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Office of Audit and Evaluation

Evaluation of NRC Herzberg Astronomy and Astrophysics (HAA) Portfolio

FINAL REPORT

November 14, 2016

National Research Council Canada
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ACKNOWLEDGEMENTS

The Office of Audit and Evaluation would like to gratefully acknowledge the management and staff of the Herzberg Astronomy and Astrophysics (HAA) Portfolio for their support and contribution to this evaluation. The evaluation team would also like to express its gratitude to members of the Evaluation Advisory Committee for their guidance and advice. Finally, the evaluation team would like to thank HAA partners and other stakeholders who provided rich information and insights in support of this evaluation.

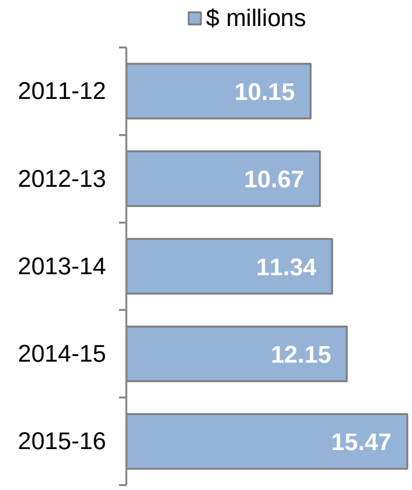
EXECUTIVE SUMMARY

Portfolio description

NRC is mandated by the NRC Act to "operate and administer any astronomical observatories established or maintained by the Government of Canada". NRC-HAA is the portfolio responsible for fulfilling this mandate, including Canada's participation in all current and future offshore facilities. HAA provides financial contributions and designs/develops instruments to support the administration and operation of observatories supported by Canada.

For the period covered by the evaluation, HAA directly supported two national observatories located in British Columbia, the Dominion Astrophysical Observatory (DAO) and the Dominion Radio Astrophysical Observatory (DRAO), as well as six offshore observatories: Canada-France-Hawaii Telescope (CFHT), Gemini, James Clerk Maxwell Telescope (JCMT), Atacama Large Millimetre/submillimetre Array (ALMA), Thirty Meter Telescope (TMT), and Square Kilometre Array (SKA).

International Telescope Agreements Gs&Cs expenditures



Scope and methodology

The evaluation examined HAA Portfolio and program spending between FY 2011-12 and FY 2015-16. A complete and in-depth assessment of the performance of NRC's internal services was not within the scope of the evaluation. In accordance with the TBS *Policy on Evaluation*, the evaluation covered the core issues of relevance and performance, including effectiveness and efficiency and economy.

Challenges and limitations

- The level of client satisfaction with CADC services was not assessed.
- NRC Corporate KPI used to assess efficiency does not include corporate administrative costs.

Overall evaluation findings

The evaluation found HAA to be relevant to NRC and federal government mandates. Further, HAA meets the needs of the Canadian astronomy community as the Portfolio ensures that its activities and funding priorities are aligned with the Canadian Astronomical Society's (CASCA) Long Range Plan 2010 (LRP2010). Canadian astronomers report that HAA plays a critical role in representing the interests of the Canadian astronomy community internationally through its involvement in existing and future observatories. Additionally, HAA's facilities at DAO and DRAO are unique in Canada, providing core capabilities and expertise in the development of observatory instrumentation.

HAA has performed very well and has had significant impacts by supporting Canada's offshore observatories as well as other telescopes around the world. HAA support has been primarily focused on financial support and the development of world-class instruments and technologies. HAA has collaborated with industry on instrumentation projects, which have resulted in positive impacts for the partnering companies. Most stakeholders perceive HAA as vital in supporting Canada's performance in the field of astronomy.

The evaluation also found that HAA has encountered operational challenges which may impact HAA's ability to meet its objectives. Challenges included procurement delays, lengthening timelines for staffing actions, and limitations in IT desktop support. Further, the evaluation found that the transfer of HAA's IT infrastructure to Shared Services Canada (SSC) has had major impacts on the Portfolio's ability to plan, implement and acquire new IT equipment and networking capacity. Despite these challenges, the Portfolio consistently delivered observatory instruments on time, on budget and according to required specifications.

The overall assessment of HAA's performance by evaluation issue is presented in the table below.

Assessment of HAA's performance

Legend: 🟢 Meets expectations 🟡 Low area of concern 🟠 Medium area of concern 🔴 Management attention required

Issue	Assessment	Associated recommendation
Relevance		
Alignment with the needs of Canadian astronomers	🟡	1
Appropriateness of current delivery model	🟢	None
Alignment with federal priorities and NRC strategic objectives	🟡	2, 3
Alignment with federal roles and responsibilities	🟢	None
Performance		
Success in providing Canadian astronomers with access to national and international telescopes and science data products	🟡	4
Scientific impacts of international telescopes administered and operated by HAA	🟢	None
Contribution to the development of novel instruments and technologies	🟢	None
Scientific and industry impacts of instruments and technologies developed by HAA	🟢	None
Support for Canadian universities by training students and post-doctoral researchers	🟢	None
Contribution to strengthening Canada's position in the field of astronomy	🟢	None
Efficiency and economy		
HAA is administered in a cost-effective and efficient manner	🟢	None
Key risks and factors influencing the cost-effective and efficient use of resources by HAA	🔴	5

Recommendations	Management response
1. The Vice-President's Office (VPO) of Emerging Technologies – National Infrastructure and Future Technologies, in consultation with HAA, should consider establishing a formal consultation process to allow the Canadian astronomy community to provide strategic advice on the Portfolio's scientific activities and priorities.	Accepted. NRC will investigate appropriate mechanisms for obtaining advice on a regular basis from the astronomy community and will develop a proposed process early in FY 2017-18.
2. HAA should continue to work with partners to expand outreach and awareness activities.	Accepted. HAA will continue to work in concert with partners to expand outreach activities. A new model to optimise use of the Centre of the Universe will be explored.
3. HAA, in collaboration with other NRC Portfolios and NRC Business Management Support (BMS), should explore opportunities to leverage competencies and astronomy-related technologies.	Accepted. HAA with support from the VPO of Emerging Technologies – National Infrastructure and Future Technologies and BMS will engage into discussions with the broader NRC community and ensure that competencies and intellectual property held at HAA are known and shared.
4. HAA should identify the reasons why Canadian PIs are not allocated observing time commensurate with Canada's financial support to ALMA operations and take the appropriate measures identified, as needed.	Accepted. HAA will work with the Canadian astronomy community and with the National Science Foundation to understand why the allocation of ALMA time to Canadian astronomers within the allocation of ALMA time to the North American Consortium has not been proportional to Canada's share of the North American Contributions and will attempt work to remove any impediments to Canadian access.
5. HAA, in collaboration with KITS, should continue to undertake efforts to find a solution related to the IT equipment upgrades and high speed networking capacity issues at the CADC.	Accepted. NRC will continue to work to find a solution to ensure that CADC services to clients are not impacted.

ACRONYMS

ACURA	Association of Canadian Universities for Research in Astronomy
AO	Adaptive optics
ATP	Astronomy Technology Program
CADC	Canadian Astronomy Data Centre
CanTAC	Canadian Time Allocation Committee
CANFAR	Canadian Advanced Network for Astronomical Research
CASCA	Canadian Astronomical Society – Société canadienne d'astronomie
CFI	Canada Foundation for Innovation
CSA	Canadian Space Agency
CSP	Central Signal Processor
DAO	Dominion Astrophysical Observatory
DRAO	Dominion Radio Astrophysical Observatory
ESPaDOnS	Echelle SpectroPolarimetric Device for the Observation of Stars
GPI	Gemini Planet Imager
HAA	Herzberg Astronomy and Astrophysics
HIA	Herzberg Institute for Astrophysics
HPC	High-performance computing
ITA	International Telescope Agreements
KITS	Knowledge and Information Technology Services
KPI	Key Performance Indicator
LNA	Low noise amplifier
LRP2000	Long Range Plan 2000
LRP2010	Long Range Plan 2010
MAG	Millimetre Astronomy Group
MTR	Mid-Term Review of the Long Range Plan 2010
NASA	National Aeronautics and Space Administration
NFIRAOS	Narrow Field Infrared Adaptive Optics System
NRAO	National Radio Astronomy Observatory
NRC	National Research Council
NRCan	Natural Resources Canada
OAP	Optical Astronomy Program
PAF	Phased array feed
PAndAS	Pan-Andromeda Archeological Survey
RAP	Radio Astronomy Program
SSC	Shared Services Canada
WIDAR	Wideband Interferometric Digital Architecture

Telescopes

AAT	Anglo-Australian Telescope
ALMA	Atacama Large Millimeter/submillimeter Array
CFHT	Canada-France-Hawaii Telescope
CHIME	Canadian Hydrogen Intensity Mapping Experiment
ESO3p6	European Southern Observatory 3.6m Telescope
EVLA	Expanded Very Large Array
GBT	Green Bank Telescope
HET	Hobby-Eberly Telescope
HST	Hubble Space Telescope
IRAM-30m	Institut de radioastronomie millimétrique

IRTF	Infrared Telescope Facility
JCMT	James Clerk Maxwell Telescope
JVLA	Jansky Very Large Array
JWST	James Webb Space Telescope
LBT	Large Binocular Telescope
MMT	Massive Monolithic Telescope
NTT	New Technology Telescope
SALT	Southern African Large Telescope
SKA	Square Kilometre Array
SOAR	Southern Astrophysical Research Observatory
TMT	Thirty Meter Telescope
TNG	Telescopio Nazionale Galileo
UKIRT	United Kingdom Infrared Telescope
VLT	Very Large Telescope

1. INTRODUCTION

This report presents the results of the 2015-16 evaluation of the National Research Council (NRC) Herzberg Astronomy and Astrophysics (HAA) Portfolio. The evaluation of HAA was conducted in fiscal year 2016-17. The timing of the evaluation is bound by the legal requirements of the Financial Administration Act, which requires completion of the evaluation of HAA's contribution to international observatories by November 2016.

The evaluation examined HAA Portfolio and program spending over a five year period, FY 2011-12 to FY 2015-16. However, when exploring the scientific and industrial impacts of the instrumentation developed by HAA, the evaluation also considered activities conducted prior to FY 2011-12.

The evaluation was led by an independent evaluation team from NRC's Office of Audit and Evaluation (OAE) and assessed the core issues of the 2009 Treasury Board *Policy on Evaluation*, including relevance and performance (effectiveness and efficiency and economy). The questions addressed by the evaluation were developed following a review of key program documents and in consultation with HAA management and the VP, Emerging Technologies.

The evaluation methodology used multiple lines of evidence and complementary research methods as a means to enhance the reliability and validity of the information and data collected. The methodology included the following lines of evidence:

- Document and literature review
- Analysis of financial, administrative and performance data
- Survey of Canadian telescope users (n=95)
- Key informant interviews (internal interviewees n=13, external interviewees n=18)
- Case studies (n=4, interviews n=18)

A more detailed description of the study methodology and its limitations is provided in *Appendix B: Methodology*.

Section 2 of this report provides a short profile of HAA. Sections 3 and 4 present the evaluation study's findings organized by broad evaluation question (relevance and performance) along with associated recommendations. Section 5 presents a brief conclusion drawn from the evaluation, while Section 6 lays out management's response to these recommendations and the actions that will result.

2. PROFILE OF HAA

In the late 1960s, NRC was mandated, through the NRC Act, to "operate and administer any astronomical observatories established or maintained by the Government of Canada" (Justice Canada, 2009). In 1974, the interpretation of NRC's mandate was broadened to include Canadian participation in offshore observatories through an agreement with France and the University of Hawaii to establish the Canada-France-Hawaii Telescope Corporation. Restructured in 2012, HAA continues to operate the programs conducted by its predecessor, the Herzberg Institute of Astrophysics (HIA), that fulfill the mandate set forth by the NRC Act, including Canada's participation in all current and future offshore facilities.

While the NRC Act underpins the NRC's involvement in astronomical research, HAA's activities are primarily guided by the Canadian Astronomical Society's (CASCA) Long Range Plan 2010 (LRP2010), a decadal plan outlining the broad goals and directions of astronomical and astrophysical research in Canada. LRP2010, as a continuation of LRP2000, puts forward a plan to "maintain Canada's position in the upper echelon of international astronomy" by securing Canadian participation in existing and future "world-leading" ground- and space-based observatories (CASCA, 2010, pp. 1–9).

For the period covered by the evaluation, HAA directly supported two national observatories located in British Columbia and six offshore observatories, presented in Table 1. Descriptions of the offshore facilities are available in *Appendix C: Overview of international telescopes supported by Canada*.

Table 1: Telescopes supported by HAA between 2011-12 and 2015-16

Telescope	Location
National Observatories	
Dominion Astrophysical Observatory (DAO)	Victoria, British Columbia
Dominion Radio Astrophysical Observatory (DRAO)	Penticton, British Columbia
Offshore Observatories	
Canada-France-Hawaii Telescope (CFHT)	Summit of Maunakea, Hawaii
Gemini	(North) summit of Maunakea, Hawaii (South) Cerro Pachón, Chile
James Clerk Maxwell Telescope (JCMT)*	Summit of Maunakea, Hawaii
Atacama Large Millimeter/submillimeter Array (ALMA)	Chajnantor Plateau, Atacama Desert, Chile
Thirty Meter Telescope (TMT) – *under construction*	Summit of Maunakea, Hawaii (planned)
Square Kilometre Array (SKA)** – *pre-construction*	Australia and South Africa (planned)

*NRC withdrew from the JCMT partnership and ceased its financial contributions on September 30, 2014.
**While Canada is committed to the pre-construction phase for SKA, the federal government has not yet decided on participation in the construction and operation phases for SKA.

