A Vision for Canadian Space Exploration

We propose a sustained and balanced program in space exploration to fuel innovation in the space sector, support Canada's world-leading space researchers, inspire the next generation of scientists and innovators, and create thousands of highly skilled, well-paying jobs for Canadians. During the next decade we recommend a total investment of approximately $1B, increasing to $1.3B in each decade that follows, including a regular flagship mission that Canada would lead and a constellation of smaller missions, either led by Canada or in collaboration with international partners.

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Executive Summary

Developing the technology required for space exploration missions (space astronomy, planetary science, and space health and life sciences) represents one of the most challenging engineering opportunities of our time and an economic driver for advanced technologies. This leads to prosperity through innovation and the associated use of technologies developed for space exploration (e.g., surgical robotics, telemedicine, remote mining, imaging), strengthening Canada's international reputation as an advanced nation in science and technology research, and raising literacy by inspiring Canadian students to pursue higher education in the STEM (Science, Technology, Engineering and Mathematics) areas critical to developing tomorrow's technically capable Canadian workforce. Indeed, space exploration, perhaps uniquely, ignites interest and motivates young minds to pursue careers in the sciences, engineering and high-tech sectors. Consequently, Canadian universities have made and continue to make substantial investments in faculty, students, cutting-edge laboratories and infrastructure related to space exploration.

Building upon early successes in space robotics and earth observation, Canada's expertise has expanded to enter a new era of investment in space exploration: the realm of planetary and space science missions. Notable successes include instrument contributions on the Phoenix Mars Lander, the Mars Science Laboratory Curiosity Rover and the Herschel Space Observatory as well as the MOST space telescope. The Canadian Space Agency is contributing to the *James Webb Space Telescope* in the form of a $170M investment in key components for NASA's flagship mission. A history of CSA support for such missions culminating in *JWST* enabled Canadian industrial partners to develop world-leading expertise in space technologies.

Having a continuous human presence in space is now an accepted fact of life. The International Space Station has been continuously populated for over sixteen years and future missions to Mars and the Moon are in advanced stages of planning. Yet, we know little about how long-duration exposure to microgravity and radiation, or the low levels of gravity found on Mars and the Moon affect the human body. We are seeking measures to counteract the deleterious effects we do know about, and Canada's strong presence in the international space research community means we are actively involved in key studies to look at the physiological and perceptual issues associated with changes in gravity.

While Canada has had a track record of impressive contributions to international space exploration missions, we have failed to join several key recent NASA mission opportunities, including the Mars 2020 rover and the MoonRise lunar sample return mission. The window is closing fast for a Canadian contribution to NASA's dark-energy flagship mission WFIRST and for the ESA X-ray flagship mission Athena. It is paramount that Canada is ready to take advantage of such opportunities when they arise to ensure that the space science and engineering community of today will remain in Canada, and that the community of tomorrow will once again push the limits of exploration. Canada is now at a critical point where it needs to set a strategy for participation in future missions.

An environment that fosters scientific and engineering innovation requires maintenance and growth in the form of substantial and reliable injections of resources. The Canadian space exploration sector is currently underfunded. Canada spends the least on its space program within the G8 countries in terms of actual dollars and the second lowest per capita. Per year, Canada spends only $16M on space exploration missions and technology, much less than comparable nations as a fraction of GDP. For example, France spends about 0.01% of GDP on space science, and the US about twice more. In the Canadian context, these would translate to $250-500M/yr, *more than ten times the current funding level*. In addition, the lack of a coherent and reliable process for allocating funding via the CSA obstructs scientific and engineering innovation: hardware investments in space missions are not followed up with support of science teams to reap the rewards of substantial investment in instruments; promising technologies are explored and never developed towards a launch opportunity because of unreliable funding streams; opportunities to join international missions are missed because of the lack of a process for responding quickly to new ventures; and finally, young scientific and engineering talent is lost to other countries with more robust support for space exploration.

Given the depth of talent already present within Canadian universities and industry, the space exploration sector is ripe for growth. In the next decade, Canada should maintain its scientific leadership in space exploration and develop its pool of young scientists. Canadian aerospace companies should be recognized as essential partners in the most exciting international space missions. Critically, *Canada should lead* a flagship space exploration mission to advance the frontiers of our scientific understanding.

Given the existing landscape of expertise and creativity, these compelling goals are feasible with a funding level now of approximately $130M/yr and the adoption of a process within CSA to allocate resources regularly and with agility. We envision a structured, long-term space exploration program for Canada, a total investment of $1B over the next ten years that ramps up to $1.3B over the following decade. This framework fuels future innovation driven by the Canadian space-science community and their industrial partners. Innovation from initial investment in space science is measured not by percent but by factors of ten. The promise of scientific discoveries inspires current and future engineers and also drives industry to develop new technologies that might not be justified by short-term financial rewards. That is, this collaboration between scientists and industry shakes up the classic risk-reward balance and encourages the aerospace industry to take calculated risks that bring new, transformative technologies into being.

A succession of competitive calls for proposals, arranged in cycles that cover ten years, will grow Canadian expertise in space science and technology, inspire our communities and reach out to our partners around the world. Moreover, it guarantees that several missions at different stages are under development simultaneously and that each mission is chosen competitively, fueling innovation and cultivating a broad and deep space industry. The outlined funding program would be divided nearly equally into small projects and missions (less than $40M, yearly calls), medium missions (up to $200M, every five years) and large missions (up to $500M, once per decade) to develop depth and continuity in the sector. A crucial aspect of a successful plan for space exploration is that funding is guaranteed at every stage of a mission, especially during the early feasibility study phase (about 10% of the mission budget) and the late science and operation phase (about 10%). For each call for proposals, two or three competing projects will be selected through rigorous peer review to go through a design phase, and this will assure both that the final selection will be robust and that a broader community of researchers and their industrial partners will develop new expertise and new technologies. The final scientific investment will ensure that the goals of the mission are ultimately achieved.

Our proposed framework over a decade will stimulate vigorous interaction between scientists and aerospace companies throughout Canada by generating a series of competitions for missions; each proposal call has several levels of competitive assessment and development, cultivating a broad range of collaborations and technologies and creating a robust industry within Canada.

The comprehensive contributions of Canadian scientists and industry to several missions over past decades means that Canada now has the expertise to lead a large (about $400M) space science mission where we invite our international partners to join our Canadian project (rather than the other way around), stimulating our aerospace industry, while inspiring a new generation of young Canadians.

