>Results related to scientific publications</u>

During the evaluation period, from 2013 to 2018, 47 peer-reviewed publications resulting from program funding were published, slightly less that the target of 50 publications for the period. This difference may be explained by the nature of the publications: the publication of space health science research results can be difficult because the studies involve fewer subjects and take longer than comparable studies conducted on Earth. Moreover, these publications involve a number of national and international collaborations, given the international nature of the ISS:

- In total, these 47 publications were cited 254 times in other scientific articles, on average 5.4 times each;
- 58% of the publications involve an international collaboration with 10 countries involving co-authors from 26 foreign teaching and research institutions and four foreign space agencies;
- The 10 countries that collaborated in writing the 47 publications are, in order of importance, Russia (11 publications), the United States (10 publications), France and the United Kingdom (four publications each) and Italy (three publications). Lastly, five countries collaborated in writing one publication each: Denmark, Japan, Germany, Belgium and Australia. The other space agencies collaborated in the writing of seven publications in total.

Overall, the intermediate results demonstrate a significant collaboration, both with foreign and Canadian universities and the Canadian industry. This collaboration has a positive effect on Canada's reputation abroad and helps advance knowledge concerning the ability of humans to live in space. Also, some projects leading to re-uses in space or uses on Earth contribute to the Canadian economy and to other social benefits, such as health care in remote areas.

4.2.5 How were the expected final results achieved?

As explained above, little data on the final results could be produced during the evaluation. Most of the data were collected from interview respondents. These partial results are nonetheless positive and demonstrate that the program achieved the desired results, especially with regard to the quality of the science and the promotion of Canada internationally.

Impact of scientific publications and quality of the science

The Agency uses a new indicator to report on departmental performance with regard to the dissemination of scientific publications: the average relative citation (ARC).[56] In the field of space medicine and life science, the ARC for all researchers in Canada was 1.02 (159 Canadian publications) for the 2011 to 2017 period. After isolating only Canadian researchers who had received funding from the CSA, the ARC is 1.46 (66 publications).[57]

Studies related to the cardiovascular system

The partial data from publications from 2009 to 2018, for 27 of 44 publications, demonstrates that 26% of publications are among the 10% most cited in the world, two articles being cited more than 60 times each.

The BP-Reg project specifically allowed Dr. Richard Hughson and his team to continue research in the cardiovascular field and to maintain a good reputation around the world in this field. Between 2016 and 2018, Dr. Hughson received four recognition awards, including the NASA Exceptional Scientific Achievement Medal.

With respect to the quality of the science, Canada is considered by main stakeholders, including a Canadian astronaut, a number of internal respondents, many universities and representatives of the industry, and some external organizations, to be a world leader in the field of human health research, particularly in fields such as muscular atrophy, osteoporosis, sensory perception, psychology and the cardiovascular system.

Canada-led research is well regarded by the international community, as was indicated by a number of internal respondents, some university respondents and some respondents from external agencies. Canadian researchers are regularly invited to make presentations during international meetings, to publish in well-regarded journals and to be part of panels and international organizations.

Also, ISS partners use an external peer review process to ensure that only the highest quality research experiments are taken into account. An internal respondent and a university representative indicated that Canadian researchers generally succeed in this process, the majority of research having been selected by an international peer review committee, and for each mission, an astronaut is chosen to participate in one or more Canadian research experiments, demonstrating the relevance and the rigorous design of Canadian experiments.

[56] The average relative citation is calculated by dividing the number of citations received for a given publication by the average number of citations received for publications published the same year in the same field. An average higher than 1 indicates that a publication is cited more than the world average in its field, [https://sites.google.com/a/etsmtl.net/bibliometrie/indicateurs-bibliometriques] (French only).

[57] The difference between the number of publications (n=47) seen in the intermediate results and the 66 publications of the ARC is explained by the fact that the period is different (2011–2017 vs 2013–2018). Also, the methodology of the ARC is different, since it includes all publications by funded researchers containing a key word in the search used for the ARC, while those in the intermediate results are validated by CSA program specialists responsible for funded projects.

Canadian researchers have won international awards (see inset box on the previous page for awards won by Dr. Hughson). For example:

- Dr. Peter Suedfeld received the Order of Canada in 2019.[58] Dr. Suedfeld is a professor emeritus in the department of psychology at the University of British Columbia and was co-researcher on Canada's first psychosocial experiment on board the ISS.[59]
- Dr. Giuseppe Iaria received the Established Researcher Award from the University of Calgary in 2017, thanks to his work on the effects of space flight on the brains of astronauts.[60]

A CSA respondent, a Canadian astronaut and an external organization respondent emphasized the importance of these successes given the limited funding provided by the CSA.

The last astronaut recruiment campaign

The final results in terms of visibility for the recruitment campaign are as follows:

- The media coverage generated an advertising value of $14M;

- The campaign generated more than 22 million media impressions and 925,000 engagements on social media;

- The astronauts' webpage was seen over two million times, the videos 396,000 times;

- Over 800 young Canadians were reached by the presentations given by the candidates.

Canada's profile abroad and its visibility in research and exploration activities

According to the respondents, Canada's role as partner of the ISS, the experiments it led and the astronauts it trained have garnered it international recognition. Some elements of the brand image (e.g. the Canadian flag on the Canadarm and the Canadian robot (MSS) on the five dollar bill) have given considerable visibility to Canada's achievements in space. The public's enthusiasm for the Agency's activities, on average 3.2 million interactions on social media per year from 2013 to 2018,[61] is high and demonstrates a true interest in space. Despite its modest financial contribution, Canada is treated as an equal partner on the ISS and is considered one of the main countries in the space field. Also, a respondent from an external organization and two internal respondents noted that Canadians have an enormous capacity for diplomacy and rallying others.