A logic model, developed as part of evaluation planning, details the activities, outputs and intended outcomes of the HAA Portfolio (*Appendix A: HAA Logic Model*). A brief overview of HAA, including its programs, clients and financial and human resources, follows.

2.1 Portfolio and program structure

To fulfill its mandate and to advance the LRP2010, HAA operates three programs: the Optical Astronomy Program (OAP), the Radio Astronomy Program (RAP) and the Astronomy Technology Program (ATP). While the HAA programs were created as distinct components in response to the restructuring of NRC, they are highly integrated within the Portfolio and many program activities are intertwined. Each program is briefly described below.

- ***Optical Astronomy Program (OAP)*****:** The OAP supports and facilitates access to optical, ultraviolet and infrared telescopes for Canadian astronomers. OAP staff provide in-kind and contracted support for the operation of Canada's observatories and act as the interface between the Canadian astronomy community and the CFHT and Gemini[1] observatories. The OAP also operates the Canadian Astronomy Data Centre (CADC), Canada's astronomy data management and archiving facility, which provides data handling and information technology services to Canadian and international astronomers.

- ***Radio Astronomy Program (RAP):*** The RAP is responsible for supporting and facilitating Canadian access to millimetre/submillimetre and centimetre observatories. The RAP is comprised of two groups: the Millimetre Astronomy Group (MAG) and the Dominion Radio Astrophysical Observatory (DRAO). The MAG acts as the interface between the Canadian astronomy community and ALMA, Canada's only offshore submillimetre observatory. The DRAO provides science and technical services to support Canada's national and international radio telescopes.

- ***Astronomy Technology Program (ATP):*** The ATP is responsible for the design and development of instruments and observatory infrastructure for the national and international telescope facilities supported by Canada. Through multifunctional teams, the ATP provides technical and advisory services, including: project management, system engineering, adaptive optics (AO), mechanical/electrical/optical/radio engineering, instrumentation science, millimetre technology, software and controls.

2.2 Clients and stakeholders

As per its mandate to operate and administer Canada's telescopes, the main clients of the HAA Portfolio are Canadian professional astronomers and university students who access the telescopes to conduct research. In order to meet the needs of these researchers, HAA partners with national and international collaborators. As such, unlike other NRC Portfolios, HAA does not serve a specific industry segment that pays to access R&D services. HAA's main client and stakeholder groups include the following:

- ***Universities and academia:*** Canadian astronomers, largely university faculty, graduate students and postdoctoral researchers, are HAA's primary clients. By partnering with other countries for the construction, commissioning and operation of observatories, Canada, through NRC, provides Canadian astronomers with access to international telescopes. Additionally, HAA consults and collaborates with the Association of Canadian Universities for Research in Astronomy (ACURA) and CASCA to ensure its activities are aligned with the needs of the astronomy community.

- ***Observatory partners:*** HAA, on behalf of the Canadian astronomy community, collaborates with other countries and international organizations to establish partnerships for building, operating and managing international observatories.

[1] The international agreement to operate the Gemini observatory requires each partner country to establish a national office to participate in the observatory's operations. In Canada, the National Gemini Office (NGO) provides support to the Canadian astronomy community regarding the observatory's proposal process, capabilities and instrumentation.

- ***Industry:*** HAA works with Canadian and international companies in the development of major instrumentation and development projects. Typically, companies are contracted for the procurement of non-standard parts and assemblies.
- ***Canadian Space Agency (CSA):*** HAA collaborates with the CSA, providing scientific and technical resources to support the CSA and its industry contractors in international space-based astronomy projects.

2.3 Portfolio resources

2.3.1 Financial resources

Table 2 presents the overall expenditures and funding sources for HAA since FY 2012-13. During this period, HAA's programs generated a total of $9.96 million in revenues. More than a third of these revenues (37 percent) were produced in FY 2015-16, and are largely attributable to the Astronomy Technology Program (ATP) ($2.5 million) from projects for MeerKAT, Gemini High-Resolution Optical Spectrograph (GHOST) and CFHT SpectroPolarimètre Infra-Rouge (SPIRou).

Table 2: HAA financial profile (in $ millions)

	Fiscal years			
	2012-13	2013-14	2014-15	2015-16
Expenditures				
Salaries	14.08	14.58	13.83	14.08
Direct operations	4.50	4.73	5.18	6.89
Indirect operations & facilities	0.58	0.74	0.55	0.81
Total	**19.15**	**20.05**	**19.56**	**21.78**
Sources of funds				
Revenues	2.20	1.67	2.43	3.66
Appropriations	16.95	18.38	17.13	17.77
TMT funding	-	-	-	0.35
Total	**19.15**	**20.05**	**19.56**	**21.78**
Expenditures funded by other sources				
G&Cs	10.67	11.34	12.15	13.55
G&Cs – TMT	-	-	-	1.91
Minor capital	0.21	0.45	0.49	0.61

Source: HAA administrative data.
Note: Financial information for FY 2011-12 is not available due to changes to the NRC accounting structure as part of NRC's transformation.

2.3.2 Grants and contributions in support of International Telescope Agreements

Table 3 shows expenditures for each of the observatories in which Canada is a partner.

Table 3: International Telescope Agreements G&C expenditures (in $ millions)

Observatories	Fiscal years				
	2011-12	2012-13	2013-14	2014-15	2015-16
In operation					
CFHT	3.11	3.12	3.32	3.57	4.25
Gemini	5.56	5.67	6.11	6.59	7.33
JCMT	0.70	0.12	0.13	0.06	-
ALMA	0.79	1.43	1.40	1.57	1.58
Under construction					
TMT*	-	-	-	-	1.91
SKA	-	0.33	0.38	0.36	0.39
Total	**10.15**	**10.67**	**11.34**	**12.15**	**15.47**

Source: Financial data provided by NRC Finance Branch.
*While Canada made an initial $1.9 million contribution to the TMT project in 2015, the bulk of the TMT contribution is design work done by HAA staff directly or through contracts with industry to deliver HAA's "workshare" contribution to the TMT project (i.e., "in-kind" contribution and not a cash payment).

Expenditures for the observatories in which Canada is a partner increased 52 percent between FY 2011-12 and FY 2015-16, with one exception. Canada reduced JCMT support and eventually withdrew from the partnership in September 2014. JCMT funding was then redirected to support ALMA operations, as recommended by LRP2000.

Increases in financial contributions for observatory operations are influenced by three principal factors:

1) Exchange rate fluctuations

Canada's financial contributions to offshore observatories are adjusted in accordance with the value of the Canadian dollar relative to the currency specified in a given observatory's governing agreement. Fluctuations in foreign currency and exchange rates result in uncertainty when budgeting and estimating operations costs for Canada's offshore facilities. Based on findings from the interviews, this was the main contributing factor for the variations observed for the G&C funding envelope.

2) Changes in observatory budgets

Funding requirements for HAA are based on obligations arising from International Telescope Agreements (ITA). The budgets of the international observatories are approved by the respective observatory Boards, of which Canada is a member. These budgets fluctuate from year to year.

To manage the two issues described above, G&Cs reflecting approximately 90 percent of the anticipated annual cost of $10 million are set and then adjustments are made accordingly via supplementary estimates and internal transfers.[2]

[2] To meet its obligations each FY, NRC usually exchanges funding either through internal adjustments or through supplementary estimates. For example, NRC's Departmental Performance Report (DPR) for 2014-15 indicates that $2.2 million in additional funding was provided through the supplementary estimates process and an internal transfer from the

3) Increased funding provided for the construction and commissioning of TMT

ITA expenditures increased 27 percent in FY 2015-16 ($3.3 million) as a result of the commencement of annual in-kind contributions to TMT. In its 2015 Budget, the federal government confirmed its commitment to allocate $243.2 million over 9 years for the construction and commissioning of TMT, which includes $218.2 million through NRC and $25 million from the Canada Foundation for Innovation (CFI). This investment is expected to secure an estimated 15 percent stake in the $1.5 billion TMT project. The first financial contribution to the project ($1.9 million) was recorded in FY 2015-16. In line with Canada's 15 percent share in the project, NRC is expected to provide an estimated $6 million per year to TMT's annual operating costs once construction is complete, which is expected for FY 2026-27.

2.3.3 Human resources

Overall, the number of individuals employed by HAA decreased by 19 percent over the last five years, from 170 to 137, mainly as a result of the centralization of common support services (within NRC Common Services and Shared Services Canada (SSC)). In particular, there were reductions in Technical Support Staff (Computer Systems Administration and Technical Category) and Administrative Staff (Administrative Support). However, it should be noted that the number of core research staff, including Research Council Officers, Research Officers, and Research Associates, increased slightly during the evaluation period from 77 in 2012 to 81 in 2016.

3. RELEVANCE

The relevance of HAA was examined through four evaluation issues: HAA's alignment with the needs of Canadian astronomers (Section 3.1); the appropriateness of its delivery model for the administration and operation of Canada's telescopes to meet the needs of Canadian astronomers (Section 3.2); its alignment with the priorities of the federal government and NRC's strategic objectives (Section 3.3); and its alignment with federal roles and responsibilities (Section 3.4).

3.1 Alignment with the needs of Canadian astronomers

The evaluation assessed the extent to which HAA is aligned with the needs of Canadian astronomers. More specifically, the evaluation examined: HAA's consultations with the Canadian astronomy community to ascertain its needs; the rationale for investing in national and international telescopes; the demand for accessing Canada's offshore observatories; and the Canadian astronomy community's needs in terms of access to telescope data provided through the CADC.

3.1.1 Consultations with the Canadian and international astronomy communities

Needs of the Canadian astronomy community identified through consultations

Key Finding 1: *HAA's activities and priorities are closely aligned with the needs of the Canadian astronomy community.*

NRC Transfer Payment Program. Specifically, $1.8 million in the Portfolio's operating funds was converted into contribution funds and approximately $400,000 was transferred from NRC-IRAP.

To ensure its activities and investment priorities are aligned with the needs of the Canadian astronomy community, HAA takes guidance from CASCA's LRP2010 and regularly consults the Canadian and international astronomy communities. The LRP2010 Panel, commissioned by CASCA with support from National Science and Engineering Research Council (NSERC), NRC, CSA, CFI and ACURA, was mandated to engage the research community and identify investment priorities in astronomy and astrophysics. Canadian astronomer interviewees confirmed that HAA's activities are aligned with the recommendations and objectives outlined in LRP2010. A Mid-Term Review (MTR) of the LRP was undertaken in 2015 which reconfirmed the directions outlined in the 2010 plan.

LRP2010 outlined nine recommendations that are relevant to HAA's role in supporting Canada's involvement in ground-based instruments and observatories. Although HAA is not required to implement the recommendations, those recommendations which could be addressed (7 in total), have been. This suggests that the Portfolio is aligned with and has been responsive to the needs of the Canadian astronomy community.

Further, HAA regularly consults the Canadian astronomy community, through its involvement in various committees. HAA staff members are involved in the Canadian Time Allocation Committee (CanTAC) and various CASCA committees. Currently, CanTAC has 11 members from Canadian and American universities and two members from HAA. In addition, as of July 2016, HAA staff members participate in nine out of 11 CASCA committees. Involvement in these national astronomical organizations allows HAA to interact directly with the Canadian astronomy community and gain a better understanding of its needs.

<u>Perspectives on the need for an HAA advisory committee</u>

Key Finding 2: *There is a need to establish a formal consultation process, such as an external advisory committee, to allow the Canadian astronomy community to provide advice on HAA's activities and strategic priorities.*

Prior to the NRC Transformation, NRC institutes each had an advisory board which provided strategic advice on institute activities and priorities. The NRC Herzberg Advisory Board (HAB) provided strategic advice to the Director General (DG)[3] on HIA's programs and activities. More specifically, the board provided:

- expert guidance on trends and developments of relevance to HIA
- feedback on research, technology and innovation issues
- advice to management on strategic directions and priorities
- oversight on the alignment of HIA's programs with the priorities of the LRP
- support to HIA in fulfilling its national mandate

The HAB was dissolved in 2011, along with the other NRC Institute advisory boards. As a result, the astronomy community in Canada does not currently have a formal mechanism through which it can provide input to the Portfolio on priorities and objectives related to astronomy. The Mid-Term Review of the LRP2010 highlighted this issue and recommended that the NRC Herzberg Advisory Board, constituted of senior representatives of academia and industry, be restored to advise HAA on its activities and programs and to represent the astronomy community's interests more effectively (CASCA, 2016, p. 99).

[3] After the NRC Transformation, the title of Portfolio heads was changed from Director General (DG) to General Manager (GM).

Some internal interviewees and most external interviewees expressed support for the creation of a formal consultation process or mechanism, such as an external advisory committee, which would allow the Canadian astronomy community to provide strategic input on HAA's activities. However, key informants acknowledged that HAA does conduct informal consultations with the community.