The Canadian Space Agency: Starved Ambition

In 2012, the Emerson report[1] found an aerospace industry without direction or sufficient funding. It argued for a new long-term space plan to update the plan from 1994 as well as renewed, sustained funding for the Canadian Space Agency and a new governance structure for the agency. The 2014 Space Policy Framework[2] outlined broad principles for the Canadian Space Agency but did not provide a steady funding stream. Now, five years after the Emerson report, we are still without a long-term plan for government investment in space and the A-base funding for the CSA is at its lowest level since 1999. Fortunately, our previous investments in space have a very long lead-time, and so we are still reaping the benefits of the planning and investments that began in the 1990s. However, if we do not choose to resume investment in space exploration soon, we will continue to lose momentum. Capabilities, once lost, are very difficult to rebuild. Canada has already missed opportunities for major missions and lost highly qualified engineers and scientists to other countries. The current plan for the CSA forecasts decreased funding[3] in general and for space exploration in particular. After a decade of neglect, further decreases in funding will decimate the Canadian capacity for space exploration. We argue that an increase in funding at least to the levels of the early 2000s, and ideally beyond, is crucial to maintain and grow Canada's space capacity and to fuel innovation.

In 1999 the Canadian government funded the CSA with $300M of A-base funding.[4] This was sufficient at the time to maintain the core programs, but did not allow the agency to grow or to commit to any large programs. Since that time, the A-base funding has actually decreased to $250M, and the government has supplemented this with ad hoc funding to meet the CSA's existing commitments, without allowing for new endeavours or growth. Furthermore, the current financial governance structure and ad hoc funding infusions for the CSA has made Canadian participation in international projects difficult if not impossible. Even modest financial decisions (at the level of a few million dollars) must be decided by the Treasury Board rather than within the CSA itself. This approval process has resulted in delays and missed opportunities for partnerships. Our proposal is to either move these decisions to a funding agency or to operate the program on a strict timeline so that the Treasury Board will know well in advance of upcoming programs in order to encourage timely decision making.

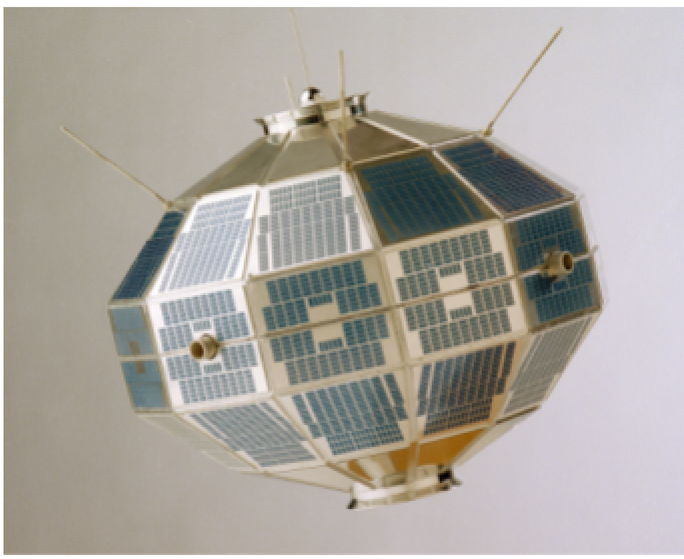
After more than a decade of stagnant funding, Canada's leadership and expertise in the space sector are beginning to erode, and without a renewed commitment to innovation and a reinvigorated vision for the CSA this loss may be irrecoverable. Our historical leadership and expertise are crucial both to Canada's internal security and to engage our international partners, which amplifies Canadian investment. Despite this recent lack of investment in future

1 http://aerospacereview.ca/eic/site/060.nsf/eng/home
2 http://www.asc-csa.gc.ca/eng/publications/space-policy/default.asp
3 http://www.asc-csa.gc.ca/eng/publications/dp-2017-2018.asp
4 http://nationofinnovators.ca/index.php?option=com_publivateideamodule&controller=media&view=media&id=169

endeavours, our past efforts are poised to bear fruit with the launch of perhaps the most ambitious science experiment ever, the James Webb Space Telescope, with the CSA as one of three key partners. Do we continue to let the CSA dwindle into obsolescence or do we take this historic achievement as an opportunity to reinvigorate the Canadian space exploration program to inspire our communities and build innovative technologies?

Societal Benefits of Space Exploration: Inspiration and Innovation

> "We choose to go to the Moon. We choose to go to the Moon in this decade and do the other things, not because they are easy, but because they are hard, because that goal will serve to organize and measure the best of our energies and skills, because that challenge is one that we are willing to accept, one we are unwilling to postpone, and one which we intend to win, and the others, too."
> US President. John F, Kennedy, 12 Sept 1962



Canada's first satellite was the scientific mission, Alouette One.