4.2.6 Did the implementation of the program have unexpected negative or positive impacts?

The evaluation did not identify any unexpected negative or positive impacts, and issues such as environmental impacts of the program (e.g. space debris) were not considered in the scope of the evaluation, and no such consideration came out of the interviews. Moreover, some indirect results were

[58] GOVERNOR GENERAL OF CANADA (2019). *Governor General Announces 83 New Appointments to the Order of Canada*, official site, [https://www.gg.ca/en/media/news/2019/governor-general-announces-83-new-appointments-order-canada]

[59] See the study entitled *At Home in Space: How astronauts adapt to life on the ISS*, [https://www.asc-csa.gc.ca/eng/sciences/at-home-in-space.asp]

[60] See the Wayfinding study: *The effects of space flight affects astronauts brains*, [https://asc-csa.gc.ca/eng/sciences/wayfinding.asp]

[61] The data are for the entire Agency.

mentioned during the interviews, such as international collaborations, from which Canadian researchers were able to benefit, what with the reputation Canada acquired after having successfully conducted research as part of the program. As outlined in the previous section (4.2.5), some of these researchers won significant national and international awards. Also, businesses that developed scientific instruments for the program had subsequent contracts in Canada and abroad, such as with other space agencies, thanks to the expertise and reputation they acquired. For example, a company in the field fo technology confirms that their experience in space inspired their product, a configurable modular switch, and the reputation acquired thanks to their participation in projects in space had helped them to attract investors. Their product is now sold on the site of a large electronics retailer.

Lastly, according to an internal interview respondent, the credibility and influence acquired over the years by the expertise of people working on the program mean that Canada is well regarded internationally, for example at the Organization of the United Nations (UN) and in interactions with countries that are developing their space programs. Human space missions are the most visible aspect of the program and have a positive impact on Canada's profile, and the space program as a whole with regard to other countries.

4.3 Efficiency and economy

Finding: The ISS partnership model provides Canada with scientific and technological opportunities that allow it to benefit from a unique research laboratory in space. The human resources working on the program are deemed competent and the time allocated for utilization of the ISS is maximized.

The evaluation focused on the qualitative aspects of efficiency given the absence of a comparable program and the varied nature of the program activities. The size of the CSA program is much smaller than those of other ISS partners, which makes quantitative analysis, for example through the use of financial ratios, not very meaningful. The evaluation considered the following: leveraging of partnerships and the elements that hindered or facilitated implementation of the program.

4.3.1 Leveraging of partnerships

International partnerships. The international cooperation required for projects as significant and expensive as the ISS allows Canada to participate in the resulting scientific and technological breakthroughs. Thanks to the ISS, Canada had the opportunity to take part in the largest scientific and technological project that humans have carried out to date. Also, Canada advanced the high technology industry (aerospace and robotics) by being involved in the ISS. In general, it was demonstrated that the technology developed for space also had applications on Earth, in areas as extensive as weather forecasts, micro-electronics, resource cartography, solar energy and laser surgery, to name just a few.

The ISS partner space agencies tend to prioritize specific research areas. Figure 4 below allows us to visualize both the absolute number and the relative share of investigations by research discipline led by

ISS partner agencies. Although the capacity of each agency to lead research is dictated and limited by its respective crew flight credits,[62] collaboration with other ISS partners allowed each agency to considerably multiply its impact (see table 10).[63]

FIGURE 4: RESEARCH AREAS FOR EACH ISS PARTNER AGENCY

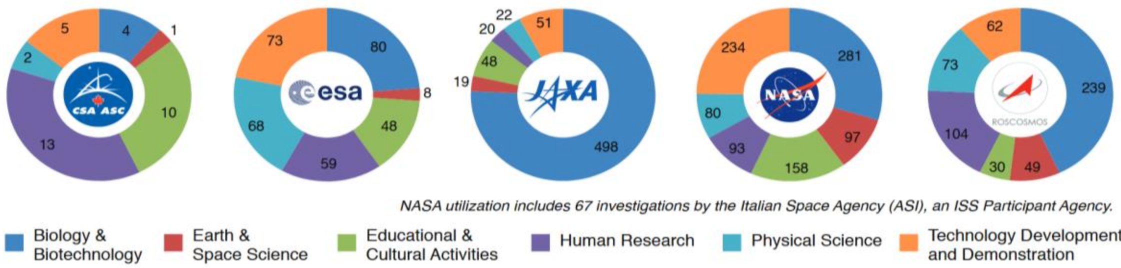


TABLE 10: THE BENEFITS OF THE ISS INCREASE THANKS TO INTERNATIONAL COLLABORATION[64]

Partner Agency	Agency Only	Collaboration (Hosting)	Investigations Implemented	Collaboration (Participating)	Total Agency Impact	% Increase Through Collaboration
CSA	25	10	35	29	62	83%
ESA	250	86	336	301	637	90%
JAXA	435	223	658	130	788	20%
NASA*	749	194	943	107	1050	11%
Roscosmos	324	233	557	251	808	45%
		Totals	2529	818	3345	32%

*NASA utilization includes 67 investigations by the Italian Space Agency (ASI), an ISS Participant Agency

In this regard, a number of internal respondents believe that it would be preferable to strengthen and increase existing international partnerships and create new partnerships in the area of health and life sciences research in space, as well as with other space agencies. According to a program manager, Canada's allocation of 2.3% is too small to be able to provide commercial opportunities, but we could consider a partnership program in health research with Canadian and American entities. This partnership could allow us to provide funding for Canadian researchers who would work with American researchers. This would be a beneficial arrangement for all parties and would open a private use component of the ISS. Also, a number of opportunities seem to be available to the CSA, whether with countries that already have an established space capacity or with other emerging countries. According to one of the internal respondents, international cooperation will be increasingly important with future missions that will also be more complex and expensive. Along those lines, another respondent indicated that it would be more sensible, from an economic perspective, if all space agencies played "on the same team."