Since NRC manages the national astronomy program, key informants noted that HAA's activities and strategic priorities should be determined in close consultation with Canadian astronomers, the Portfolio's core client community. A few key informants indicated that there is a need for more frequent consultations between HAA and the astronomy community (e.g., annually) given that the LRP and MTR processes are only every five years. According to key informants, the creation of an advisory committee has potential benefits, including:

- offering a level of transparency and oversight of HAA's activities
- fostering trust between HAA and its client community
- ensuring more frequent formal consultations between the Portfolio and the Canadian astronomy community with regard to priorities (i.e., annually as opposed to every five years)
- informing the community of ongoing challenges faced by HAA

On the other hand, a few key informants reported that creating an external advisory committee would likely result in additional financial costs (e.g., travel and accommodations for committee members) that may be incurred in HAA's operating budget. The creation of a new committee would also result in additional time commitments for HAA and the astronomy community, such as additional reporting requirements and meeting preparation. A few key informants noted that if a new consultation process was to be instituted, there may be a need to manage community expectations as it relates to the level of the committee's influence on HAA's activities. While the committee would provide strategic advice to HAA, it would not have direct authority over program activities (i.e., HAA is responsible for delivering NRC's mandate).

Recommendation 1: The Vice-President's Office (VPO) of Emerging Technologies – National Infrastructure and Future Technologies, in consultation with HAA, should consider establishing a formal consultation process to allow the Canadian astronomy community to provide strategic advice on the Portfolio's scientific activities and priorities.

Consultations with the international astronomy community

In addition to its consultations with the Canadian astronomy community, HAA is engaged in consultations with international partners, through its participation in the governance of international observatories. As of July 2016, HAA is represented at five international observatories: CFHT, Gemini, ALMA, TMT and SKA. Data indicates that a total of fourteen HAA representatives are members of twelve different boards and committees across the five observatories. Most importantly, HAA had at least one representative on the board and science advisory committee at each of the five observatories. This involvement allows HAA to gain a better understanding of the needs and requirements of observatory partners and to represent the interests of the Canadian astronomy community at the observatory level.

3.1.2 Need for international and national observatories

Key Finding 3: *There is a need for HAA to support administration and operation of telescopes to ensure that Canadian astronomers have access to world-class facilities.*

Need for international facilities

The evaluation confirmed the findings from the 2011 evaluation and the 2011 Hickling Arthur Low “Astronomy in Canada” study (HAL, 2011) that identified the importance of Canada’s contribution to international telescopes for:

- ***Cost-sharing between countries for increasingly expensive and complex research facilities and instruments:*** The scale, cost and technological complexity of building large telescopes are driving increased internationalization of observatory instrumentation and infrastructure development. As a result, Canada and other countries rely on international partnerships, which normally require financial and in-kind contributions, to operate and manage observatories.

- ***Providing contracting opportunities for Canadian industry and universities:*** For example, Canada’s investment in SKA and TMT will likely lead to new commercial benefits for Canadian companies and will result in opportunities to attract and retain highly skilled workers into Canada’s workforce (CASCA, 2016, p. 46; Doyletech 2014). Contracting opportunities also exist with CFHT, Gemini and ALMA.

- ***“Pay to play” principle:*** Through its financial and in-kind contributions, Canada is guaranteed observing time at the observatory and is given the opportunity to participate in the facility’s governance structure. This provides Canada with the ability to promote the interests of the Canadian astronomy community and to have some degree of influence over the scientific direction of the observatory.

- ***Accessing observatories to conduct competitive research:*** Canadian astronomers need access to world-class facilities to conduct competitive research, as highlighted by the LRP2010 (CASCA, 2010).

According to key informants, two additional reasons for supporting international observatories are:

- ***Collaborations:*** Observatory partnerships are multilateral in nature and involve partners from different countries. This enables researchers to facilitate knowledge and personnel exchange through research projects.

- ***Training of students:*** Access to international observatories is key to training students and providing them with experience in the field (e.g., preparing a proposal and conducting their own observations).

Need for national facilities

Supporting and operating Canada’s national observatories, DAO and DRAO, serves a number of purposes, including training students, contributing to science and supporting the development of instrumentation projects for Canada’s international observatories. Examples of how Canada’s national telescopes are contributing to new research and discoveries include:

- The DAO 1.8m Plaskett Telescope was fitted with a new polarimeter module (dimaPol) in 2012 which is being used to detect new magnetic stars and determine rotation periods and longitudinal magnetic field curves (Bohlender & Monin, 2013; Monin, Bohlender, Hardy, Saddlemyer, & Fletcher, 2012).

- Observations using the DAO 1.2m telescope are automated and are fitted for remote observing mode, allowing users to access the telescope remotely through the Internet. This feature has increased the telescope's subscription rate by 50 percent as telescope users no longer need to travel to the DAO to conduct their observations (Monin, Saddlemyer, & Bohlender, 2014).

- The DRAO 26m John A. Galt Telescope is one of the best telescopes in the world for studying the role of magnetic fields in the structure and physics of the interstellar medium (the matter that exists between star systems).

- DRAO's automated Solar Radio Flux Monitor provides values of the 10.7cm Solar Flux solar activity index to the CSA and Natural Resources Canada (NRCan), allowing data to be used by a number of agencies around the world, including the National Aeronautics and Space Administration (NASA), the National Oceanic and Atmospheric Administration, and the US Department of Defense (NRCan, 2015).

- The DRAO site is host to instruments from other partners requiring a radio-quiet environment, such as the university-led Canadian Hydrogen Intensity Mapping Experiment (CHIME) radio telescope, currently under construction, which will be used to measure the expansion of the universe.

- The national observatories also play a role in public outreach.

The DAO and DRAO facility staff also support instrumentation and technology development for international observatories supported by Canada and for other observatories around the world. Instrument development and integration for international telescopes is one of HAA's major activities, and one for which they are widely recognized. Close consultations between engineering and scientific staff from HAA programs during the instrumentation development process ensure the relevance and success of the instruments developed. For example, approximately 70 percent of the research time available at the Gemini Observatory employs instrumentation designed and constructed by HAA staff. More information about HAA's contribution to Canada's global standing in astronomical research, particularly as it relates to the development of instruments and technologies, can be found in Sections 4.1.1, 4.1.5 and 4.1.8.

3.1.3 Alignment of current suite of international telescopes with the needs of Canadian astronomers

Key Finding 4: *The current suite of telescopes supported by Canada is well aligned with the needs of Canadian astronomers.*

<u>Level of alignment</u>

The evaluation found that Canada's participation in international telescope agreements is aligned with the needs of Canadian astronomers. In fact, nearly all survey respondents (89 percent) "strongly agree" or "agree" that accessing international telescopes supported by Canada is critical to meeting their research needs. Survey respondents and key informants had a generally positive perception of telescopes supported by Canada. More than two thirds of survey respondents (68 percent) reported that the current suite of telescopes supported by Canada is aligned with their research needs. In terms of optical telescopes, Canada's involvement in CFHT (4m class telescope) and Gemini (10m class telescope), as well as its future involvement in TMT (30m class telescope), were described by several key informants as critical for Canada's role in advancing astronomy. For radio astronomy, some external key informants also commended Canada for its involvement in ALMA, which was described as having the potential to create whole new fields of astronomy.

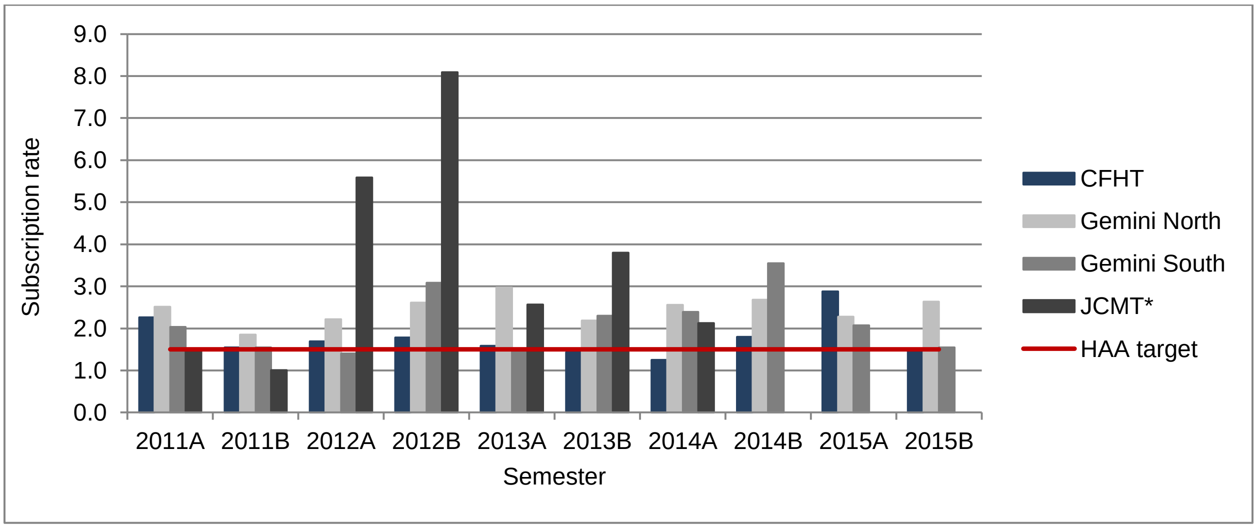
A few key informants, however, expressed dissatisfaction with the astronomy community's decision to withdraw from the JCMT, noting that Canada's smaller share in ALMA has led to challenges for Canadian astronomers applying for observing time. These same interviewees admitted the decision to withdraw from JCMT was widely accepted in the astronomy community and that NRC had adequately implemented the community's decision, as expressed in the LRP2000 and reiterated in the LRP2010.

<u>Subscription rates</u>

The standard measure of community demand for access to an observatory is its subscription rate, i.e., the ratio of time requested to time available (STF, 2014, p. 22). A subscription rate of greater than one (1.0) is an indication that demand exceeds time available.

Over the period of the evaluation, the average Canadian subscription rate for the international telescopes Canada supports was 3.03, well above HAA's target subscription rate of 1.5. As shown in Figure 1, Canada's offshore observatories were generally oversubscribed during this period and rarely fell below HAA's target subscription rate.

Figure 1: Canada's subscription rates for CFHT, Gemini North and South, and JCMT by semester



Source: HAA performance data.
*Subscription rates for JCMT are not available after semester 2014A since NRC withdrew from the JCMT partnership in September 2014.

ALMA has also been consistently oversubscribed since early science observations began in 2011. ALMA's time allocation process is based on cycles (which can vary from 9 to 16 months), which is much longer than a semester (usually 6 months). Therefore, data on subscription rates for Canadian Principal Investigators (PIs) to the observatory is shown separately in Table 4. The Canadian subscription rate for ALMA is high, averaging approximately 5.7 between Cycles 0 to 3, well above HAA's target.

Table 4: Canadian PI subscription rate for ALMA by cycle

Cycle	Start date	Subscription rate
Cycle 0	September 2011	11.68
Cycle 1	January 2013	3.33
Cycle 2	June 2014	3.89
Cycle 3	October 2015	3.91

Source: HAA performance data.

While Canada's offshore observatories were generally oversubscribed between 2011 and 2015, there have been notable fluctuations in the subscription rates over the past five years (as shown in Figure 1 and in Table 4). Aging instruments, the commissioning of new instrumentation, and moves by some observatories to larger survey programs, were identified by observatory partners as factors that may have an impact on subscription rates.

Access to other telescopes not supported by Canada

While evidence of demand for access and findings from key informant interviews reinforce the rationale for investing in Canada's current suite of telescopes, it should be noted that Canadian astronomers also access telescopes not supported by Canada. Results from the survey show that more than two thirds of respondents (69 percent) were awarded time on ground-based telescopes not supported through HAA's ITA Program between 2011 and 2015. Overall, 62 different observatories were accessed by survey respondents. When asked to describe the reasons for accessing these telescopes, approximately three quarters of respondents (76 percent) reported that the telescopes have instruments or capabilities that are not available with the telescopes currently supported by Canada.

Two key factors influence the decision to access telescopes outside Canada's current suite of observatories:

- a desire for multiple data sources from a diversity of telescopes and instruments
- the need to access telescopes with unique capabilities or which provide access to specific parts of the electromagnetic spectrum

Canadian astronomers gain access to other facilities either through the "open time" allocation (or "open skies" policy) of other observatories or through another country's allocation (by joining an international team). The concept of open access is fundamentally based on *quid pro quo* relationships between collaborators, whereby countries will gain access to other facilities as long as they have something to offer in return. Therefore, as long as Canada is perceived as "pulling its own weight" in terms of its support for science (i.e., by providing financial allocations to observatories through ITA or by developing telescope instrumentation) then Canadian astronomers will continue to be welcomed collaborators.