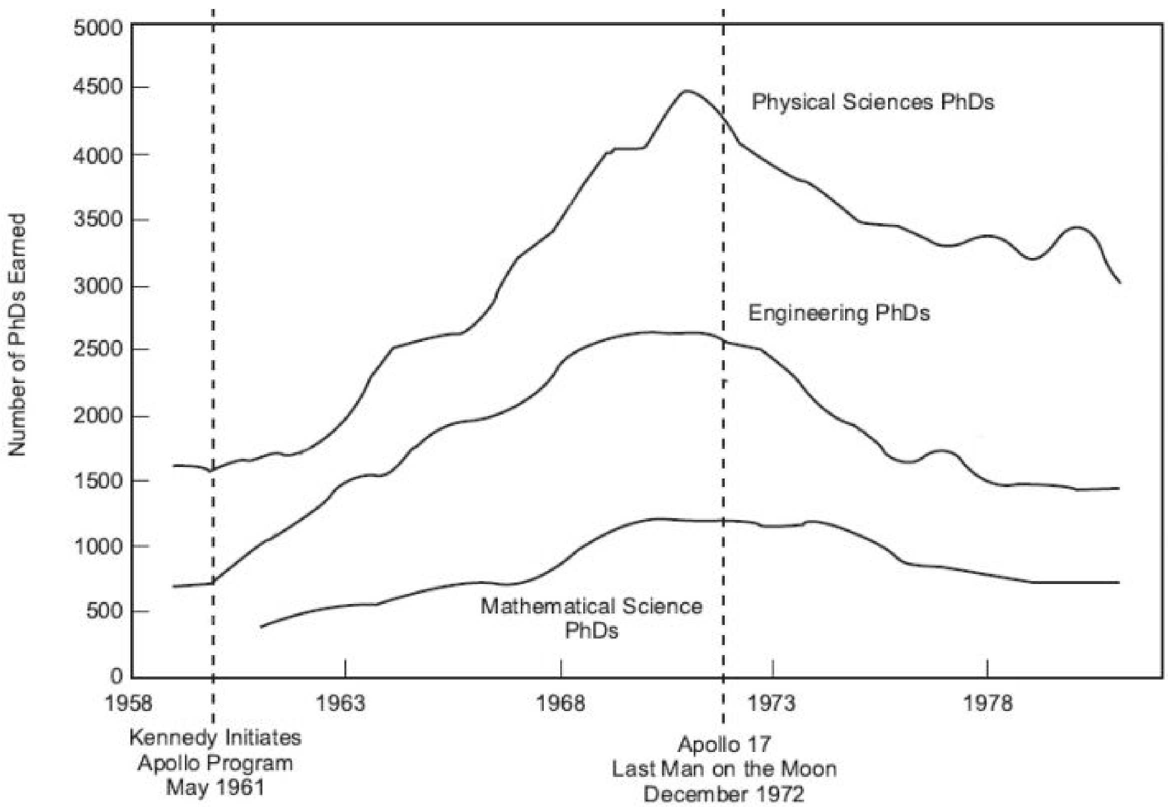
The Naylor report (*Canada's Fundamental Science Review*[5]) recognized that "societies without great science and scholarship [...] are impoverished in multiple dimensions."[6] Two of these dimensions are the inspiration that motivates young people, and the innovation that fuels economies. In perhaps no other human endeavor are inspiration and innovation more tightly linked than in space exploration, and Canada has been part of it since the beginning. Just 17 days after John Kennedy set the US on a course to the moon, with *Alouette 1*, Canada became the third nation to construct a satellite and the fourth to operate one in space.

Inspiration

Exploration is a fundamentally human endeavour motivated by our natural curiosity to understand the functioning of the world. Space exploration in particular causes us to cast our view beyond the bounds of our planet to our Solar System, our Milky Way, and beyond to the earliest light from a nascent Universe. We can frame our urge to explore space as seeking to answer the following three questions.

[5] http://www.sciencereview.ca/eic/site/059.nsf/eng/home

[6] p. 5, *Investing in Canada's Future, Strengthening the Foundations of Canadian Research*



The advent of Kennedy's Apollo program had a direct positive effect by inspiring students to pursue STEM fields. From Siegfried, W.H., "Space Colonization—Benefits for the World", Space Technology and Applications International Forum, 2003.

What's out there? If we only ever look within the boundary set by our own atmosphere, we miss out on much of the complexity and diversity of the Universe. Within our Solar System, the highest mountains are on Mars, clouds of poisonous gas surround Jupiter, and solid chunks of iron orbit the Sun in the asteroid belt. Icy visitors come from beyond Pluto as comets. Beyond the Solar neighbourhood, extreme gravity bends spacetime around black holes, dark matter keeps galaxies in their perpetual merry-go-round, massive stars explode and provide newly forming star systems with the elements that are the building blocks of future planets and even life. The extreme - and more typical - environments in the Universe are not accessible without exploration into space, and we can learn about the fundamental forces by probing these environments in ways that are impossible on Earth.

Where did we come from? The appearance of complex life on Earth is a circumstance arising within the present epoch in the evolution of our Galaxy, around a specific type of star, on a particular rocky planet. We do not yet know exactly how life arose on Earth or how unusual life is in the Universe. Are the peculiarities of our planet necessary, or is the appearance of life quite robust? Addressing this question requires historical exploration to understand the nature of an early Earth and to identify other locations within our Solar System and around nearby stars where life may arise.

How can humans explore space? As we cast our view beyond Earth, we recognize that our green and blue planet is special and unusually hospitable in a Universe hostile to fragile human bodies. To bring ourselves outside our protective atmosphere is an extensive undertaking that requires substantial investments in the machinery to keep humans alive in space, and the health sciences to keep our bodies robustly functional. Physically transporting humans to space to explore our Solar System requires investment.

These big questions fuel the desire of many young people to pursue STEM fields, so that they learn about the boundaries of our present knowledge, and develop the tools to contribute to further knowledge. Astronomy 101 classes in colleges and universities across the country are filled with students from all fields who are fascinated by the weird and wonderful Universe we live in, and motivated by the remarkable achievements of space exploration in planetary science and astronomy. Third graders have countless questions about black holes, planets around other stars, how people survive in space, and the most recent spacecraft they have been following in the media. Aerospace companies attract the best engineers to work on instruments for space exploration.

Innovation

> "Space is at the cutting edge of innovation."
> Hon. Naveep Baines, Minister of ISED

In the funding landscape of research and development, support for space exploration plays a unique and powerful role. It is essentially curiosity-driven, usually by members of the higher-education community (so it falls under the category of university research and development), but the bulk of funding is usually ultimately directed to the private sector. This reverses one of the key Canadian funding models of the past decade, with support for basic research only to serve the private sector (e.g., the NSERC SPG and CRD programs). Space exploration is a powerful driver of innovation because the goals are necessarily long-term and transformative. Scientific missions routinely achieve ten-fold jumps in capabilities beyond the current state of the art. A brilliant example is the JWST mission, to be launched in 2018, for which the Canadian Space Agency partnered with NASA and ESA: over most of its range of sensitivity, JWST is 30 to 100 times more sensitive than current technology. This leap in capability is required in space exploration missions due to the challenging nature of the science questions that drive the missions.

Furthermore, support of space exploration, driven by the curiosity of our nation's scientists, naturally creates powerful innovation clusters.[7] The top scientists in our government

[7] http://www.ic.gc.ca/eic/site/062.nsf/eng/home

laboratories and universities seek out the expertise of our best engineers in the aerospace industry with the key goal of creating transformative technologies. In Canada, aerospace is a leader in innovation, with a rate of research and development investment higher than in Europe and other industries within Canada. Furthermore, every $1B invested in space generates an additional $1.2B of immediate economic activity,[8] meaning new markets and new jobs; more than half of the new positions are HQP in STEM disciplines. The indirect activity generated by investment in space is much larger. Canadian space researchers in astrophysics and planetary science account for nearly seven percent of the world's research publications in these areas. Canada thus ranks between third and sixth worldwide for impact (depending on the discipline). Space exploration specifically teams two of the strongest innovation engines in Canada — space science researchers and Canadian aerospace companies — to build the next Moon (or Mars) shot.