[62] These credits are regulated by agreements related to the ISS and are mainly based on the financial or technological contribution of each agency.

[63] ISS Program Science Forum, 2018, p. 2.

[64] ISS Program Science Forum, 2018, p. 3.

National partnerships. Canada leveraged scientific research in a number of areas related to life sciences and health. Since discovering new ways of treating illnesses, creating technology and finding new advances in life sciences and health, Canada funds various programs, such as the Canada Research Chairs Program, the National Research Council of Canada and other grants, and makes contributions to industry leaders, university researchers and public research centres.[65] During the evaluation period, the program collaborated with a number of partners on a national scale, including government departments and agencies, the research industry and academia.

Case Study
Bio-analysis – Microflow project

A number of best practices were highlighted by members who participated in the project. These include the following:

- *The highly qualified CSA, NASA and INO teams worked effectively together; the collaboration was positive and results-based.*
- *INO's and the CSA's project managment skills and clear and effective communication were mentioned on numerous occasions by NASA. This contributed to the efficiency and speed of approval delays across various phases of the project. The project implemented a team structure with clear roles and channels of communication, ensuring a common understanding of the mandates.*

Departments and other government agencies

The CSA collaborates constantly with a number of agencies and federal government departments in order to develop and carry out projects that will benefit not only space exploration, but also the Government of Canada and Canadians in general. These federal departments and organizations have developed working relationships with the CSA in order to develop projects and programs in the areas of satellite communication, the environment, resource management, security and sovereignty, and science and technology. Overall, these collaborations produced beneficial programs while participating more in the development of space technology.[66] Those involved included the following federal departments and agencies: Canadian Institutes of Health Research (CIHR), the Department of National Defence, Health Canada and the National Research Council of Canada (NRCC).

The last astronaut recruitment campaign

A number of collaborations between the CSA and its partners were a measure of success for this campaign. First, the collaboration between Canadian military centres and the CSA for the evaluation of candidates was mentioned as having been very effective, causing some international partners to explore the possibility of proceeding in a similar manner to select their own astronauts.

Industrial research

Industrial research in Canada is competitive internationally in a number of niches in life sciences and health. Industry leaders generally invest millions of dollars in research and development. Interesting

[65] CENTRE FOR PUBLIC MANAGMENT INC. (2011). *Op. cit.*
[66] *Ibid*.

research and developments in the private sector include the study of bone cells in microgravity (CSA, 2011).[67]

An internal respondent stated that it was difficult to have new industrial players in the space field. The entry threshold in the space sector is generally fairly high. This can be explained in particular by the fact that the space sector is a very specific niche that massively limits the number of players, and that there are few chances for a business to participate in this field. Also, the criteria required to go to space are very demanding. As a result, the respondent considers that if there were a way to bring in more players, very qualified people in niche areas, this would be good for the economy, since we are referring to the knowledge economy.

Canada has robust industries in a large number of different fields applicable to space, and one respondent said that the CSA should plan to establish partnerships with smaller businesses or with organizations in sectors that are not traditionally related to the space sector.

Academia

Canada benefits from some of the more prestigious universities in the world. The research carried out at Canadian universities is ground-breaking and innovative and concerns research areas. Some research could be relevant for the space sector, such as portable microbiological diagnosis, mental health, renewable energy, the effect of radiation, genetics and the physiology of sleep.[68]

4.3.2 ISS model

Interview respondents said that the memoranda of understanding underlying the IGA, governance and the multiple committees and working groups between partners are efficient and well-established. Also, because sending samples to Earth for analysis is less efficient than developing analysis capabilities on board the ISS, the CSA is currently working on developing these abilities. Canada's contribution in this area is significant. The 2013–2018 period represents a pivotal step in the development of new Canadian technology that will allow us to support the health of astronauts during long missions beyond low orbit. Microflow[69] was used for the first time on board the ISS by Chris Hadfield in 2013 and the bio-monitor[70] was sent to the ISS in December 2018 so that David Saint-Jacques could use it first. It was also during this period that the bio-analyzer[71] technology was completed, which allowed it to be used for a first time in May 2019 by David Saint-Jacques. Lastly, in 2014, engineers and scientists from the National Research

[67] CENTRE FOR PUBLIC MANAGEMENT INC. (2011). *Op. cit*.
[68] *Ibid*.
[69] CSA (2019). *Microflow: Bringing Earth's lab technology to space*, *Op. cit*.
[70] CSA (2019). *Bio-monitor: Keeping an eye on astronauts' vital signs*, *Op. cit*.
[71] CSA (2019). *Bio-analyzer: Near-real-time biomedical results from space to Earth*, *Op. cit*.

Council of Canada (NRCC) began to design the MicroPREP[72] technology, a "chip-based laboratory" that is already considered a significant asset for future exploration missions in deep space.

However, the document review and interviews carried out as part of this evaluation raised two factors that could potentially present an efficiency issue for the program in the long term.