3.1.4 Astronomy community's needs in relation to accessing telescope data

Key Finding 5: *In order for Canadian astronomers to conduct ground-breaking scientific research in astronomy, there is continued need for Canada to invest in research data management infrastructure and capabilities (e.g., data storage, cataloging, networking, high-performance computing, software and data management skills).*

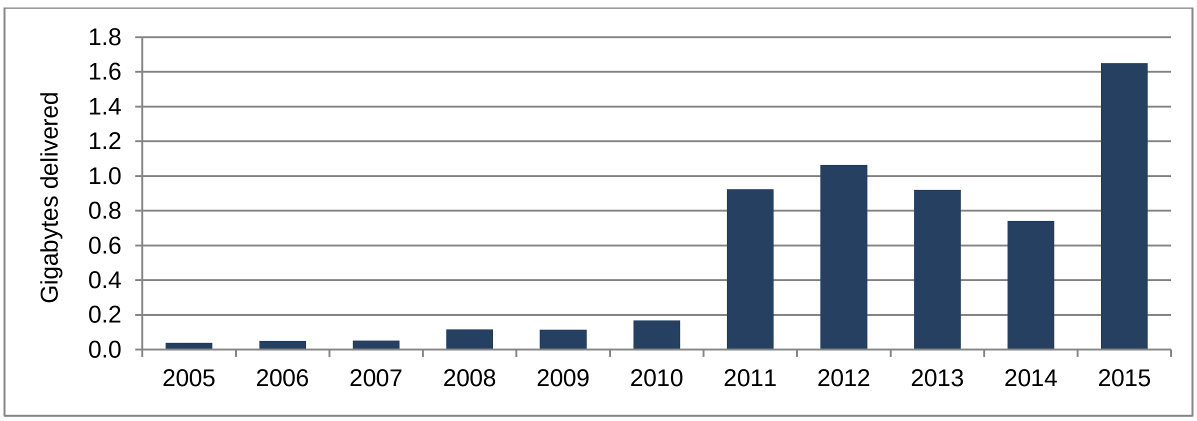
<u>Need for storage and the provision of access to data</u>

The Canadian Astronomy Data Centre (CADC) is the access point for researchers to retrieve their data after observations have been executed on many of the supported telescopes. However, ALMA and Gemini currently use their own data storage systems. In the case of specific observatories, such as CFHT, JCMT and other international telescopes, the CADC is responsible for protecting NRC investments by providing security for the data they produce. When considering the costs to plan, build and operate the supported telescopes, the CADC archives contain hundreds of millions of dollars' worth of data gathered over the last 40 years.

> *"You'll find increasing generations of young astronomers who want access to that data. It will be important years from now […] I just want to emphasize that this is a key component. We want to be sure that the whole entity is there for later generations. This is how discoveries are made."*
>
> Canadian astronomer interviewee

As shown in Figure 2, there has been an exponential increase in the data delivered to users over the last 10 years. During the period covered by the evaluation, the amount of data delivered annually by the CADC increased 79 percent.

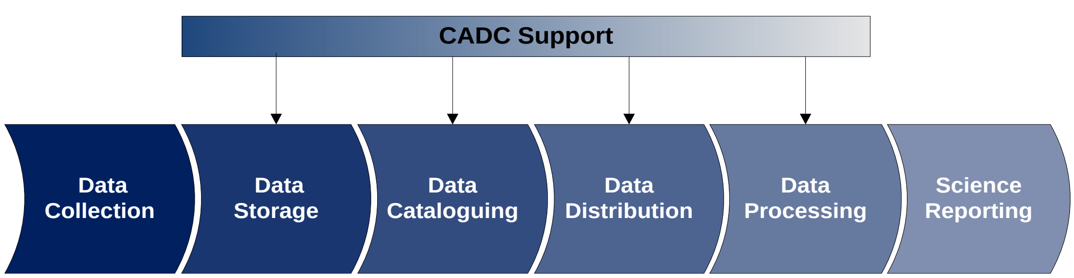
Figure 2: Data delivered by the CADC to users from 2005 to 2015 (in millions of gigabytes)



Source: HAA performance data
Note: Data used does not distinguish between Canadian and global use of the CADC.

Figure 3 illustrates the "Data to Knowledge" Flow Diagram, a simplified visualization of how HAA supports the astronomy community through the CADC.

Figure 3: Data to Knowledge Flow Diagram



- ***Data Collection:*** Observatories collect data under optimal weather conditions.
- ***Data Storage:*** Raw data is stored and data integrity is maintained by CADC.
- ***Data Cataloguing:*** Data is sorted and catalogued by CADC staff so that astronomers can easily search through and access the data that they need.
- ***Data Distribution:*** Data is downloaded by astronomers. Due to the large volume and traffic of data, there is a need for high speed networking to meet demand.
- ***Data Processing:*** Raw data is processed into meaningful information for use in generating new knowledge about the universe.[4] For some astronomers high-performance computing (HPC) is a critical component for processing this data. It should be noted that for certain observational data, CADC pre-processes the data prior to distribution so that it is science-ready, these are referred to as "advanced data products".
- ***Science reporting:*** The last step refers to the publication of papers.

Internal and external key informants noted that there is a need for 'advanced data products' (science-ready data). Processing larger sets of data ("big data") requires advanced knowledge in data management, such as the development of novel algorithms, which may be beyond the expected skill levels/areas of expertise of a given astronomer. For example, the Canadian astronomy community has a strong scientific interest in conducting large sky surveys that generate vast amounts of data. This is a driving force behind the need for pre-processed "advanced data products".

> *"CADC is fabulous. It allows me to do science rather than get caught up in the complexities and intricacies of the data. One can access data from other places, but using the CADC as the conduit has been the most satisfactory."*
>
> External interviewee

Need for advanced data management infrastructure

Interviewees indicated that Canada does not currently have the needed data management infrastructure (i.e., networking, data processing and storage) in place to manage data for the next generation of world-class observatories (e.g., SKA). The needs of the astronomy community have shifted beyond simple data storage and distribution to high-speed networking, high-performance computing, and the skills and software needed to process and analyze large volumes of data. Evidence from the evaluation indicates that the scale of observational data necessary to conduct leading-edge scientific research in astronomy is growing. As observatories become increasingly complex there is an accompanying need for complex infrastructure, such as data management equipment and services, networks, software and skills, to distribute and process large and complex observational datasets. This was the impetus for Canadian Advanced Network for Astronomical Research (CANFAR), an HPC cloud computing network solution for advanced research in astronomy (CASCA, 2016, p. 96). By working with partners to support CANFAR, HAA helps enable remote access to high-performance computing, throughput, and data storage for advanced data products.

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4 After approximately one year, the proprietary access period will end and the "telescope data product" will become available for use by other astronomers. Making archival data available increases the value from past observations allowing them to be reused, potentially for a completely different purpose.

The management and funding of Canada's high-performance computation and networks is a complex issue that spans local, provincial and federal jurisdictions, and implicates other research disciplines with similar needs for advanced computing and networking (CASCA, 2010, p. 49). Documents reviewed from CASCA's Computation and Data committee argued that "(f)uture research goals in astronomy will be held back without a consistent approach, and long-term, reliable funding for computing, data, and networks" (CASCA, 2012, p. 22). For example, the SKA telescope will place exceptional demands on processing and storage, producing petabyte to exabyte datasets, with daily data collection expected to be approximately 10 times the data of the current global internet traffic (SKAO, 2016). This demonstrates the continued need for advanced data management infrastructure to support ongoing access to astronomy data. Additional details regarding the CADC's current capabilities and challenges related to infrastructure and networking capacity are discussed in Section 4.2.4.

3.2 Appropriateness of current delivery model

To assess the relevance of HAA, the evaluation asked key informants whether other potential delivery models exist that could better service the needs of Canadian astronomers.

Key Finding 6: *There are benefits associated with the current delivery model. No other delivery model was identified as more appropriate for the administration and operation of Canada's telescopes.*

Key informants agreed that the current delivery model, whereby HAA is responsible for the administration and operations of Canada's telescopes, is appropriate. They also commended HAA's "excellent" work in supporting the Canadian community over the last five years.

These findings are contrary to the MTR 2016 which indicated that "serious consideration should also be given to the possibility that astronomy in Canada might be better served by an entirely new national organization" (CASCA, 2016, p. 98). According to the MTR 2016, this new organization could be created to address two key issues identified by the astronomy community in the report (CASCA, 2016, p. 99):

- the lack of clear and formal processes for the community to lobby the Canadian government for future telescope opportunities.
- the perceived impact of NRC's increased focus on industrial innovation on HAA's ability to deliver its mandate.

When asked whether a new model would address these issues, key informants did not agree with the MTR 2016 and noted that changing the model would not necessarily be a panacea for these problems. In terms of alternatives, a few key informants mentioned that ACURA could, hypothetically, play a role if the delivery model was to be reviewed. However, one interviewee noted that under such a scenario, ACURA would "need a significant evolution" and additional funding would be needed to pay for the increase in its operations.

While a more appropriate alternative model to the administration and operation of Canada's telescopes was not identified by key informants, the evaluation found that there are advantages associated with the current model:

- **Financial flexibility**: Being part of NRC allows HAA to access other internal sources of funding to minimize the financial impact resulting from devaluation of the Canadian dollar against other currencies.

- **Ability to negotiate and engage in international agreements**: As a federal government organization, NRC has the legislative authority to sign international agreements with third party organizations and to administer Grant and Contribution (G&C) funding.

- **Neutrality:** As a national entity, HAA equally represents the interests of all Canadian universities involved in astronomy, regardless of their size.

Some key informants noted that having a federal laboratory fully dedicated to operating facilities and conducting astronomy and instrumentation research is an excellent model. They explained that as the observatories and their instrumentation increase in value, duration and complexity, the stability and core expertise provided by a federal lab are particularly important.

3.3 Alignment with federal priorities and NRC strategic objectives

The evaluation assessed the extent to which the objectives and activities of HAA were aligned with federal government priorities and NRC's strategic objectives. It also examined the effect of NRC's transformation on HAA's outreach activities.

3.3.1 Alignment with federal priorities

Key Finding 7: *HAA's activities, including investment in international observatories, are aligned with federal government priorities.*

While astronomy was not explicitly identified as a key priority for the previous government, the announcement of the investment in the TMT project in Federal Budget 2015 underlined the importance of investing in astronomy projects. Former Prime Minister Stephen Harper announced that Canada was proud to be an official partner in the TMT and that the project "will advance Canadian and international scientific discovery" as well as "generate new capabilities and technologies in Canada which will help create and maintain high-quality jobs in communities across the country" (Government of Canada, 2015).

While the new strategic priorities of the current government have yet to be fully articulated in a formal strategy, the Minister of Science's Mandate Letter from the Prime Minister requests that the new Minister: "examine options to strengthen the recognition of, and support for, fundamental research to support new discoveries" (Office of the Prime Minister, 2015).

Further, the CADC initiative is aligned with Canada's federal science priorities, as its operations are innovative in the field of "big data'" and promote open science. The *2014 Federal Science and Technology Strategy* stated that "nations must swiftly … harness large and complex data systems ("big data") and adopt "open science" policies to foster collaboration" (Industry Canada, 2014, p. 1).

3.3.2 Alignment with NRC's strategic objectives

Key Finding 8: *Although HAA's mandate is reflected in NRC's Strategy, the alignment between HAA's activities and the objectives of NRC and the Emerging Technologies Division is unclear.*

<u>Alignment with objectives of NRC and the Emerging Technologies Division</u>

NRC's Strategy 2013-2018 focuses on market-driven innovation outcomes and benefits to Canada. The strategy describes four business lines, one of which includes the provision of access to world-class science infrastructure, enabling clients to effectively use some of Canada's most specialized, large-scale scientific infrastructure. This aligns with HAA's mandate.

However, according to many internal key informants, HAA is not aligned with NRC's overall strategic goal to "spur economic prosperity by delivering technology development programs and specialized national facilities and services, all with an eye to boosting industrial R&D". Further, some internal key informants feel that HAA's core mandate, to provide access to scientific infrastructure to generate key discoveries and scientific knowledge, is not aligned with the objective of the Emerging Technology Division, which is "to understand, anticipate and build capacity to address emerging markets with technologies essential to Canada's future industrial and societal needs".

Evidence shows that HAA is supporting industrial R&D through the engagement of Canadian firms to develop, manufacture and install telescope instruments for national and international observatories. However, its primary aim is to serve the astronomy community.

3.3.3 Impact of NRC's transformation on HAA's outreach activities

Key Finding 9: *HAA's ability to conduct outreach activities was limited over the last five years, particularly as a result of the decision to close the Centre of the Universe.*

Public outreach and awareness are considered by HAA stakeholders as an integral part of the Portfolio's activities. NRC's transformation to a Research and Technology Organization (RTO) in 2012 primarily affected HAA by changing its organizational structure (from an institute model to a portfolio model). According to internal stakeholders, this change has limited its ability to engage in outreach activities.

Additionally, the evaluation found that some NRC-level decisions largely affected HAA's outreach activities, particularly the 2013 NRC decision to close the Centre of the Universe.[5] This decision was based on financial considerations and the view that the public outreach mission of the Centre of the Universe was not aligned with the mandate of the HAA programs. The Portfolio is exploring alternative operating models for the Centre of the Universe, such as, for example, by recently signing a License to Occupy with the Friends of the Dominion Astrophysical Observatory, a non-profit organization, for use of the Centre of the Universe for public outreach purposes. However, in spite of these efforts, access to the centre continues to be limited.

Recommendation 2: HAA should continue to work with partners to expand outreach and awareness activities.

3.3.4 Collaborations with other NRC Portfolios

Key Finding 10: *There were some informal interactions between HAA and other Portfolios over the last five years. While future opportunities for collaborations and knowledge exchange may exist, HAA and the other Portfolios of NRC need to better understand each other's capabilities, activities and needs.*

There were no formal collaborations between HAA and the other NRC Portfolios from 2011 to 2015. As one indicator of formal collaboration, SAP data provides information on labour sharing between portfolios (i.e., labour in dollars received from and sent to other portfolios) for FYs 2013-14 and 2015-16, the only period for which data is available. Overall, the data shows that

[5] The Centre of the Universe was the public interpretive centre for the DAO that was regularly open to the public between May and September.

the average amount of labour shared between NRC portfolios over the three-year period was approximately one million dollars per portfolio per year, whereas HAA was shown to have none. According to internal key informants, this dissimilarity can be explained by the high rate of staff utilization, a lack of awareness of competencies available in other portfolios and difference in mandates. However, key informants provided some anecdotal evidence of informal interactions with other NRC portfolios. For example, a key informant noted that HAA provided low noise amplifiers (LNAs) to support research by the Security and Disruptive Technologies (SDTech) Portfolio.