Back on Earth, spending on space exploration fuels a wide range of economic activity. The 2015 report, *Comprehensive Socio-Economic Impact Assessment of the Canadian Space Sector*[8], estimated that the total revenue of the Canadian space sector was $5.4B annually, giving jobs to nearly 25,000 Canadians. About 53% of these positions were HQP, where the mean contribution of these HQP to the Canadian GDP is $160,000, twice the national average. Furthermore, job creation in this sector is six times the national average and the sector as a whole is growing at 3.6% annually, twice the rate of the economy in general. The space industry is growing and creating high quality jobs for Canadians.

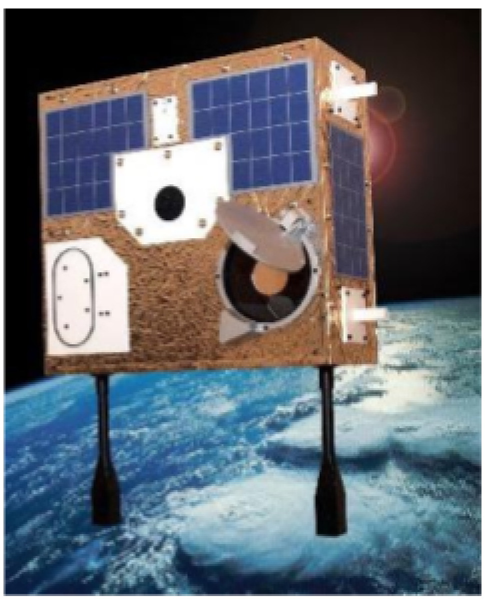
The bulk of the direct revenues in the space sector come from satellite operations and services; that is, they come long after the initial investment in research and development and the actual manufacture of satellite and launch systems. The development and launch of space systems are low-profit-margin activities, and substantial value is added downstream; therefore, a short-term strategy to reap rewards from research and development in space technology is unlikely to succeed. On the other hand, this means that the government investment in this area can have substantial beneficial effects. In particular, although Canada accounts for less than one percent of total government spending on space world-wide, its share in the world space market is nearly two percent. The dynamic downstream industry for services based on space technology thrives on the infrastructure built in part through government investments in space technology development and space missions. For example, CSA's $4.7M investment in the ESA ARTES program resulted in $99M in sales of products developed for the program by COM DEV. Despite these successes, the *Impact Assessment* concluded that the baseline funding of the CSA was not sufficient to maintain Canadian space capabilities in the long term and furthermore that the budget instability and unpredictability had an especially detrimental effect on small and medium-sized enterprises.

The Naylor report[9] argues that decisions guiding government investment in research and

[8] http://www.asc-csa.gc.ca/eng/publications/2015-assessment-canadian-space-sector.asp
[9] http://www.sciencereview.ca/eic/site/059.nsf/eng/home

development should especially focus on the positive externalities of the support. Government support of research is most crucial in cases where the benefits of the research are least likely to accrue for the research organization itself. Without government support, such potentially transformational work would simply not get done. These positive externalities are strong in the space industry, as we described earlier, and they are most powerful for space exploration where the benefits are huge, but the timescales to impact are difficult to predict... In 1975, during the ramp down in NASA spending after the end of the Apollo program, Michael Evans ("The Economic Impact of NASA R&D Spending" known as "The Chase Report"[10]) studied the economic effect of diverting $1B annually from other government programs to research and development at NASA. After ten years he concluded that $1B yearly investment would result in an increase of $23B in annual GDP; the most dramatic increases were at the end of the decade and continuing to grow. Therefore, for a total investment of $10B, the total increase in GDP over the decade would be $83B. By the end of the decade 800,000 more people would have jobs because of the yearly investment. In fact, toward the end of the decade, he argued that the economic benefits of the research and development would increase by 30% annually, so continued investment would reap dramatically larger benefits.

For Canada the evidence is more anecdotal, but many technologies developed in Canada for space exploration have built industries on the ground. It all started with Canada's first satellite, the science mission Alouette One.[11] The team of engineers had no experience in satellite building, and their design was vastly more ambitious than other satellites of the time; it had 50-metre antennas and solid-state electronics. The twin objectives of the program were to study the ionosphere and develop Canada's space capacity. Of course, it achieved both. The prime contractor, de Havilland of Toronto, became Spar Aeropsace (now part of MacDonald, Dettwiler and Associates). Spar and later MDA built the Canada arms for the space shuttles and the ISS, cementing Canada's leadership in space robotics.



MOST, launched in 2003, was Canada's first scientific satellite since 1971 and the fifth overall.

More recently we look to the development of the attitude control system for Canada's first space telescope, MOST. To achieve its scientific goals, MOST had to point stably for weeks on end with one-arcsecond precision. This precision was far better than had ever been achieved before in a microsatellite, the mass of MOST being 60kg. It also pioneered the use of commercially available electronics on an effectively open-source bus from AMSAT for a scientific mission,

[10] https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19760017000.pdf
[11] http://bit.ly/alouette_national_post

dramatically reducing the costs. The economic legacy of MOST lies in the dozens of satellites for which members of the MOST team subsequently designed key elements. The Canadian-led missions BRITE Constellation and NEOSat are among these, but so are many micro- and nano-satellites from around the world. This precision attitude control system allows Moore's Law of computing to carry over into space with small, cheaper, more reliable and more capable satellites. The technical heritage of MOST is the all-purpose micro- or nano-satellite that is revolutionising the space industry today, and Canada is a world leader in this technology.

Canadian Investment in Space: Principles and Practices

The recent Naylor report outlines several key principles for a successful program of government-sponsored research which apply equally well to space.

Curiosity-Driven

At the most basic level, government-sponsored research should be driven by the interests of the researcher themselves. We quote from the review:

> A key lesson emerging from the foregoing is that governments must give researchers the support and freedom to pursue their very best ideas, any one of which holds the potential to result in a discovery or insight that is the seed of a future innovation or industry. Indeed, the collective effort of the research enterprise is most fruitful when scientists and scholars can let their curiosity and passions guide them to those areas where they can make their very best contributions. As observed by Bill Downe, Chief Executive Officer of BMO Financial Group, "breakthroughs happen when brilliant minds are given the freedom to probe the nooks and crannies of reality—when exceptional people ask fundamental questions about the deepest problems and make extraordinary discoveries that benefit us all."[12]

World-leading and Globally-Collaborative

As a small and well-off country Canada must focus its government research support to achieve excellence over a wide range of subjects and foster global leadership in areas vital to Canadian interests, such as space.[13] Furthermore, Canadian researchers can use this leadership role to foster global collaborations to maximise their impact.