1- Some nations do not participate in research projects. Although it is undeniable that the existing international partners help Canada increase the benefits of its research and investments (see section 4.3.1), almost all respondents would like the CSA to collaborate more with other space agencies. One of the internal respondents indicated that it would be more reasonable, from an economic standpoint, for all agencies to play on "the same team" and for the CSA to develop partnerships with emerging countries. According to interview respondents, the increase in partnerships would accentuate the leverage effect of partnerships and would therefore be beneficial for the efficiency of the program in the long term. However, Canada's collaboration with certain countries represents an issue with regard to the transfer of technology and intellectual property.

2- Contribution and flight opportunities. Historically, Canada has negotiated its flight opportunities by percentage of flight time, which is 2.3% owing to Canada's initial contribution to the ISS, rather than in terms of quantity of flights as other countries do (e.g. Italy). For example, Chris Hadfield's last mission in 2008 was negotiated for a duration of 142 days in orbit. Interview respondents indicated that this way of working could potentially become an issue for the CSA over time. Long missions are increasingly becoming the norm, and this means that other countries now benefit from more long flights to the station than Canada.

4.3.3 CSA model

CSA governance

Size of the CSA. Canada is the smallest ISS partner; however, this does not prevent it from making very significant accomplishments. Also, Canada has a good reputation internationally in the space field, whether for its contribution in science and robotics, its efficiency or even the quality of its collaboration.

Advantages: The small size of the CSA is not an obstacle to its efficiency. On the contrary, it would seem that its size allows it to be agile and efficient in some situations. The Agency adapts well and quickly to situations and unexpected occurrences, since it is often easy to make strategic or organizational changes when required. Moreover, the CSA's efficiency was mentioned a number of times during interviews, given its small budget. For example, the CSA is known for the quality of its scientific experiments, which are

72 CSA (2019). *MicroPREP: New advances in sample purification*, [https://asc-csa.gc.ca/eng/sciences/microprep.asp].

carried out with very few resources compared with those of other ISS partners. It can therefore be confirmed that the small size of the CSA represents an asset with regard to the efficiency and effectiveness of its actions.

Disadvantages: Although Canada has a good reputation internationally for its skills in the space sector, a number of stakeholders said that the country risks being progressively left behind by its international partners. According to the stakeholders, the CSA's small contribution is inseparable from its small influence in significant strategies that affect the ISS. The budget allocated to the CSA often represents a fraction of the budget of other ISS partners, which gives less weight to the CSA and less ability to play a more leading role in space medicine, for example. Lastly, according to some respondents, the small size of the CSA is an issue for employee development (operational skills) and career opportunities. Often the same employees carry out the same roles on the same teams for a number of years. Given the limitations on the program's salary budget, this could also have consequences for the Agency, since it then becomes more difficult to renew and refresh the program staff over the long term.

Administrative load related to the approval process. Some interview respondents indicated that the increase in administrative requirements in recent years had placed additional pressure on human resources, through the increase in approval delays and through the implementation of a new approval process. Since October 2017, each investment proposal worth more than $75,000 is presented to the Integrated Investment Review Board (IIRB). The presentations are formalized and program specialists must gather all the necessary information repeatedly, which they say requires a lot of time. That said, interview respondents agree with the solid foundation of the process, which is more demanding than before in terms of preparation and remains nonetheless more rigorous.

Agency's long-term priorities and objectives. It was stated more than once during interviews that it would be preferable to use long-term program activity planning that is mandated by the federal government in order to see the overview and general scope of these activities. The announcement of the Space Strategy for Canada in spring 2019 and the current work on long-term planning should have a positive impact on this element.

Program governance and delivery

Highly qualified and recognized personnel. The vast majority of respondents recognize that the human resources assigned to the program are very competent, collaborative and efficient. In particular, astronauts are generally very satisfied with the work done on Earth to assist them during space missions. They feel that they are heard and believe that the CSA supports them efficiently in the achievement of their objectives. Moreover, it was suggested during interviews that the CSA could create more opportunities to encourage the development and mobility of its employees. For example, the CSA would benefit from rotating program personnel on international assignments in order to give them a more overall view of the situation in the world and to help Canada maintain good relationships with its main international partners.

The last astronaut recruitment campaign

The selection board was described as having been highly motivated, professional and having the required competencies to carry out its mandate. Project management principles were applied rigorously, maximizing the ability to hold parallel activities and team engagement. Clear and efficient communication through the adoption of visual tools recalling the various deadlines and deliverables used by all partners involved helped implement a common and strategic vision for all members. The recruitment team received the Public Service Award of Excellence from the Governor General. The distinction says that all members significantly contributed to professionalism, team building, creativity and the team's commitment to excellence.

Chris Hadfield and expeditions 34 and 35

Canada's approach to training astronauts is very well perceived by the stakeholders interviewed, since this process is multidimensional, covering a wide array of intellectual and behavioural competencies (hard and soft skills).

This finding is reflected in the ability of Canadian astronauts to take on increasing responsibilities in relation to ISS activities.

Competent astronauts: All the stakeholders interviewed on the topic believe that the CSA astronauts are competent and very well trained. This is highlighted by the fact that Canadian astronauts receive increasingly prestigious positions on their space missions. For example, Chris Hadfield was the first Canadian to become commander of the ISS during expedition 35, and David Saint-Jacques held the position of co-pilot of the Soyouz a few years later.