Further, one key informant indicated that attending the NRC's Tech-X event helped increase his awareness of what was available and potential opportunities for collaboration in the field of photonics. However, he believed that his team's current workload would not allow him to pursue these potential collaborations.

Recommendation 3: HAA, in collaboration with other NRC Portfolios and NRC Business Management Support (BMS), should explore opportunities to leverage competencies and astronomy-related technologies.

3.4 Alignment with federal roles and responsibilities

The evaluation assessed the extent to which the strategic objectives and activities of HAA were aligned with federal government roles and responsibilities.

Key Finding 11: *HAA's activities and strategic outcomes are aligned with federal roles and responsibilities, as expressed in the National Research Council Act.*

The National Research Council Act states that the Council may "operate and administer any astronomical observatories established or maintained by the Government of Canada" (Justice Canada, 2009). Documentation reviewed as part of the evaluation support the role played by the federal government in administering Canada's national and international telescopes. Large-scale, multi-national endeavours generally require the federal government to be a signatory and NRC has a well-recognized role as the Canadian signatory in international astronomy agreements.

> *"Without an organization like [HAA], Canada could not be a credible and productive partner in major international observatory facilities."*
>
> *LRP2010 (CASCA, 2010, p. 38)*

4. PERFORMANCE

The evaluation assessed HAA's performance in terms of its effectiveness (Section 4.1) and efficiency and economy (Section 4.2).

4.1 Effectiveness

To assess HAA's effectiveness, the evaluation examined the Portfolio's success in providing Canadian astronomers with access to national and international observatories and science data products, its involvement in next-generation telescopes, its contribution to the development of observatory instrumentation, the industry impacts of instrumentation projects, as well as the productivity and scientific impact of Canada's offshore telescopes.

4.1.1 Access by Canadian astronomers to national and international telescopes

<u>Observation time awarded to Canadian astronomers</u>

Key Finding 12: *HAA's involvement in offshore observatories, mainly through financial support and contributing to the development of instrumentation and infrastructure, is critical to ensuring that Canadian astronomers are able to access international telescopes to conduct their research.*

Key Finding 13: *Observing time awarded to Canadian astronomers at ALMA is not commensurate to Canada's financial contribution to the observatory's operations.*

CFHT, Gemini and JCMT

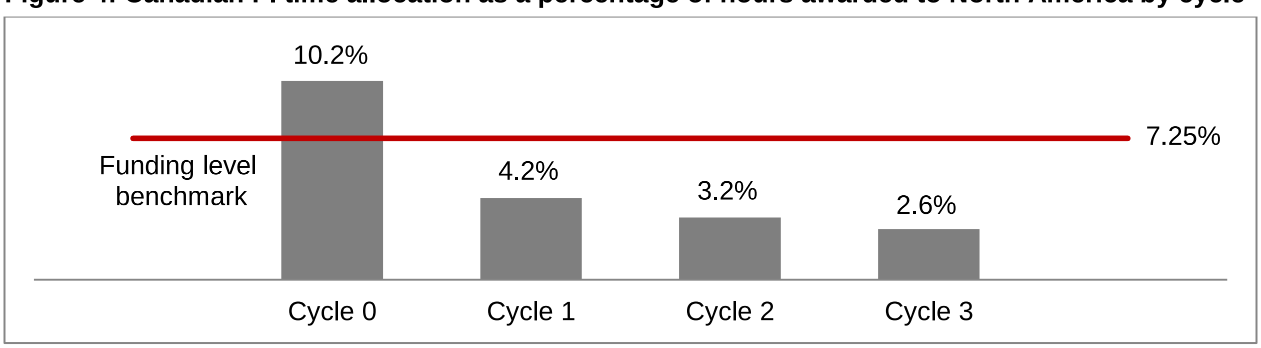
Through its funding support to observatory operations, Canada is guaranteed a proportion of the total time available for each facility's telescope. Currently, Canada is allocated 42.5 percent of the observing time available at CFHT and 17.8 percent of the observing time available at Gemini (CFHT, n.d.; Gemini Observatory, 2014). Before withdrawing from the JCMT partnership in 2014, Canada's share of the observing time at JCMT was 25 percent (CASCA, 2014a). HAA representatives confirmed that the time awarded to Canadian astronomers at CFHT, JCMT and Gemini during the period covered by the evaluation was consistent with the fraction of time earmarked for Canada at the observatories.

ALMA

ALMA is a partnership of Europe, North America and East Asia in cooperation with the Republic of Chile. The North American portion of the partnership, which includes NRC HAA, the NRAO and the National Science Council of Taiwan, provides annual funding to ALMA representing approximately 37.5 percent of the total funding allocation from all ALMA partners. Canada's annual funding is approximately 7.25 percent of the North American portion of ALMA funding. Canada's allocation gives Canadian astronomers access to the North American portion of ALMA time. Unlike CFHT and Gemini, there is no portion of time earmarked specifically for Canadian astronomers.

As discussed in Section 3.1.3, the Canadian PI subscription rate for ALMA time is significant, averaging approximately 5.27 between Cycles 0 to 3, which ran from 2011 to 2015. During this period, Canadian PIs were awarded a total of 66.2 observing hours at the facility, representing approximately 4 percent of the hours awarded to all North American researchers during this period. However, data indicates that the proportion of time awarded to Canadian PIs is not commensurate to Canada's annual funding support to ALMA. Data is presented in Figure 4.

Figure 4: Canadian PI time allocation as a percentage of hours awarded to North America by cycle



Source: HAA performance data.

It should be noted that ALMA time allocated to PIs is based on merit and through a peer review process that includes Canadian astronomers as proposal reviewers. It should also be noted that Canadian astronomers have been successful in obtaining observing time at ALMA through other means, mainly as collaborators, or co-Investigators, on other research teams, including those outside North America. Overall, Canadian co-Investigators were awarded a total of 581 hours between 2011 and 2015, which represents 11.3 percent of the global time allocation at ALMA during this period. Additionally, Canadian astronomers were co-authors on 13 of the top 30 most cited ALMA papers.

While the time allocated to Canadian PIs has decreased during the evaluation period, HAA management indicated that ALMA is a newly operating telescope (operational since 2011) and that the allocation to Canadian PIs is expected to improve with time. However, since there is no portion of time earmarked specifically for Canadian astronomers (i.e., commensurate with Canada's funding support to ALMA), further consideration should be given to identifying barriers, if any, that are impacting Canadian PI access to the observatory and finding potential solutions to improve access.

Recommendation 4: HAA should identify the reasons why Canadian PIs are not allocated observing time commensurate with Canada's financial support to ALMA operations and take the appropriate measures identified, as needed.

<u>HAA's involvement in and contribution to next generation telescopes</u>

Key Finding 14: *HAA's participation in the pre-construction and construction phases of next generation telescopes is important to securing Canadian access to observatory facilities.*

The extent to which a country's researchers are able to gain access to an observatory facility is related to that country's financial and in-kind contributions to the facility. HAA and the Canadian astronomy community are significantly involved in the planning of two major new observatories, TMT and SKA. A brief description of Canada's involvement and contributions to both observatories is provided below.

TMT

The TMT project began in 2003 as a collaboration among ACURA, the California Institute of Technology (Caltech), and the University of California (UC). Federal and provincial partners, including NRC, provided an estimated $31 million in funding to support the design and pre-construction phases of the project. These pre-construction activities were managed by ACURA in consultation with HAA. In April 2015, the Government of Canada announced an allocation of $243.2 million over 9 years to NRC for the construction and commissioning of TMT and, consequently, NRC assumed responsibility for Canada's participation in the observatory. Further, representatives from the Canadian astronomy community and HAA are members of the TMT's Board of Governors and Science Advisory Committee.

Through its participation, Canada is making two major contributions to the construction of the TMT:

- ***TMT enclosure:*** Dynamic Structures Ltd., located in Port Coquitlam, BC, is responsible for the design and construction of the enclosure. The observatory enclosure will be spherical with a circular aperture to match the telescope reflector's field of view, which will be essential in preserving the TMT's image quality and will reduce the mass of the facility, resulting in lower costs (CASCA, 2014c, p. 14).

- ***Narrow Field Infrared Adaptive Optics System (NFIRAOS):*** HAA, in collaboration with industry, is developing the AO system for TMT. The system is integral to the TMT observatory as it corrects degradations in image quality that result from observing objects through the Earth's atmosphere and from aero-thermal and optical imperfections within the observatory itself, resulting in sharp and stable images (CASCA, 2014c, p. 7). Further, NFIRAOS will support other TMT instruments, ensuring that the instruments achieve their specified performance (CASCA, 2014c, p. 9).

Portfolio documentation also indicates that an Integration and Test (I&T) facility is expected to be built in Victoria to support TMT instrumentation projects. These contributions will provide Canadian astronomers with access to the telescope and will enable Canada to play a significant role in defining the future operation and capabilities of TMT (CASCA, 2014c, p. 14).

Construction of the TMT began in October 2014 on Mauna Kea in Hawaii. However, on-site work has been on hold as of December 2015.[6]

SKA

Canada, represented by NRC, formally joined the SKA Organization (SKAO) in early 2012 and is committed to delivering in-kind work for the SKA pre-construction phase, which began in 2013. The ACURA Advisory Council on the SKA (AACS), which includes representatives from universities and industry, is responsible for overseeing Canadian participation in SKA.

As part of Canada's contribution to the pre-construction design work for SKA, HAA is contributing to the following projects (CASCA, 2014b, pp. 3–4):

- ***Digital signal processing:*** HAA is leading the Central Signal Processor (CSP) Consortium for designing the correlators and beamformers as well as non-imaging pulsar search and timing processors.

- ***Phased-array feeds (PAF):*** HAA is involved in the work to demonstrate PAFs on dishes, focusing on cryo-cooled PAFs.

- ***Low noise amplifiers (LNA) and RF digitizers:*** HAA has developed cryogenic LNAs that will be part of the EMSS L-band and Ultra high frequency (UHF)-band receivers on MeerKAT. Further, as part of the Dish Consortium work, HAA is responsible for the digitizers for single-pixel feed.

- ***Telescope management:*** HAA is involved in the design of the SKA1 monitor and control system as well as interfaces of the SKA Telescope Manager.

Additionally, the Canadian astronomy community and HAA have representation on SKA's Board of Directors, Science and Engineering Advisory Committee, Science Review Panel and 11 of the 13 SKA science working groups.

[6] Additional information regarding the status of the TMT project is available on the TMT Organization website: http://www.tmt.org/

4.1.2 Access by Canadian astronomers to science data products

Key Finding 15: *Through the CADC, HAA has been successful in providing astronomers with access to science data. Further, CADC's data management has contributed to increasing research productivity (scientific output) of Canada's offshore telescopes.*

<u>Data management services provided by the CADC</u>

HAA uses the 'number of refereed publication acknowledgments of the CADC' as a proxy indicator for its contribution to scientific impact in astronomy. The annual number of acknowledgments referring to the CADC has increased by 55 percent over the last five years, going from 120 in 2011 to 186 in 2015. The increase in data delivered to users (as shown in Figure 2 in Section 3.1.4) and global acknowledgments of the CADC in astronomy literature demonstrate that the CADC is successfully providing astronomers with access to science data and advanced data products.

The evaluation identified several notable scientific impacts resulting from the use of CADC archives, such as:

- **Archival research using CFHT data:** Between 2013 and 2015, research papers utilizing CFHT archival data represented over a third of CFHT papers produced (CFHT, 2016c). These publications show that the CFHT — despite being a 4m class telescope operating in an environment of 8-10m class telescopes — remains scientifically competitive in terms of publications output (as shown in Figure 5 in Section 4.1.3).

- **Identification of instrument degradation at CFHT:** In late 2014, a CADC staff member used archival data to identify a discernible drop in the amount of light collected by a key instrument, leading to the early discovery and subsequent repair of a degrading component in its most popular instrument (CFHT, 2016a; CADC, 2016b).

- **The New Horizons space probe:** Launched by NASA in early 2006, the probe visited the dwarf-planet Pluto in July 2015. Archival data from the CADC fed into NASA's navigation process, aiding the guidance of the probe on a collision-free approach during its encounter (CFHT, 2015; CADC, 2016a).

> *"[The CADC is] more than just a data store; they are a partner in how we get data out, and publications out."*
>
> Observatory partner

<u>Development of advanced data products</u>

The evaluation highlighted several HAA contributions to the development of advanced data products. Key informants described the CADC's work in providing advanced data products as follows:

- Data provided by the CADC is "science-ready", making it more useful for researchers.
- CADC is one of the few astronomy data archives that provides semi-processed stacked data, describing it as "a mine ready to be tapped."
- Large surveys, such as the CFHT Legacy Survey, are critically dependent on the data management services provided by the CADC to process the data.

- CADC's search and imaging preview capabilities are useful as they enable astronomers to efficiently judge if the quality of underlying data is sufficient to answer a specific scientific question.