Balanced

A successful program should balance the portfolio over projects with a range of sizes, research

[12] As quoted in: Universities Canada. Universities Canada's Response to the Government of Canada's Review of Federal Support for Fundamental Science, p. 4. Ottawa: Universities Canada; September 2016.

[13] https://sencanada.ca/content/sen/committee/421/SECD/Reports/DEFENCE_DPR_FINAL_e.pdf

areas and investigators. Small projects provide training grounds for more ambitious endeavours. Such balance will foster the growth of the expertise of both early-career and established researchers, investing both in today's leaders and those of the future.

Meritocratic

The process of selecting the projects to fund should be open, well-defined and based on the merits of the proposals themselves as well as the research team leading the project. A panel of experts in the area of research and the implementation of the project should be the final arbiters of the choice of projects to fund.

Efficient

The available funds to support research of any sort are limited, so it is crucial to limit waste. In the context of space exploration it is also crucial for efficiency to limit risk as well, both the risk in terms of the costs of a program ballooning and in terms of the mission failing. A multi-tiered approach of selecting several programs for initial design and cost studies, followed by down selections mitigates both of these risks and increases efficiency. Meanwhile it also supports a broader community of researchers. The teams that are initially unsuccessful in the full competition develop both technologies and expertise in the first rounds and still have the opportunity to be successful in subsequent competitions. Furthermore, efficiency requires that the funding be consistent, so that both academic researchers and their industrial partners can develop capacity and retain HQP.

Best Practices

These principles should guide the design of a sustainable, balanced space exploration program for Canada. We briefly outline below a sample process (further detailed in Appendix A) based on these principles, taking into account successful examples from other space agencies. In this model, the program will be organized around a series of calls for projects and missions. The questions that these missions will answer are only limited by the imagination of our scientific community within the area of planetary exploration, space astronomy and space health and life sciences. The calls will invite projects of a particular budget envelope with more frequent calls for small projects and a single, decadal call for the largest projects. This tiered approach will create a balanced and efficient program where a diverse group of researchers and industrial partners can participate and innovate. Furthermore, the larger-scale competitions will be coordinated with our global partners such as NASA and ESA to foster and grow the international collaborations that CSA developed in the 1990s and 2000s through missions such as JWST and the Curiosity Rover.

We examined the approaches of space exploration programs throughout the world to find the best practices for a vibrant space exploration program. Furthermore, the Naylor report guided our thinking. In particular the general process follows the outline of the review for the assessment of an investment in a large scientific facility (we quote from the Naylor report):

- a peer-reviewed decision on beginning an investment;

- a funded plan for the construction and operation of the facility, with continuing oversight by a peer specialist/agency review group for the special facility;
- a plan for decommissioning; and
- a regular review scheduled to consider whether the facility still serves current needs.

Drawing from the ESA Cosmic Vision program we augment this general process with two additional levels of peer review. Space exploration is a high-risk, high-reward endeavour, and as such specific actions must be taken to mitigate these risks. In particular the selection of a large or medium mission (budgets greater than $50M) will include two costing phases before the final selection of a particular mission. In the first phase several (e.g. 4 or 5 per call) possible missions will be chosen and funded for analysis and definition (phase 0), with the science team and an industrial partner completing the study in collaboration with the CSA. At the second peer review, two missions will be chosen on the basis of scientific merit, technological readiness and initial cost estimates. These two missions will each be funded for two independent feasibility, preliminary design studies (phase A/B). Finally, the third peer review will choose from among these designs the successful mission.

A tiered approach not only manages the risks of this program, but it also builds a robust space exploration community. Although at the end only one science team and industrial partner are chosen for each mission, the process in fact creates and fosters up to five innovation clusters of scientists and industrial partners at the first stage, and possibly four new collaborations at the second stage. Looking at other space programs, some missions that are chosen in the first stage but initially unsuccessful in one of the final two stages can build upon the funded development in the unsuccessful call to propose a successful mission in a subsequent call. Having a sustained and predictable investment in space exploration ensures that our persistent investment bears continued innovation and results. These tiered studies foster the growth of expertise and capacity, especially for small and medium-sized enterprises, fostering a broader and deeper space industry.

Given the principle of efficiency espoused above and in the Naylor report, the question arises of whether the Canadian Space Agency should become a large funding agency itself or should it provide guidance in design and procurement in service of the proposers. In this latter case, the proposed framework could be funded through new A-base funding at either NSERC or CFI, but in this case space exploration would have to be added to the agency mandate. Such a program would mirror the success of the Planetary Science Directorate (PSD) within NASA. PSD funds $1.6 billion of research while spending only $7.1 million on management. In any case Canada would have to commit to this new funding envelope over a decadal timescale because space exploration is a long-term investment. For example, Canada's participation in JWST began around 1997 and may continue through 2028.

Launching a CSA for the 2020s: Canadian Space Exploration Program

Overview

The Canadian Space Agency needs continuous funding and a clear governance structure to fuel innovation in Canada and inspire the next generation of scientists and engineers. The current uncertain funding and sluggish decision making process at the CSA actually stifle innovation in space science and prevent Canadian researchers and industry from partnering with their peers around the world. Canadian space scientists and space industry are world leaders and aspire to collaborate together, as demonstrated for example in the CASCA Long Range Plan (LRP)[14] and the funding of industrial research chairs by space industry leaders at Canadian universities, but it is impossible to develop this world-leading team with the current level of funding and governance model at the CSA.

The 2012 Emerson report on "Canada's Interest and Future in Space" identified a key challenge to the Canadian space community:

> The first lies within government: inadequate clarity of purpose with respect to Canada's space program and its role in providing services and advancing national priorities. This lack of focus appears to go back at least a decade and has been manifested in weak planning, unstable budgets, and confusion about the respective roles of the CSA and those government departments that are major space users. In a sector whose undertakings are, by definition, long-term, expensive, and complex, it is especially important to have concrete goals, predictable funding, and orderly implementation.