Utilization time of the ISS and partners' unused time recovered by the CSA. The program maximizes utilization time of the ISS. On average, 116% of the time allocated to Canada for research was used during the evaluation period (see 4.2.2 Outputs). Moreover, interview respondents said that the CSA has the ideal conditions to conduct a lot of intensive scientific experiments before 2024, the year during which the funding for the ISS could cease if Canada decides not to continue its participation with the ISS. The next space station will take a long time to reach the current level of the ISS. Therefore, there seems to be a certain urgency to act. Also, space missions that are part of the Lunar Gateway will have more restricted research opportunities. As a result, the period from today to 2024 is pivotal and one during which we must make maximum use of astronauts' time.

That said, interview respondents stated that when utilization time is freed up in real time on the station (because of an unexpected event, a breakage or other reason), the partners are invited to propose reserve activities to fill this time. In some cases, the CSA successfully used these opportunities to carry out additional scientific experiments. The CSA therefore successfully uses opportunities that present themselves. Also, it was said that the Agency has ways to maximize collaboration time, either by combining activities with its partners or making agreements and partnerships. There can also be exchanges by contributing to various aspects of the ISS program and thus getting additional time for our astronauts. The Agency encourages activities that are likely to yield notable outcomes, since the main selection criterion is quality.

Strategic and advisory aspect. The information collected during the interviews suggests that it would be beneficial to choose long-term objectives (i.e., over a period of at least five years), to determine how the program can do this and to document the CSA's long-term strategic planning. It is important to note that work is already under way to develop the latter.

4.3.4 Are there more cost-effective ways to implement the current program?

Participating in commercial flights is one of the alternatives suggested by interview respondents. It was said that commercial flights would increase utilization time but that they would result in high costs. However, other respondents said that this option would be difficult to carry out, since our utilization e time is calculated according to our contribution to the ISS. Canada has a utilization time of 2.3%, independent of the possibility of sending an astronaut to the station on a commercial flight. These considerations demonstrate that we still need to conduct analyses to determine the cost-effectiveness of the use of commercial flights, with the aim of increasing the program's utilization of the ISS.

Moreover, according to the plans outlined in the ISS program, new astronaut transportation vehicles that will be developed by private businesses SpaceX and Boeing will allow us to have a fourth astronaut assigned to the station. The addition of a fourth astronaut will add 35 utilization hours to the 35 existing hours, which will be shared among the partners, doubling the time to carry out experiments.

4.4 What are the impacts of the program on GBA+ groups?

Finding: The CSA directly integrated considerations related to GBA+ into its recruitment campaign of the two new astronauts, as well as in some studies.

During fiscal year 2016–2017, the federal government published its Policy on Results and its Directive on Results, which clarify the expectations related to Gender-Based Analysis Plus (GBA+), which federal departments and agencies must implement. This political framework requires that program managers integrate considerations related to GBA+ into the management of their programs and activities, and that the evaluation of these programs and activities also integrate these considerations. In March 2017, the CSA adopted its own GBA+ directive, which allows us to operationalize this requirement in the specific framework of the Agency.

First, it is important to note in this context that these various GBA+ initiatives were implemented at the end of the period covered by this evaluation. Nonetheless, the findings that emerged from the evaluation indicated that the CSA managed its activities related to Human space missions and ISS Utilization so as to not have a negative effect on diverse groups of women and men.

CSA efforts were particularly of note during the last astronaut recruitment campaign, when Jennifer Sidey-Gibbons and Joshua Kutryk joined the group of Canadian astronauts in 2017. Specifically, the following activities were undertaken:

- All members of the recruitment committee received training on GBA+ before carrying out their work;
- The CSA ensured that all regions of the country and women and visible minorities were directly targeted by the recruitment campaign. There were consultations on this topic with Status of Women Canada (now the department of Women and Gender Equality Canada);
- Efforts were also made to engage northern communities and Indigenous communities. There were consultations with Crown-Indigenous Relations and Northern Affairs Canada; and
- The recruitment campaign included promotion activities in professional fields that are not traditionally associated with the space exploration program, such as the field of nutrition.

The evaluation indicates that the considerations related to GBA+ were also integrated into other activities related to space exploration, including studies on bed rest and isolation supported by the CSA's Health and Life Sciences, in collaboration with the ESA.

The integration of GBA+ into activities undertaken for Human space missions and ISS Utilization is an ongoing process that will require the Agency's sustained effort. Interviews conducted as part of the evaluation confirm that, although the GBA+ objectives are generally well understood, stakeholders would like to improve their understanding of the scope of this requirement and the best way to integrate these considerations into their work. Ongoing support therefore seems necessary and desirable.

5 Action plan

	Responsibilities Organization/ Function	Response from the directorate	Detail from the action plan	Schedule
Recommendation				
N/A	N/A	N/A	N/A	N/A

APPENDIX A: List of scientific research and instruments that received program funding between March 1, 2013, and March 31, 2018