CANFAR's cloud computing solution is a key evolution in how the CADC serves the Canadian astronomy community. Since 2011, over 500 publications cite CANFAR support (CASCA, 2016, p. 96). The evaluation identified several notable results from HAA's collaboration in CANFAR, such as:

- The Next Generation Virgo Cluster (NGVC) survey gathered a large data set from over six years of observations with the CFHT. The CADC, through CANFAR, provided support to the NGVC team enabling them to archive and process their massive data set (University of Victoria, 2012).

- In 2014, CADC data analyzed through CANFAR led to the identification of a Kuiper Belt Object (KBO) with a diameter of approximately 30 km and within reach of NASA's New Horizons space probe. NASA may visit this object in January 2019 (CANARIE, 2014).

<u>Factors hindering HAA's ability to provide access to science data products</u>

The evaluation identified two main factors hindering HAA's ability to provide the astronomy community with access to science data products:

- outdated IT infrastructure, such as servers and storage systems equipment, supporting the CADC.
- limited network capabilities available to the CADC (there is a need to upgrade from one gigabit per second to 10 gigabits per second).

Additional details regarding these issues are provided in Section 4.2.4.

4.1.3 Observatory productivity and impact

Key Finding 16: *Canada's offshore observatories have performed well internationally in terms of productivity and impact (i.e., the relevance of observatory publications).*

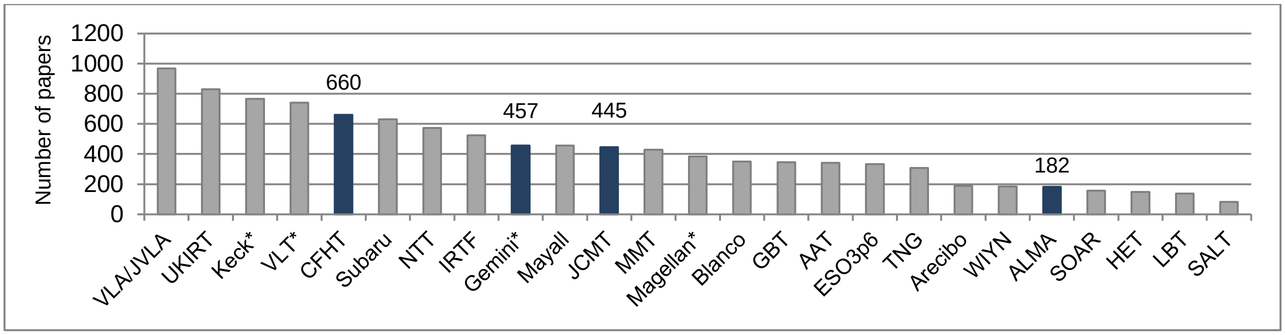
As one indicator of performance, the evaluation consulted various bibliometric data provided by HAA to assess the performance of Canada's offshore observatories, specifically in terms of publication outputs and impacts. The evaluation's findings are provided below.

<u>Productivity – number of papers produced annually</u>

The number of papers produced annually by a telescope represents a measure of its contribution to the generation of new knowledge and the return on capital investment for the construction of the telescopes and their instruments (Crabtree, 2008). To provide an accurate assessment of an observatory's performance, productivity is examined in conjunction with the observatory's impact, which is measured through citation counts of the papers it produces. Observatory impact is discussed in greater detail in the next section.

Figure 5 presents the productivity, in terms of papers produced annually, of Canada's offshore observatories and 21 other international telescopes between 2010 and 2014. Overall, two of Canada's observatories were ranked amongst the top-10 in terms of productivity during this period: CFHT ranked fifth and Gemini ranked ninth. While ALMA is twenty-first overall, the observatory's productivity has increased progressively year over year since it began operations in 2011 and is expected to continue to do so as the observatory's scientific operations ramp up.

Figure 5: Normalized number of papers published for Canada's offshore telescopes and other international ground-based observatories, 2010 to 2014

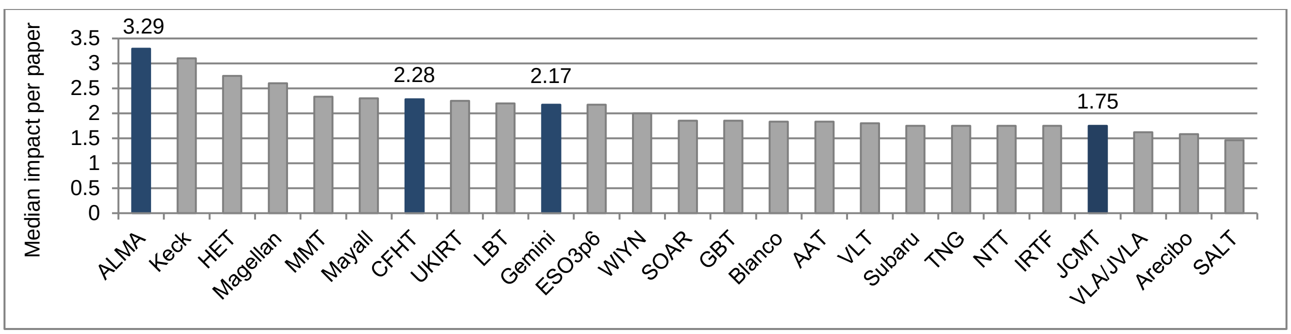


Source: HAA performance data.
*Some observatories have more than one telescope. In order to normalize the results, the number of papers produced by each observatory was divided by the number of telescopes. For example, VLT consists of four telescopes, while Gemini, Magellan and Keck have two.

Impact – count of citations

Citation counts (i.e., the number of times a paper is cited in literature) are used to measure an observatory's impact in terms of the relevance of the papers it produces (Crabtree & Zhang, n.d.). Figure 6 presents the median[7] number of citations per paper for Canada's offshore observatories and 21 other international telescopes. Overall, data indicates that three of Canada's observatories are amongst the top-10 in terms of median impact per paper, with ALMA ranked first overall followed by CFHT in seventh place and Gemini in tenth place.

Figure 6: Median impact per paper for Canada's offshore telescopes and other international observatories, 2010 to 2014

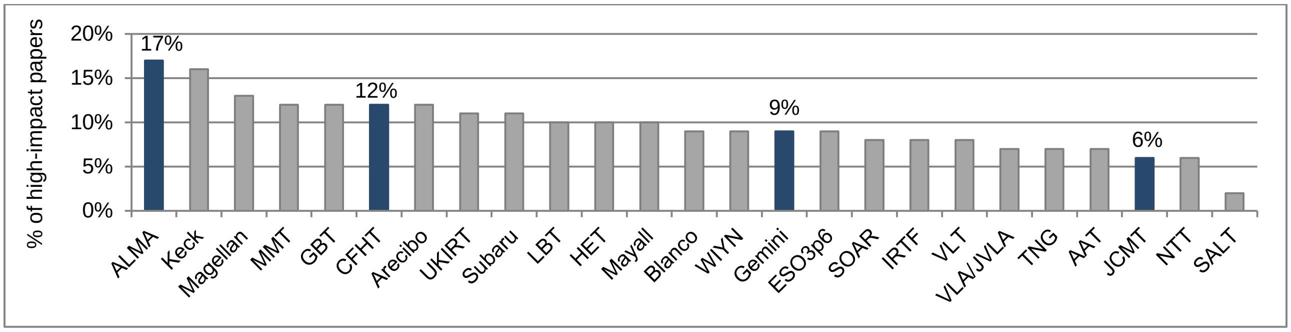


Source: HAA performance data.

Another measure of relevance is the number of "high-impact papers" produced by an observatory (i.e., papers in the 90th percentile for number of citations or the top 10% most cited papers). Figure 7 presents the percentage of papers that are considered "high-impact" for Canada's offshore telescopes and other international observatories. Overall, two of Canada's observatories are amongst the top-10 observatories, including ALMA in first place and CFHT in sixth place.

7 To assess an observatory's impact, the analysis relies on the median impact per paper rather than the average impact per paper, as the latter can be skewed by a small number of very high impact papers. It should be noted that data on impacts are not normalized.

Figure 7: Percentage of high-impact papers for Canada's offshore telescopes and other international observatories (90th percentile), 2010 to 2014



Source: HAA performance data.

4.1.4 Examples of scientific impact and key discoveries

Key Finding 17: *The use of Canada's international observatories has resulted in a number of important discoveries over the last five years.*

Evidence indicates that the use of Canada's offshore observatories has resulted in significant discoveries over the last five years. Data gathered from program documentation and key informant interviews provide a number of examples of scientific impact resulting from the use of Canada's international telescopes. Examples of key discoveries are presented in Table 5.

Table 5: Examples of discoveries resulting from the use of Canada's offshore observatories

Discovery	Description
ALMA	
Images of protoplanetary disc surrounding HL Tauri	In 2014, astronomers captured, what is considered to be, the best ever image of planet formation around an infant star. The image revealed, in fine detail, the planet-forming disc surrounding HL Tauri, showing multiple concentric rings separated by clearly defined gaps. These observations provide valuable information on the planet-formation process (ESO, 2014; NRAO, 2014).
CFHT	
Discovery of dwarf planet 2015 RR245	In February 2016, an international team of astronomers, led by a researcher from HAA, discovered a dwarf planet, approximately 700 km in diameter, orbiting in the Kuiper Belt.. 2015 RR245 is one of the largest worlds beyond Neptune to be identified. This discovery, coming from the Outer Solar System Origins Survey (OSSOS) which uses CFHT's MegaPrime/MegaCam, allows astronomers to gain a better understanding of the history of the Solar System (CFHT, 2016b).
Pan-Andromeda Archaeological Survey (PAndAS)	The Pan-Andromeda Archaeological Survey (PAndAS), led by an HAA researcher and conducted at CFHT, provided the largest and deepest panoramic image ever obtained of a galaxy that is similar to the Milky Way. The project has resulted in the discovery of a large number of new structures: • Approximately 20 new "satellite" galaxies that appear to map out an enormous "ring", and appear to be rotating uniformly around Andromeda. This coordinated behavior was completely unexpected and cannot currently be explained. It implies a fundamental misunderstanding of the process of how galaxies form. • Approximately 100 new "globular clusters", each of which contains millions of stars. (The survey results increased the number that was known to exist by about 25%) • Many new stellar "streams" (i.e., the remnants of small galaxies that have since been "ripped apart" by Andromeda). While researchers suspected that this process

Discovery	Description
	was occurring, it was not clear how often it takes place; the survey results have proven useful in trying to understand the importance of this process.
Gemini	
Discovery of supermassive black holes at the centre of galaxies NGC 3842 and NGC 4889	In 2011, observations using the Gemini North telescope provided evidence of the largest black holes ever measured in our nearby cosmological neighbourhood in the galaxies NGC 3842 and NGC 4889. Both black holes are approximately 10 billion times more massive than the Sun. The research is expected to provide information on how black holes and galaxies form over the history of the universe (Gemini Observatory, 2011; NSF, 2011).

For more comprehensive lists of discoveries consult the websites: (ALMA) http://www.almaobservatory.org/en/press-room/press-releases, (CFHT) http://www.cfht.hawaii.edu/en/news/, (Gemini) http://www.gemini.edu/science/publications/index.html

4.1.5 Contribution to the development of novel instruments and technologies

Key Finding 18: *HAA has been involved in and has made significant contributions to the design and development of world-class instruments and technologies for Canada's observatories and for other observatories around the world. Further, the utilization of these instruments has resulted in a number of scientific impacts and discoveries.*

ATP staff have developed or contributed to the development of a total of 11 instrumentation projects undertaken for seven observatories over the last five years. Three of the instruments developed by HAA since 2011 were examined as part of the case studies, including:

- ***ALMA Band 3 cryogenic receivers:*** HAA collaborated with Canadian industry to develop and manufacture a suite of ultra-low noise 84–116 GHz cryogenic heterodyne receivers. The receivers play a role in array commissioning and are the most commonly used band for science observations. HAA is responsible for the ongoing maintenance of the receivers.

- ***Gemini Planet Imager (GPI):*** An imaging instrument installed at the Gemini South telescope, the GPI achieves high contrast at small angular separations, allowing for the direct imaging and integral field spectroscopy of extrasolar planets around nearby stars. The instrument is considered the most advanced of its kind for imaging and analyzing planets around other stars. HAA staff provided the optical-mechanical structure, mechanical control software and system engineering for the instrument.

> *HAA staff "have leading international reputations for developing innovative cutting-edge instrument designs and delivering highly reliable instruments on time and on-budget". As well, the instruments developed by HAA "are on a scale that cannot be duplicated in university labs."*
>
> LRP2010 (CASCA, 2010, pp. 38–39)

- ***Wideband Interferometric Digital Architecture (WIDAR) Correlator:*** HAA staff were responsible for developing WIDAR, the signal processing correlator responsible for combining the signals from each of the Jansky Very Large Array's (JVLA) 27 antennas. The correlator is one of the most powerful machines of its kind in the world. For example, it can perform 10^{16} calculations per second (10 petaflops) and has the capacity to process the equivalent of about 50 million simultaneous telephone calls.

Findings from the case studies indicate that these instruments have greatly improved their respective observatories capabilities and have made significant contributions to a number of discoveries since 2011.

Some key informants characterized HAA as a world leader in designing and developing observatory instrumentation, particularly in adaptive optics systems, digital systems design and fine guidance sensors. For example, HAA's design and development of the WIDAR correlator for the JVLA established its reputation in digital system design and delivery, and provided the experience which underpinned the Portfolio's involvement in the SKA CSP consortium (CASCA, 2014b, p. 3).