We propose a structured, long-term space exploration program for Canada, including space astronomy, planetary science and space health and life sciences, a total investment of $1B over the first ten years and $1.3B over subsequent decades. A succession of calls for proposals, arranged in cycles that cover ten years, will grow Canadian expertise in space science and technology, inspire our communities and reach out to our partners around the world to explore the Universe. Moreover, it guarantees that several missions at different stages are under development at every moment and that each mission is chosen competitively, fueling innovation and cultivating a broad and deep space industry. Canadian space scientists are world leaders in fields from planetary surfaces and atmospheres to cosmology and high-energy astrophysics, and Canadian researchers have played and continue to play key roles in scientific missions from Phoenix and MOST to Curiosity and JWST. This leadership will not continue unless the CSA's funding and selection processes are revitalised.

A framework such as we describe fuels future innovation driven by the Canadian space science community and their industrial partners. Because of the technical challenges,

[14] http://casca.ca/wp-content/uploads/2016/03/MTR2016nocover.pdf

innovation in space science is outsized compared to the initial investment. The promise of scientific discoveries inspires current and future engineers and also drives industry to develop new technologies that might not be justified by the immediate financial rewards. That is, the close collaboration between scientists and industry enables the aerospace industry to take calculated risks to develop novel and transformative technology.

Such a framework over a decade will create integrated communities of scientists and aerospace companies throughout Canada by generating a series of competitions for missions; each call has several levels of competitive assessment and development, cultivating a broad range of collaborations and technologies and creating a robust industry for Canada. Furthermore, the calls focus on missions of various sizes to engage our international partners and to encourage growth for the broad aerospace and space science community — not only the established players. Within the broad area of space exploration, the calls will not be restricted by topic, and so the community itself will determine where best to invest and grow.

Canada's Global Role

Although Canada's space sector is small by international standards, it is a world leader in specific technologies such as communications, space-based radar, robotics, optics, data analysis and scientific instrumentation. It is one of the few countries (and one of the smallest) with an end-to-end space industry, where an idea can go from a university classroom to its realisation in space. This powerful combination of a broad and deep space industry makes Canada unique and a sought-out partner for international collaboration. Within Canada this combination means that an entrepreneurial individual can have a huge impact and be a great catalyst for innovation.

> "In 1983, NASA invited Canada to fly three payload specialists, in part because we had contributed the robotic arm that is used on the shuttle." Hon. Marc Garneau, Minister of Transport

Canada has an enviable position. Although it is an ESA associate member, Canada chooses which parts of the ESA science program to participate in (e.g., Planck, Herschel) by collaborating with the payload teams. This leaves the Canada space exploration community the freedom to collaborate alternatively with the US (e.g., JWST, Curiosity), Japan (e.g., Hitomi), India (e.g. ASTROSAT) and other nations, and Canada also has the expertise to go it alone. Canada sits at the crossroads of space exploration worldwide, creating great growth and innovation opportunities for Canadian industry and researchers that are unique in the world.

Mission Insignia for JWST

Why now?

Canadian investment in space exploration in the past decades is now reaping rewards. The long-term commitment to JWST that began in the 1990s will culminate with the launch of perhaps the most ambitious science experiment ever. JWST will explore the Universe from a vantage point nearly 1,500,000 km from Earth. Canada's contributions to this mission made us a key partner in this nine-billion-dollar effort with a relatively modest investment of about $200M.

The Canadian Space Agency, Canadian scientists and industry built a world-leading collaboration to study the solar system as well. Researchers at York University in collaboration with MDA built the premier instrument of the Phoenix Mars Mission, the LIDAR weather station to measure cloud structure above the surface of Mars. This was the first LIDAR system to be deployed beyond Earth. Our success with Phoenix led NASA to invite Canada to build the Osiris-Rex Laser Altimeter (OLA) instrument contribution, our largest planetary contribution to date. This shows a pattern of contributions in areas of particular expertise. For the NASA flagship mission to Mars, Curiosity, NASA called on a consortium of Canadian universities, the CSA and MDA to build the Alpha particle X-ray spectrometer (AXPS). AXPS can measure the composition of materials on the surface of Mars.

Canadian-Built AXPS on the Surface of Mars

Because of Canada's demonstrated space capabilities, international partners in the US, Europe and elsewhere are continuing to look to Canada for expertise and leadership in optical design, communications, robotics and metrology for many proposed missions, but for the past ten years, Canadian investment in space has been much more modest than earlier when the foundations for today's great missions were built. Since the first decade of the 2000s, the baseline spending for the CSA has declined from $300M to just over $250M. Meanwhile, government investment in space has increased worldwide. In the last ten years, this low level of Canadian baseline funding has been augmented with several ad hoc injections of funding. Even including this additional spending, Canada's investment in 2013 on space relative to GDP lagged behind the world average and all of the large world economies except for the UK. Though the space program has kept hobbling along, this funding pattern discourages sustained investment by scientists and industry. Most troubling, it discourages innovation.

Unless we resume investment in Canadian space exploration, our expertise and leadership will be lost. Just as Canadian scientists will be starting to make amazing discoveries with these ground-breaking missions, Canada will have the choice to reinvigorate its investment in space or abandon it. Ultimately, expertise and leadership are really about people, people who will either move on to other areas or other countries. Once these people are lost, Canada's current role in space will be nearly impossible to regain. Instead, we can build upon our successes to develop a balanced program of missions and even lead a flagship mission in space exploration. The comprehensive contributions of Canadian scientists and industry to several missions over the past decades means that Canada now has the demonstrable expertise to lead a large (say about $400M) space astronomy or planetary mission and to invite our international partners to join our Canadian mission (rather than the other way around).

Appendix A: The Framework

We present a representative framework for the selection, scheduling and budget for a comprehensive program of space exploration over the next decade and beyond. Although we understand that in practice the details may end up being different than this example, it is nevertheless important to give some specifics to make our proposal more concrete.

Mission categories, costs and time frames

Missions are divided into the following categories (total cost of development, launch, operation and science):

- S — small-sized missions and technology development programs, divided into microsats (MS) missions, with a budget below \$50M, nanosats (NS), below \$25M, and studies below \$10M at 2017 economic conditions;
- M — medium-sized missions that should not exceed the finance envelope of \$160M, at 2017 economic conditions;
- L — flagship missions with a budget of about \$430M, at 2017 economic conditions;
- MoO — missions of opportunity. MoO will be included into the M (or L) calls for proposals if their cost is comparable with the M (or L) budget, otherwise, they will be considered separately each year and their cost will come from the S-mission budget.

The plan envisages a \$130M investment per year, with a lighter expense in the first years and steadily increasing until it reaches a stable value. In the first year of the decadal time frame of the plan, a call for proposals for a L mission will be issued for a mission to be launched in the eighth year of the plan.