Name of research/ instrument	Description	Years	Primary researcher	University or company	Partner(s)	Field(s)
Scientific Research						
BCAT	This series of experiments studied the effects of microgravity on colloids—microscopic particles suspended in another material such as a liquid. Colloids are found in commercial products from paint to electronic polishing compounds to mayonnaise. The outcomes of the study might include finding innovative ways to produce plastics or extend the shelf life of consumer products.	2009-2014	Barbara Frisken	Simon Fraser University	ZIN Technologies Incorporated (USA)	Physical sciences
Radi-N	The RaDI-N experiments use bubble detectors to measure neutron radiation on board the ISS to help researchers understand astronauts' risk of exposure. Canadian-designed bubble detectors are the most precise neutron radiation dosimeters in the world. These studies identify what proportion of space radiation consists of neutrons and advance our understanding of the role of neutron radiation in genetic damage or mutation, which can lead to cataracts and cancer.	2009-2010	Harry Ing	Bubble Technology Industries Inc.	Institute of Biomedical Problems Russian Academy of Sciences	Health risks linked to human spaceflight
Radi-N2		2012-2014	Martin Smith	Bubble Technology Industries Inc.	Institute of Biomedical Problems Russian Academy of Sciences, UOIT	Health risks linked to human spaceflight
Vascular	The Vascular study aims to determine the impact of long-duration space flight on the blood vessels, which tend to stiffen in space much like a process seen in aging on Earth. By comparing blood samples collected before, during and after space flights, researchers hope to develop countermeasures to prevent cardiovascular problems in astronauts and apply the knowledge to prevent cardiovascular problems associated with aging on Earth.	2009-2014	Richard Lee Hughson	University of Waterloo		Human body in Space
BP Reg	The adaptation of the circulatory system to space affects blood pressure in such a way that astronauts have a significant risk of fainting and dizziness when they return to Earth. The BP Reg experiment aims to identify which astronauts would be susceptible to the largest drop in blood pressure and would need countermeasures to mitigate the effects. BP Reg has important implications for testing of individuals on Earth, especially the elderly, who are at risk of fainting.	2012-2015	Richard Lee Hughson	University of Waterloo		Human body in Space
Microflow	Microflow was the first miniaturized flow cytometer tested on the ISS. With this testing, the CSA demonstrated flow cytometer technology, which is used to measure different biological components, such as different types of blood cells or hormones. The ultimate goal of the project is to develop a smaller, safe instrument that can be used for real-time medical care during space flight, as well as in remote communities here on Earth.	2013	Luchino Cohen	CSA	Ozzy Mermut (INO)	Testing Technology
At Home in Space	The At Home in Space study (Chez soi dans l'espace) aims to understand how a shared culture is developed on the ISS, where crew members from various backgrounds live together for months, and how the astronauts make the environment feel like home. The outcomes could help make their time in space more comfortable and reduce the stress that the astronauts and their families experience with long separations. Many people on Earth could benefit from the results of the study, including elderly people living alone or in retirement homes, military members, and people who live or work in remote, confined or isolated areas.	2015-2018	Phyllis Jonson	UBC		Humanities and social sciences

Name of research/ instrument	Description	Years	Primary researcher	University or company	Partner(s)	Field(s)
Scientific Research (cont'd)						
Marrow	In space, microgravity affects the bone marrow and the blood cells it produces. On long missions, astronauts face the risk of anemia, infections and increased sensitivity to radiation. To mitigate those risks, the MARROW study measures changes to astronauts in microgravity using magnetic resonance imaging and blood and breath samples. On Earth, the outcomes could help combat the effects of physical inactivity and improve the rehabilitation of bedridden patients, those with reduced mobility, and seniors.	2015-2020	Guy Rudel and Odette Laneuville	University of Ottawa		Human body in Space
T-Bone	The Tbone study examines the effect of microgravity on the quality of bones, which age faster in space. The bone mass that astronauts lose during a space mission is almost fully recovered when they return to Earth. However, we know little about the effects of space flights on bone strength. The new 3D imaging technology used will not only enable researchers to measure bone density, but also to examine their structure and strength. In addition to helping astronauts, the outcomes of TBone could be used to identify those who are predisposed to bone loss on Earth, and lead to individualized treatment strategies.	2015-2020	Steven Boyd	University of Calgary		Human body in Space
Vascular Echo	The Vascular Echo study examines the mechanisms that underpin accelerated arterial stiffening in astronauts in order to develop countermeasures to slow vascular aging in astronauts, and in people on Earth. The study examines the changes that occur in the heart and blood vessels during a space flight and tracks the participants' recovery after their return to Earth.	2015-2020	Richard Lee Hughson	University of Waterloo	Philippe Arbeille, Université de Tours Kevin Shoemaker, Western University	Human body in Space
Vection	Using a virtual reality system, Vection examines how microgravity affects astronauts' perception of their motion in space. "Vection" is a feeling that you are moving even though you are immobile, brought on by seeing something else moving. It can lead to operational risks in space, such as astronauts misinterpreting the direction and speed of other objects. Astronauts face this risk when carrying out tasks involving robotics, as in captures of unpiloted spacecraft using Canadarm2. This study will assess how crew members judge distances and process their own movement while they are immersed in a virtual reality environment. The knowledge gained through this study will help design safer methods of moving around the International Space Station. Vection aims to: (1) learn more about how visual information creates the impression of self-motion in weightlessness (2) explore whether astronauts' perception of their surroundings is affected by weightlessness (3) create a model of how the space environment influences how we process visual information The study's findings may also lead to positive interventions/applications on Earth, including: (1) understanding disorders affecting movement and posture, like Parkinson's disease (2) using virtual reality to assist people recovering from a stroke or damage to their balance organs (3) understanding the effects of aging on visual perception (4) improving the use of technologies like remotely-operated robots used in surgery	2016-en cours	Laurence Harris	York University		Human body in Space
Wayfinding	In order to create an accurate mental map of its position and surroundings, the brain processes visual, self-sensing, and vestibular (inner ear) information. Living in a weightless environment like the International Space Station (ISS) challenges an astronaut's internal orientation system. In microgravity, the brain cannot rely on the same signals to map out the location of important features like space modules or emergency escape hatches. Astronauts' orientation and navigation challenges can also affect their ability to perform complex operations in space, like robotics tasks. Wayfinding's results will teach us more about structural and functional changes that the brain undergoes when working in these tricky conditions. This will help astronauts better prepare for and recover from space missions.	2016-2022	Giuseppe Iaria	University of Calgary	Jacob Bloomberg (NASA)	Human body in Space