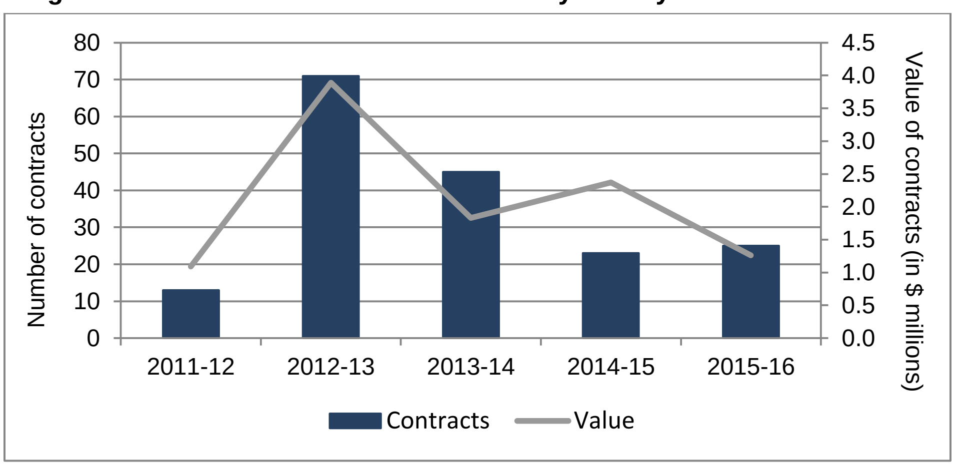
4.1.6 Industry collaborations and impacts

Key Finding 19: *HAA's involvement in international observatories has allowed Canadian companies to contribute to the development of telescope instrumentation and to benefit from financial returns and enhanced expertise and technological capabilities.*

HAA engages industry primarily through the provision of procurement opportunities. Therefore, assessing HAA's contribution to industrial R&D differs from other portfolios in that revenue may not be the most appropriate indicator of the Portfolio's engagement with and impact on industry.

Canada's participation in international telescope agreements provides Canadian firms with the opportunity to bid on Requests for Proposal issued by either the partner observatories or by HAA. Between FY 2011-12 and FY 2015-16, HAA awarded a total of 177 contracts, valued at approximately $10.4 million, to 104 institutions and companies for the provision of services to support various research and instrumentation projects. There was a peak in the number of contracts in FY 2012-13, mainly as a result of the addition of 36 contracts for SKA-related projects, including the DVA1 and CSP projects, valued at $1.6 million. Contract data is presented in Figure 8.

Figure 8: Number and value of contracts by fiscal year



Source: HAA administrative data.

Between FY 2011-12 and FY 2015-16, nearly all of the contracts (88 percent), valued at $9.04 million, were awarded to private sector firms. Universities also benefited from contracts with HAA, with 22 contracts, valued at roughly $1.4 million, awarded to these institutions.

In addition to the financial benefits discussed above, evidence from the key informant interviews and case studies shows that HAA's work with companies has strengthened their industrial research capacity and provided them with access to specialized equipment and training. Table 6 provides examples of companies and organizations that have benefited from their involvement in telescope projects. Industry stakeholder interviewees noted that they would not have obtained the contracts for the instrumentation projects had it not been for HAA's direct involvement in the observatories. They noted that it is difficult to obtain contracts for astronomy instrumentation and infrastructure projects outside of Canada as foreign governments and astronomy organizations tend to award contracts to domestic companies.

Table 6: Examples of Canadian companies involved in telescope instrumentation projects

Name of Firm	Description of contribution and impacts
Nanowave Technologies Inc., Etobicoke, ON	Nanowave Technologies successfully produced highly customized components for the ALMA Band 3 receivers (briefly described in Section 4.1.5). Nanowave representatives reported that, as a result of the company's involvement in the development of the ALMA Band 3 receivers, they gained new capabilities, know-how and specialized skills related to the development of cryogenically cooled LNAs and precision wire bonding. NRC licensed the LNA technology to Nanowave, enabling the company to manufacture the amplifiers. Currently, Nanowave is working with HAA for the development of LNAs for MeerKAT radio telescope.
FiberTech Optica Inc., Kitchener, ON	FiberTech Optica Inc., in collaboration with HAA, built the fibers for the Gemini Remote Access to CFHT ESPaDOnS Spectrograph (GRACES) instrument. As a result of its involvement in the project, the company gained know-how related to the design and development of optical fiber cables. The company is now developing similar cables for the National Astronomical Observatory of Japan and for postsecondary institutions in the US, including Yale University and MIT.
Dynamic Structures Ltd. (DSL), Port Coquitlam, BC	DSL designed and built enclosures for a number of observatories around the world, including Gemini and CFHT. The company was subsequently able to translate its expertise and experience in building observatory enclosures to become a world leader in the design and manufacturing of amusement park rides. DSL was selected in 2015 by the federal government to design, build and deliver the precision-steel enclosure for TMT and will receive an investment of up to $70 million for that purpose (Empire, 2015, n.d.; ISEDC, 2015).
Institut national d'optique (INO), Ville de Québec, QC	As a result of its collaborations with HAA, INO has: • helped develop, build and test the optics for GPI (Université de Montréal, 2015). • built the calibration unit for Raven Multi-Object Adaptive Optics (MOAO). • been awarded four contracts for engineering and design services for various NFIRAOS subsystems, including the off axis paraboloid, beamsplitter, instrument selection mirror, and turbulence generator (PWGSC, 2014a, 2014b, 2015a, 2015b). According to an INO representative, HAA offered a one year internship to one of INO's scientists, which allowed them to gain experience in designing adaptive optics and in testing instruments operating at low temperatures.

<u>Projected economic impacts of Canada's participation in TMT and SKA</u>

In 2014, NRC commissioned the Doyletech Corporation to conduct a study to assess the commercial value and potential commercial applications of astronomy-related technologies under development by HAA for the TMT and SKA projects. The study found that technologies being developed for TMT and SKA have the potential to be applied to a number of fields. For example:

- AO technology for TMT may be used to improve products and services in the areas of sonar and radar, biomedical imaging (e.g., MRI and microscopy), ophthalmology and smart-phone cameras (Doyletech, 2014, p. 5). As of 2014, the market for AO technology was approximately US$325 billion, increasing to US$470 billion by 2019. TMT technologies adapted to various markets could cause firms in these domains to double their sales from approximately US$4.2 billion in 2014 to US$8.8 billion by 2019 (Doyletech, 2014, p. 1).

- Technologies currently being developed for the SKA, such as amplifiers, digital signal processing, PAFs, and dish antennas, can be utilized in the telecommunications, radar, biomedical imaging and aerospace sectors (Doyletech, 2014, p. 6). As of 2014, SKA technologies are applicable to a US$100 billion market, increasing to US$137.6 billion in 2019 (Doyletech, 2014, p. 1). These technologies could enable user companies to increase their sales from approximately US$9.3 billion in 2014 to US$14.9 billion by 2019 (Doyletech, 2014, pp. 1–2).

4.1.7 Support for universities

Key Finding 20: *HAA contributed to the training of students and post-doctoral researchers in Canada.*

HAA contributed to the development of an average of 22 students (Students and Co-op) and eight research associates annually through temporary employment at NRC. Internal key informants and data indicated that this is an important part of HAA's talent management strategy, as some of HAA's current employees were initially hired as students/research associates.

HAA contributes to the training of students in the following manner:

- ***Participation of research associates and students in general program activities, including the development of instrumentation:*** For example, the ALMA Band 3 receiver project involved the participation of four co-op students, two graduate students and one post-doctoral researcher. Also, through HAA's partnerships with universities there are opportunities for students to be involved in other instrumentation projects.

- ***HAA staff working as adjunct professors:*** While data for the entire evaluation period was incomplete, an internal report shows that from January to March 2016, 16 HAA staff had positions as adjunct faculty at three Canadian universities and 11 HAA staff were supervising 18 students from four Canadian universities.

- ***Providing students with access to national and international telescopes:*** Data was unavailable to provide a complete picture as to the extent of student use of Canada's telescopes, however, the survey of telescope users showed that during the evaluation period at least nine graduate/PhD students and five post-doctoral researchers applied and received time on one or more telescopes supported by HAA.

- ***Providing access to archival data from the CADC:*** HAA staff encourage student use of archival data and periodically visit Canadian university astronomy departments to make presentations to faculty and students regarding the CADC. Interviews with two Canadian astronomers indicated that CADC archival data was being used for the training of students. One interviewee reported that archival data is being used in the classroom for training students and considered that the access to telescopes and to telescope data is a critical component to recruiting young astronomers to study in Canada.

The evaluation team examined a sample of 15 students hired by HAA in order to understand the career path of some students. It was found that some former students have received opportunities as post-doctoral researchers at other institutions and others are professors at universities. Similarly, several past Research Associates are currently employed by HAA, whereas others are professors at Canadian and international universities. Recent former students of HAA have also sought careers outside of astronomy and are positioned in fields such as engineering, finance, programming and software development.

HAA staff expressed concern with how changes to NRC's 2011 Visiting Worker Policy may have created barriers to hiring graduate students. More specifically, provisions in the policy in the areas of IP, publishing, insurance, security and stipends have been viewed by HAA management as limiting their ability to engage with universities for the hiring of students. Further, HAA staff noted that the NRC transformation affected their ability to collaborate with universities as part of instrumentation projects and their ability to hire students.

4.1.8 Canada's position in the field of astronomy

Key Finding 21: *In certain areas of astronomical research, Canada plays an important role or is considered a world leader. Further, HAA's activities in astronomical research and, in particular, observatory instrumentation design and development are considered critical to supporting Canada's overall performance in astronomy.*

Canada's position in the field of astronomy

The evaluation could not conclusively determine whether there has been a change in Canada's position in the field of astronomy since 2011 (the period of the evaluation). However, findings from the survey and key informant interviews do provide some insights on Canada's role, performance and expertise in the field of astronomy over the last five years.

Nearly half of survey respondents (40 percent) indicated that Canada's position in the field of astronomy has stayed the same and a quarter indicated that Canada's position has improved.

Key informants generally described Canada as one of the world leaders in the field of astronomy. International expert interviewees noted that Canada "punches above its weight" and "does better than it should" in astronomy given the size of its population and the funding provided for astronomical research. Key informants indicated that Canada has particular expertise or is a leader in areas such as:

- extrasolar planets (exoplanets)
- pulsars
- stellar evolution
- large astronomical survey research
- cosmology (including galaxy formation and evolution)
- astroseismology
- cosmic magnetism

HAA's role in supporting Canada's position in astronomy

Key informant interviews and results from the survey of telescope users indicate that HAA plays an important role in supporting Canada's performance in astronomy.

Nearly all survey respondents (82 percent) “strongly agree” or “agree” that HAA has been an important factor in supporting Canada’s performance in astronomy over the last five years. Similarly, key informants note that the Portfolio’s role in observatory governance, research and instrumentation projects is a critical factor that supports Canada’s performance and leadership position in the field of astronomy.

> *“Overall, NRC Herzberg’s publications stand out at the world level in terms of scientific impact, particularly for its core publications published in the subfield of Astronomy and Astrophysics, which are much more cited on average than similar publications at the world level.”*
>
> (Science-Metrix, 2016, p. 22)

Some key informants observed that HAA’s General Manager (GM) has played a key leadership role by actively participating in observatory governance and representing Canada at various observatory boards and committees, and has been effective in communicating Canadian interests. A few Canadian astronomers and international experts considered the GM’s involvement in the governance and planning for TMT and SKA as one of Canada’s main contributions to these projects.

4.2 Efficiency and economy

To assess the efficiency and economy of HAA, the evaluation examined stakeholder satisfaction with the application process for time allocation at Canada’s national and international observatories; HAA’s delivery of instrumentation projects, observatory initiatives and programs to reduce costs; as well as key risks and factors affecting HAA’s ability to operate efficiently.

4.2.1 Efficiency of the time allocation process for observatories

Key Finding 22: *The large majority of Canadian astronomers are satisfied with the application process to national and international observatories.*

Access to DAO and DRAO

Survey respondents who accessed DAO and DRAO expressed a high level of satisfaction with all the aspects of the application process. More specifically, all of the respondents who accessed DAO were satisfied with the overall efficiency of the application process and only one participant was dissatisfied with the application process for DRAO. While no specific improvements were recommended for the DAO, some survey respondents suggested that HAA provide remote access to the DRAO telescopes. Some respondents expressed concerns about the security screening requirements for foreign nationals which were perceived as a barrier for accessing DRAO telescopes. As noted by HAA management, HAA delivers science-ready data products for the Synthesis Telescope and users usually ask to visit in order to understand the data processing. Additionally, HAA sometimes requires users to come and operate the telescope for safety and staff resources reasons. However, this is not always possible since the NRC is required to follow Treasury Board policies and standards on operational and physical security.

Access to international observatories

<u>Overall efficiency of the application process</u>

Both the survey results and the interviews conducted with Canadian astronomers confirmed that the application process for accessing telescopes is well administered, including the operations of the CanTAC.

Strong levels of satisfaction, with the overall efficiency of the application process, were expressed by survey respondents who applied for time on the CFHT (92 percent), Gemini (89 percent) and JCMT (79 percent) observatories. In the case of Gemini and JCMT, only one survey respondent expressed dissatisfaction with the overall efficiency of the application process.