In the third and eighth year of the plan calls for a M class mission will be issued These calls for the medium-sized missions could be scheduled to coincide with NASA and ESA announcements of opportunity (AOs) to fund development of Canadian contributions to international missions. The first medium mission would be launched in the tenth year of the plan, and the latter mission will still be under development at the end of the decadal cycle.

Calls for S missions are issued every year, or the budget can be allocated for MoO. All the space exploration (astronomy, planetary science and space health) missions will compete in the same selection process.

Medium and Large Mission Selection Procedure

Calls for proposals

A call for proposals for an L mission will be issued every ten years; every five years for an M mission. Along with Canadian-led missions, participation to other agencies' missions (MoO) with a contribution in the same range as the budget of the call can be proposed. In principle, the calls for M class missions could be scheduled to coincide with NASA and ESA AOs.

A letter of intent will be due two months after the call. The deadline for the proposals will be three months later. Submissions will be assessed by peer reviewers. The science committee

(JSECC) and the sub-themes committees (JCSA and PECC) will select three or four missions. The decision will be based on a list of priorities, and the selection process will take approximately four months.

Mission Selection Rubric

- **Scientific priority**
- **Projected cost**
- **Technological readiness**
- **Projected launch date**
- **International collaboration**
- **Program balance**

Mission of opportunity proposals must describe the role and responsibilities of all the partners included. The share of CSA responsibilities must be stated in order to assess the cost. Proposals must be accompanied by letters from the agencies involved, clearly stating their interest in the proposed collaboration and their commitment to support the eventual Assessment Phase activities.

Assessment phase

The missions selected will enter the assessment phase funded by CSA. A science team will be appointed responsible for each mission and each science will be assigned a CSA liaison. The assessment phase will last approximately eighteen months and it will be divided into two parts. In the first six months, the science team will produce a draft for the mission architecture and the payload definition. This will be the guideline for the following one-year long in-depth industrial assessment phase. This second part of the assessment phase will be carried out by two industrial contractors for each selected proposal. It is crucial that funding will be provided in this phase to ensure the technical feasibility of the missions and to reduce the programmatic risk (see table 1).

Furthermore in the case of international missions with proposed Canadian participation, the scope of Canadian participation will be negotiated between the CSA and the international agencies.

At the end of the assessment phase, the result of the studies will be presented to the committees and to the scientific community.

First down-selection and definition phase

In the first down-selection, the science committees (JSECC, JCSA and PECC) recommend two missions for the definition phase, based on scientific excellence and feasibility. The Deputy Ministers' Governance Committee on Space (DMGC) approves the two missions. For each of the two missions, two competing industrial contractors carry out the spacecraft design study. The payload can be funded by CSA directly, in which case an announcement of opportunity is issued. Alternatively, other partners, like NSERC and CFI, can take the responsibility for the payload and the instrument selection process.

At the end of the definition phase of a duration of approximately one year and a half, a detailed study on the design and a detailed cost estimation will be presented. In table 1, the funding allocated for this phase includes the spacecraft design and the payload.

Final selection and implementation phase

The two missions will undergo a thorough evaluation by the scientific committees, which will select one mission. The DMGCS approves the mission for the implementation phase and selects the final industrial contractor. Again, funding for implementation can be provided by CSA and other partners and an estimate is shown in table 1.

The implementation phase will take approximately 5 years.

Launch and operation

Launch will be scheduled at the end of the implementation phase. To maximize the scientific achievement of the mission, it is crucial that funds will be allocated after the launch for ground-based activities, scientific and operational support.

For example for the area of space astronomy, the CASCA long range plan, that is expected to be ready by 2020, could provide input for the first down-selection, giving indications on which missions are to be considered a priority for Canadian astronomy.

Funding, Table 1 (millions of Canadian dollars)

	M mission budget	L mission budget
Assessment Phase	2-3	7-8
Definition Phase	8-10	25-30
Implementation Phase	50-60	160-170
Launch	30	50
Ground segment	25	70
Administration	13	40
Science and operation	7	20
Contingency	12	40
Total	147-160	412-428

Large-Mission Timing, Table 2

	Date
Call for Proposals	May 2018
Letter of intent due	July 2018
Mission proposal due	November 2018
Peer-review assessment	December 2018 - February 2019
JSECC with JCSA and PECC select 3 or 4 large missions	March 2019
Assessment Phase	April 2019 - end August 2020
Presentation of the results and JCSA-PECC recommendation for 2 L missions	September 2020
JSECC down-selection to 2 L missions	October 2020
The DMGCS approves the 2 missions	November 2020
2 groups in competitive definition phase	December 2020 - March 2022
JSECC/JCSA/PECC select L mission	April - May 2022
The DMGCS approves the L mission	June 2022
Implementation phase	July 2022 - mid 2027
Launch	end of 2027
Commissioning and science	to the end of 2029

First Medium-Mission Timing, Table 3

	Date
Call for Proposals	May 2020
Letter of intent due	July 2020
Mission proposal due	November 2020
Peer review assessment	December 2020 - February 2021
JSECC with JCSA and PECC select 3 or 4 medium missions	March 2021
Assessment Phase	April 2021 - end August 2022
Presentation of the results and JCSA-PECC recommendation for 2 M missions	September 2022
JSECC down-selection to 2 M missions	October 2022
The DMGCS approves the 2 missions	November 2022
2 groups in competitive definition phase	December 2022 - March 2024
JSECC/JCSA/PECC select 1 M mission	April - May 2024
The DMGCS approves the M mission	June 2024
Implementation phase	July 2024 - mid 2029
Launch	end of 2029
Commissioning and science	to the end of 2031

Second Medium-Mission Timing, Table 4

	Date
Call for Proposals	May 2025
Letter of intent due	July 2025
Mission proposal due	November 2025
Peer review assessment	December 2025 - February 2026
JSECC with JCSA and PECC select 3 or 4 medium missions	March 2026
Assessment Phase	April 2026 - end August 2027
Presentation of the results and JCSA-PECC recommendation for 2 M missions	September 2027
JSECC down-selection to 2 M missions	October 2027
The DMGCS approves the 2 missions	November 2027
2 groups in competitive definition phase	December 2027 - March 2029
JSECC/JCSA/PECC select 1 M mission	April - May 2029
The DMGCS approves the M mission	June 2029
Implementation phase	July 2029 - mid 2034
Launch	end of 2034
Commissioning and science	to the end of 2036

Small Mission Selection Procedure

Calls for proposals

Calls for proposals for small-sized missions and studies will be issued once every year. The total budget for every announcement will be $50M. Depending on the nature of the submissions, more than one mission can be selected and brought to completion, within the limit of the $50M budget.