Name of research/ instrument	Description	Years	Primary researcher	University or company	Partner(s)	Field(s)
Scientific Research (cont'd)						
Vascular Aging	The Vascular Aging study examines the cardiovascular system, and one of its aims is to determine exactly why astronauts' arteries lose their elasticity. Vascular Aging is also looking at other issues known to pose risks to astronauts' health, like radiation and insulin resistance, a precursor of Type 2 diabetes. Studying the responses of the cardiovascular system in space better equips us to understand how our arteries age here on Earth. The study will also track astronauts' recovery process after they return from the station.	2017-2023	Richard Lee Hughson	University of Waterloo	Kevin Shoemaker, Western University Danielle Greaves, University of Waterloo, Ontario Philippe Arbeille, Université François-Rabelais Martina Heer, University of Bonn, Germany Carole Leguy, German Aerospace Center Laurence Vico, Université de Lyon	Human body in Space
ImmunoProfile	Immuno Profile will be the first study to monitor astronauts' immune systems for the entire duration of their missions aboard the International Space Station (ISS). It will explore changes in immune hormones and white blood cells, the first line of defence against pathogens like bacteria and viruses.	2017-end of ISS	Chen Wang	Sinai Health System	NASA	Health risks linked to human spaceflight
HANA Study - Blaber	Astronauts often experience dizziness and lightheadness upon standing after landing, which could lead to fainting and falls. This research investigated the interactions between the control of posture muscle contractions and the regulation of the heart and blood vessels in response to blood pressure changes upon standing. The head-down bed-rest (HDBR) was used to simulate human physiological changes during spaceflight. The effects of HDBR on cardio-postural interaction was assessed before and after HDBR. During HDBR, the cardiovascular regulation was also monitored. The research hypothesized that adaptive changes in cardiovascular and postural controls during HDBR contribute to post-HDBR deconditioning.	2016-2019	Andrew Blaber	Simon Fraser University		Human body in Space
HANA Study - Trudel (bedrest)	Conditions that remove mechanical loads such as bedrest and spaceflight, adversely affect the marrow cell populations and their functions. Bone marrow houses mesenchymal and hematopoietic cells, with absolute importance for survival. The gross composition of the marrow irreversibly changes from red (hematopoietic) to yellow (fatty) upon exposure to microgravity, disrupting the production of blood cells. The study used non-invasive methods of medical imaging to measure fat content in the marrow and biochemistry assays to assess circulating blood cells functions of participants in this bedrest study. Findings could be applied to evaluate candidate countermeasures to mitigate fat accumulation in marrow.	2016-2019	Guy Trudel	University of Ottawa		Human body in Space
HANA Study - Jasmin	Muscle atrophy, or muscle wasting, is associated with reduced quality of life and decreased life expectancy. Understanding the genetic, cellular and molecular underpinnings of muscle atrophy, as well as its relation to muscle disuse, is key to gaining insight into the mechanisms that lead to muscle impairment. This knowledge is also necessary for the development of efficient countermeasures and rehabilitation approaches. This research was intended to uncover new targets for the development of therapeutic interventions aimed at countering and/or preventing detrimental changes in skeletal muscle mass, structure and function due to disease and/or disuse conditions; including microgravity.	2016-2018	Bernard Jasmin	University of Ottawa		Human body in Space

Name of research/ instrument	Description	Years	Primary researcher	University or company	Partner(s)	Field(s)
Scientific Research (cont'd)						
HANA Study - Suedfield	In two Antarctic stations, crewmembers recorded conversations, oral diaries, and text read aloud. Content and technical aspects (rhythm, speed, pitch, loudness, etc.) were analyzed for stress, positive and negative emotions, problems and solutions, interpersonal relations, etc. The study developed a unique combinatorial measures of how people in an isolated, confined environments react during a full year together. The results will identify early signs of distress or poor adaptation, so that interventions can begin quickly, to enhance wellbeing in polar stations, spacecraft, to many kinds of isolated situations, including the living conditions of many elderly people.	2016-2019	Peter Suedfeld	UBC		Human body in Space
Matroyshka III - Rando	CSA has an Implementation Agreement with DLR to participate in the multi-year Matroyshka III study. Matryoshka III will use a Phantom (Rando) Platform imitating human torso to measure radiation doses at internal organ level. This information is important for more accurate risk assessment and development of radiation health countermeasures. Canadian participation includes the integration of Canadian technologies, starting with the Bubble Detectors. Data from other multiple instruments will be made available to the Canadian space radiation health community.	2018-end of ISS	Martin Smith	BTI	DLR	Health risks linked to human spaceflight
Jasmin – uOttawa	Bernard Jasmin at the University of Ottawa collaborated with Angèle Chopard (France) in a series of ESA-sponsored bed-rest studies. This specific unsolicited grant was awarded to allow Dr. Jasmin to complete gene expression studies from muscle tissue collected during the 'protein and bicarbonate supplementation bed-rest study' which took place at DLR in 2011-2012.	2012-13	Bernard Jasmin	U. Ottawa	Dr. Chopard was a visiting scientist at U. Ottawa at this time.	Health risks linked to human spaceflight
Hughson - Waterloo CCISS	Six objectives were addressed; data acquired during the Cardiovascular Control on ISS (CCISS) study were analysed to meet these objectives, which allowed increased impact from the CCISS study.	2010-2011	Richard Hughson	U. Waterloo		Health risks linked to human spaceflight
Instruments						
Bio-Monitor Astroskin System testing	The original Astroskin prototype bio-monitoring garment was developed in 2014 under contract to Carré Technologies. Following development, the device under went testing through a number of activities: 1) at UQAM laboratories and as part of Antarctik, an Antarctik expedition; 2) as part of a NASA Human Exploration Research Analog (HERA) analog mission, as well as; 3) the device was integrated into NASA AMES's Medical Data Architecture (MDA), a prototype medical data management infrastructure for future missions beyond LEO. Laboratory testing as well as usability testing during the Antarctik mission occurred under contract with the University de Quebec a Montreal (UQAM). Technical support for all testing was accomplished through a service contract with Carre Technologies. As a result of this testing Carre Technologies was able to make improvements in their experimental and commercial devices.	2014-2019	UQAM: Dr. Alain Comtois Carré: Jean-Francois Roy	Université du Québec à Montréal Carré Technologies	NASA Ames	Health risks linked to human spaceflight Autonomous Medical Care
PRET Validation	Performance Readiness Evaluation Tool (PRET) prototype was developed by the CSA with the aim of providing neurocognitive (NC) assessment tool for long-duration space missions, capable of providing an objective evaluation of performance readiness prior to critical tasks. It was designed to provide NC assessment capability using a 3D virtual reality simulator with transparently embedded validated NC tests. Tests were designed to assess: Working memory, Concentration, Visual scanning & perception, divided attention, Planning & decision making, Situational awareness, Sustained attention, Fatigue. The Prototype was subjected to usability testing and validation tests in M500, IBMP, Russia, 2010-2012 and in 2012-2016 at the Carleton University Cognitive Engineering Lab. Results have been posted on Open Government Canada site.	2010-2016	Matthew Brown	University of Carleton		Health risks linked to human spaceflight