A variable number of missions, between 3 and 12, depending on their size, will be selected for the assessment phase. Funding will be provided for this phase, for a total of $1.5-2M to be shared between the projects. At the end of the assessment phase, which will last one year, the scientific committees have to decide, depending on the quality of the proposals, if only one mission will be adopted at the end, with a budget between $30M and $50M (an MS mission), or more than one mission, each within a budget of $25M (NS missions). This yields a yearly budget of about $50M, and a total investment of $500M over ten years.

Furthermore, additional studies (with a maximum funding of $10M per program) that do not necessarily result in a mission would be funded through this call.

Depending on this decision, the process that follows will differ.

Microsat missions

One or two projects will be selected to proceed to the definition phase, with two competing industrial contractors per each mission. The definition phase will take 1.5 years. Funding for this phase will be provided for $4-7M total.

At the end of this phase, one mission will be selected to continue to the implementation phase. The DMGCS selects the final industrial contractor. The implementation phase will last approximately 3 years and will cost approximately $25M.

The rest of the budget will be allocated for:

Launch services, $3-4M
Ground segment, $5M
Administration, $4M
Science and operations support, $2M

Nanosat Missions

The final decision for the missions that will proceed to the implementation phase is taken at the end of the assessment phase. The implementation phase will take 2-3 years and the total cost will be $20-30M to be divided between the groups depending on the size of the missions. The rest of the budget will be allocated for launch services, ground segment and administration, depending on the size of the missions. For example, for a $20M mission:

Launch services, $1M
Ground segment, $1.5M
Administration, $1M
Science and operations support, $1M

Space Science Studies

Through the yearly call for small missions, the CSA will also fund studies in space health and life sciences, as well as technological development for space astronomy and planetary science with a cap of $10M per project, although it is anticipated that many small projects will be funded through this initiative.

Summary of Yearly Funding (rounded to nearest million of Canadian dollars)**, Table 5**

Year	Event	Large	Medium	Small	Total
2018	AO L1	0	0	50	50
2019	Start L1	16	0	50	66
2020	AO M1	24	0	50	80
2021	Start M1	68	6	50	124
2022	Choose L1	25	8.5	50	84
2023		42	22.5	50	115
2024	Choose M1	42	8.5	50	101
2025	AO M2	42	14.5	50	107
2026	Start M2	42	20.5	50	113
2027	Launch L1	75	23	50	148
Total 2018-2027		376	104	500	980
2028	AO L2	53	37	50	140
2029	Start L2, End L1, Launch M1, Choose M2	73	47	50	170
2030	AO M3	28	33	50	111
2031	Start M3,End M1	68	39	50	157
2032	Choose L2	25	23	50	98
2033		42	37	50	129
2034	Choose M3, Launch M2	42	47	50	139
2035	AO M4	42	33	50	125
2036	Start M4, End M2	42	39	50	131
2037	Launch L2	75	23	50	148
Total 2028-2037		543	358	500	1348

Appendix B: Missions

The AIAC Space Innovation white paper, "The Future of Canada's Space Sector", outlines several representative missions and programs. We list those within the proposed space exploration framework here.

Mission	Description	Partners	Earliest Launch
Advanced Crew Medical System (ACMS) Space Medicine Decision Support System (SMDSS)	Demonstration mission of clinical decision support system capable of detecting pre-selected medical conditions and inferring possible and likely outcomes for given health state and symptoms		2020
Advanced Telescope for High- ENergy Astrophysics (ATHENA)	ATHENA - a large X-ray telescope (formerly known as IXO) and selected as 2nd large mission in ESA Cosmic Vision.	ESA	2028
Canadian micro-sat/rover mission (secondary payload)	Small exploration science mission as secondary payload		TDB
Cosmological Advanced Survey Telescope for Optical and UV Research (CASTOR)	Cdn space telescope astronomy mission that would provide unique panoramic, high-resolution imaging of the Universe in the UV/optical spectral region		2024
eXTP	Cdn contribution to flagship X-ray mission: spectroscopy, timing and polarimetry	CAS, CNSA	2024
JUICE	JUICE - JUpiter ICy moons Explorer - the first large-class mission in ESA's Cosmic Vision 2015-2025 programme	ESA, JAXA, NASA	2022
KARI Lunar Pathfinder Lunar Rover	Lunar lander and rover mission with NASA support	KARI, NASA	2020
KARI Pathfinder Lunar Orbiter (KPLO)	Lunar orbiter mission with NASA support and hosted payloads	KARI, NASA	2018
LiteBird	Cdn instrument contribution to cosmic microwave radiation mission	NASA	2025
LSRS Bio-Analytics	Diagnostic system on ISS for quantifying soluble biomarkers in a liquid sample and analyzing the presence of biomarkers on cellular surfaces		2019
Lunar science rover (human precursor)	Human Lunar Exploration Precursor mission with focus on Lunar Sample Return and future Human Surface operations		2030
MSR-Mars 2024 rover	Robotic sample return from Mars	NASA	
NeMO (Mars 2022)	Mars communication orbiter with potential international contributions (system, science)	NASA	2022
SPICA	Cdn contribution to future IR space telescope	ESA, JAXA	2030
WFIRST	Cdn instrument contribution to Wide Field IR space telescope	NASA	2025
XIPE	Cdn contribution to future X-ray space telescope	ESA	2026

Appendix C: Glossary

AO	announcement of opportunity
CAS	Chinese Academy of Sciences
CRD	Collaborative Research and Development
CNSA	China National Space Administration
CSEW	Canadian Space Exploration Workshop
DMGCS	Deputy Minister Governance Committee on Space
ESA	European Space Agency
HQP	highly qualified personnel
JAXA	Japan Aerospace Exploration Agency
JCSA	Joint Committee on Space Astronomy
JSECC	Joint Space Exploration Consultation Committee
JWST	James Webb Space Telescope
KARI	Korea Aerospace Research Institute
LIDAR	light detection and ranging
MoO	mission of opportunity
MoU	memorandum of understanding
PECC	Planetary Exploration Consultation Committee
SME	Small and Medium Enterprise
SPG	Strategic Project Grant
STEM	science, technology, engineering and mathematics
TT	CSEW Topical Team