Name of research/ instrument	Description	Years	Primary researcher	University or company	Partner(s)	Field(s)
Instruments (cont'd)						
LSRS early study: Carré	Five concept studies were carried out at the beginning of the LSRS project. This was the first step in identifying Canadian life sciences research systems that are mature enough to be adapted for use in space, on the ISS, to support the identification, characterization and mitigation of risks associated with human space flights. Two technologies were carried into the next step, and became the Bio-Analyzer and the Bio-Monitor.	2013-2014	N/A	Carré Technologies	N/A	Health risks linked to human spaceflight
LSRS early study: Comdev			N/A	ComDev	N/A	Health risks linked to human spaceflight
LSRS early study: Calm			N/A	Calm Technologies	N/A	Health risks linked to human spaceflight
LSRS early study: Bubble Technology			N/A	Bubble Technologies	N/A	Health risks linked to human spaceflight
LSRS early study: INO			N/A	INO		Health risks linked to human spaceflight
LSRS - Bio M	A new wearable technology has been designed to fit into an astronaut's daily routine aboard the International Space Station (ISS) while monitoring and recording vital signs. This system, which includes a smart shirt and dedicated tablet application, will help keep an eye on astronauts' health and enable new science by continuously measuring physiological data.	2017-end of ISS	N/A	Carré Technologies/Calm Technologies	N/A	Health risks linked to human spaceflight
LSRS - Bio A	The Bio-Analyzer is a new tool the size of a videogame console that astronauts aboard the International Space Station (ISS) will use to easily test different body fluids such as blood, saliva, and urine. Using just a few drops of liquid—no big needles required!—it quickly returns key biomedical analyses.	2017-end of ISS	N/A	Honeywell	N/A	Health risks linked to human spaceflight
Compact Canadian Neutron Spectrometer	Bubble detectors are passive neutron dosimeters manufactured by Bubble Technology Industries, Chalk River, ON. They contain superheated liquid droplets dispersed in an elastic polymer gel. Particles with high linear-energy transfer (LET) interact with the droplets to form bubbles. Bubble detectors have been used to monitor neutrons in space since 1989 on recoverable Russian Biocosmos (Bion) satellites, the Mir space station, the space shuttle, and the ISS.	1989 to date	Harry Ing/Lianne Ing	BTI	Institute of Biomedical Problems Russian Academy of Sciences, UOIT, AECL/CNL, NASA, DLR	Health risks linked to human spaceflight
NRC – MicroPREP	A Memorandum of Understanding was established with NRC Boucherville wherein NRC and CSA have collaborated on the development of automated biological sample analysis capability.	2015--2019	Teodor Veres	NRC Boucherville		Bio-medical analysis
Advanced Crew Medical System (ACMS)	SonixTelemed is a software solution to enable remote control of an Ultrasonix scanner over an IP network and real-time streaming of ultrasound images from the scanner to connected clients. It includes a Graphical User Interface (GUI) providing visual controls (buttons, knobs, etc.) for the user to interact with the ultrasound scanner and change its configuration remotely, as if the user were using the buttons provided on the scanner. The UI shows a live video of the ultrasound images so that the user can feel as if they were sitting in front of the scanner display itself. The software was developed, under contract with Ultrasonic Medical Corporation, the only Canadian manufacturer of medical ultrasound machines. The Telemed software was tested as part of a different contract (Dr. Andrew Kirkpatrick Inc.) in a realistic emergency scenario in association with Calgary Foothills Hospital.	Development 2011-13 Testing 2014-2015	Ultrasonic Medical Corporation & Dr. Andrew Kirkpatrick	Enterprise	N/A	Medical Imaging / Medical Autonomy