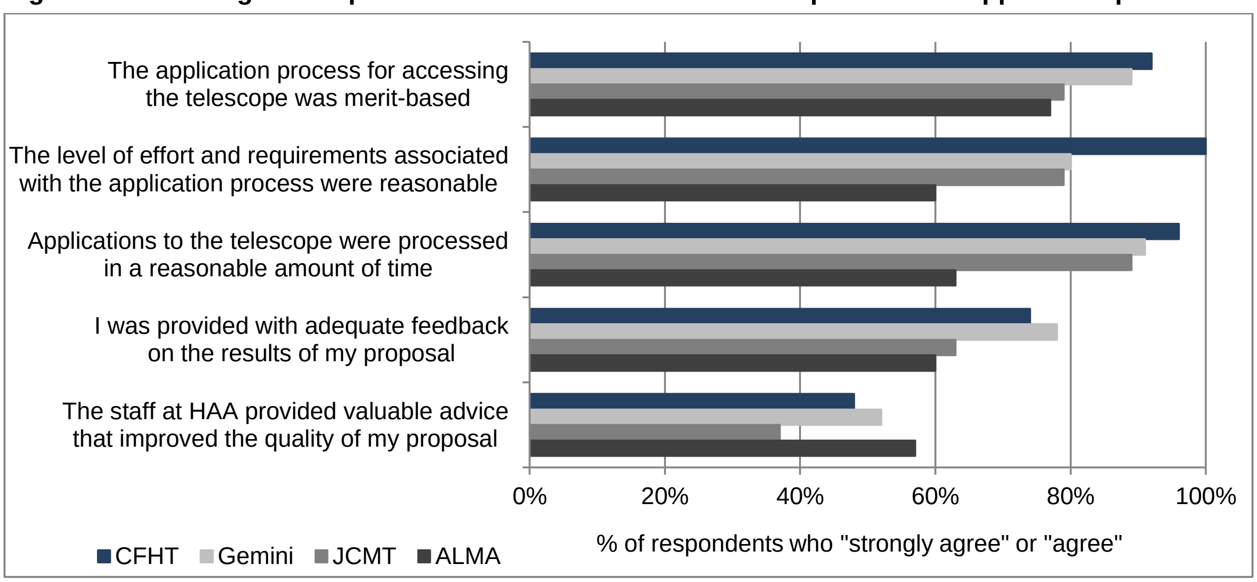
While the ALMA applicants who participated in the survey expressed a lower level of satisfaction (63 percent) when compared with the other international telescopes, it should be noted that only seven percent of these survey respondents expressed a negative view of the application process. Over one quarter (27 percent) “neither agree nor disagree” with the statement.

It should also be noted that the application process for ALMA is administered by the Joint ALMA Observatory (JAO). Canadian astronomers are, however, involved in the proposal review and time allocation process. Comments from HAA management indicate that the survey results are reasonable given that ALMA is still maturing from an operational perspective and the community is still familiarizing itself with the telescope and the time application/allocation process.

<u>Specific aspects of the application process</u>

As shown in Figure 9, a majority of survey respondents have positive perceptions of nearly all aspects of the application process for accessing telescopes.

Figure 9: Percentage of respondents who were satisfied with aspects of the application process



The survey results also show that satisfaction levels were lowest, for all four international telescopes, in relation to the value of advice provided by HAA staff on proposals. However, most of the respondents who did not agree with this statement answered “Neither agree nor disagree” (8%), “Don’t know” (5%) or “Not applicable” (28%).

4.2.2 Portfolio indirect costs

Key Finding 23: *HAA is operating with a small amount of overhead; the smallest overhead of any NRC Portfolio.*

One of the corporate KPIs used to assess HAA’s efficiency is indirect expenditures (overhead) as a proportion of total expenditures. For the period of FY 2012-13 to FY 2015-16, HAA’s indirect expenditures accounted for nine percent of total expenditures, which is less than the 12 percent target set by HAA.[8] These indirect expenditures do not include the administrative costs associated with services provided by NRC Corporate in support of HAA activities (e.g., Human Resources (HR), Business Management Support (BMS), Administrative Services and Property Management (ASPM), and Communications). Adding these expenditures would increase the overhead costs associated with HAA operations. In addition, internal key informants noted that corporate requirements, in particular reporting requirements, decrease the efficiency of HAA.

Key Finding 24: *Reporting requirements under the Portfolio/program structure are perceived as “burdensome” and “artificial”.*

All internal key informants reported that the portfolio/program structure imposed by NRC was artificial and that the formalization of this structure “on paper” through the NRC Program Lifecycle did not result in any real changes in the way HAA actually operates. Reporting requirements associated with the new structure, such as quarterly program reports, was the main issue identified, since these reporting requirements have created overhead which does not add value for HAA.

4.2.3 Efficiency in delivering instrumentation projects

Key Finding 25: *HAA delivered projects on time, on budget and according to required specifications.*

There was a consensus among key informants who collaborated on instrumentation projects with HAA (i.e., representatives from observatories, research collaborators and industry representatives) that the Portfolio consistently delivered its projects on time, on budget and according to technical specifications. HAA management and staff were characterized by external collaborators as “team players” who have a strong focus on clients.

> *“HAA has been developing instruments for [observatory name] for 20 years and is a reliable and good contributor. In the first place, we like to work with them because they’re very rigorous. They can deal with deliveries. HAA has excellent engineers. (...) They have expertise and they have one of the top three to five groups in the world for instrument building.”*
>
> Observatory partner

The evaluation found that HAA has developed strong project management skills and tools through the delivery of increasingly complex R&D projects that involve large teams of national and international collaborators. HAA also demonstrated its ability to adapt to the

8 It should be noted that a review of NRC Corporate KPI data revealed that HAA has an average staff utilization rate of 96 percent for the period 2012-13 to 2015-16, which is much higher than other NRC portfolios. While HAA staff utilization rates appear to be unusually high when compared to other NRC portfolios, the evaluation did not conduct a thorough assessment of the reasons for this discrepancy.

various project management requirements of the observatories that contract HAA.

However, when asked about the benefits of the new project management processes and tools implemented by NRC Corporate as part of NRC's transformation, internal key informants indicated that these tools are not used for the management of projects and felt that they did not add value to HAA's operations. In fact, they perceived the project management function of the SAP system as a reporting tool that exclusively benefits NRC Corporate. Moreover, internal key informants reported that the requirements imposed by NRC Corporate to enter project data in SAP creates overhead for the Portfolio because an employee has to dedicate a significant amount of his or her time to enter all HAA project information in SAP on a quarterly basis. The Vice-President's Office of Emerging Technologies – National Infrastructure and Future Technologies is aware of these issues and has initiated discussions with HAA management.

4.2.4 Key risks and factors influencing the efficient use of resources by HAA

Evidence suggests that the context in which HAA operates has created operational challenges and risks to its ability to achieve its objectives. More specifically, the main factors are: the volatility of the Canadian dollar, challenges associated with common services, and key changes to the general Information Technology (IT) environment at the federal government level. This section briefly discusses these factors and their impacts.

<u>Volatility of exchange rates</u>

The decreasing value of the Canadian dollar has had a significant impact on the cost of the G&C portion of HAA's expenditures. The impact relates primarily to the difference between the rate used to construct HAA's annual forecast and the rate that is in place at the time an invoice is due. A fluctuation in the exchange rate of, for example, 10 percent can mean a change in the cost of over $1 million (CAD). HAA, with the help of NRC Finance, has implemented controls and mechanisms to plan for and mitigate the impact of these increased costs. For more on this issue, consult Section 2.3.2 of this report.

<u>Challenges associated with common services</u>

As part of the implementation of NRC's Strategy 2013-2018, many administrative functions (e.g., HR, finance, communication, facility management, business management, procurement and IT support) that were previously under the purview of institutes were centralized. An extensive evaluation of NRC Common Services was not conducted as part of this evaluation. Still the evaluation did observe some inefficiencies with some of the services provided to HAA.

Key Finding 26: *Operational challenges were encountered in the areas of procurement, hiring and IT support.*

Key Finding 27: *HAA requires access to specialized IT desktop support for UNIX and Mac. However, NRC Knowledge and Information Technology Services (KITS) desktop support is provided almost exclusively for Microsoft Windows.*

Internal key informants indicated that the centralization of NRC Corporate services resulted in a reduction in the level and quality of many administrative functions. Key challenges most frequently identified by internal key informants and in HAA planning documents include:

- **Procurement services:** Increased demand for procurement services, particularly in the short term due to expanding workloads associated with the TMT project, was identified as a key risk which could limit HAA's ability to deliver instrumentation projects. This could result in potential project delays and adverse impacts on the Portfolio's reputation and its ability to obtain future instrumentation projects. As a result of the NRC centralization, FTEs supporting the procurement process were reduced from four to two. To meet its procurement needs, HAA contracted a local Public Works and Government Services Canada (PWGSC) contracting officer on a part-time basis to facilitate the later stages of the procurement process.

- **Hiring:** The average time to complete a staffing action more than doubled between FY 2012-13 and FY 2015-16, increasing from 69 days to 155 days. Internal key informants reported that the length of the staffing process has been a contributing factor to at least one candidate dropping out of the hiring process. However, this increase was not found to be a major impediment to the attraction of highly qualified personnel, likely due to HAA's reputation. HAA continues to attract world-class researchers in the field of astronomy.

- **IT Desktop support:** KITS support is provided almost exclusively for Microsoft Windows users, whereas almost all HAA researchers are UNIX and Mac users. According to HAA researchers, the UNIX system is customary for research in astronomy since software used and developed by and for the astronomy community is written for UNIX machines (Macs natively run a standard variant of UNIX). While KITS has recently created a group to provide desktop support for UNIX and Mac users, internal key informants did not mention having access to the services provided by this group during the evaluation period.

Evidence suggests that if these challenges are not addressed they could impact the Portfolio's ability to achieve its mandate moving forward.

<u>General IT environment – Shared Services Canada (SSC) and NRC cyber-intrusion</u>

Key Finding 28: *The transfer of HAA's IT infrastructure to Shared Services Canada has limited the Portfolio's ability to provide data management services to its clients (the astronomy community).*

In July 2012, HAA's IT infrastructure (servers and networking) for providing access to Canadian astronomy data transitioned to a new centralized government department, SSC. The impact of the transfer of CADC resources to SSC has been characterized by HAA as "serious" in terms of their ability to plan, implement and procure new equipment and network capacity. Issues with the service levels provided by SSC are not unique to HAA, but are consistent with the Office of the Auditor General report published in the Fall of 2015 which details how SSC has had difficulty maintaining IT service expectations with its clients across the federal government (OAG, 2015). The NRC cyber intrusion in 2014 further challenged the delivery of these services (since SSC and KITS efforts were focused on issues related to the cyber intrusion).

The evaluation found two key issues that were faced by HAA, during the period covered by the evaluation, with regard to providing access to telescope data:

- ***Need for IT Equipment Upgrades:*** According to internal documentation, the collaboration process with SSC to procure IT equipment upgrades posed challenges as communications were "sporadic or non-existent." The need to replace outdated servers and storage systems equipment placed NRC at risk of non-performance against contracted service obligations and affected the overall quality of service provided to its clients. Rather than continue to pursue SSC to provide IT infrastructure upgrades to support the CADC, HAA addressed this issue through the establishment of a development contract with Compute Canada (CC). This project is currently underway.

- ***Need for High Speed Networking to Provide Access to Users:*** The previous 2011 evaluation concluded that "CADC's services are not optimized due to lack of access to required high-speed network that restricted the service levels that the CADC could provide its clients".[9] As of July 2016, the network has not yet been upgraded from one gigabit per second to ten gigabits per second in order to match the speeds available to researchers using other networks. Currently, there is no agreement between KITS, SSC, and HAA on how to procure a solution that satisfies all parties. According to internal key informants, the need for a network improvement is an ongoing critical issue for HAA. Internal data reveals that limited network capabilities at the CADC have negatively impacted HAA's ability to provide access to telescope data. The demand for access to CADC's data often resulted in over-saturated networks, causing network failures and interruptions of the services to users and disrupting services of other NRC enterprise users. As an interface with the world astronomy community, inconsistency in the CADC's service levels presents a potential risk to the reputation of NRC.

Additionally, the cyber-intrusion and its corollary, the creation of a new IT infrastructure (referred to as the "green zone"), was found to add a layer of complexity to the functionality of the NRC IT environment. In fact, HAA staff felt that having to navigate between the IT infrastructures with two laptops has made simple tasks, such as time entry and service requests to NRC Common Services, burdensome. Additionally, according to HAA management, the provision of Green laptops at DRAO was done without any prior consultation and "forced the observatory to spend many hours to design and test new radio frequency interference (RFI) containment boxes for those machines". According to this manager, the cost of the RFI boxes far exceeds the cost of the laptops which, moreover, are not useful for HAA research activities.

When describing the current IT environment at NRC an HAA researcher mentioned that "it is hard to believe that such a highly regarded organization was so inefficient in terms of providing basic IT support". According to the key informant, this situation could create a major barrier to HAA's ability to retain world-class researchers.

Recommendation 5: HAA, in collaboration with KITS, should continue to undertake efforts to find a solution related to the IT equipment upgrades and high speed networking capacity issues at the CADC.

4.2.5 Efficient use of funding by administrators of international telescopes

Key Finding 29: *Observatory administrators are implementing initiatives and programs to reduce costs and improve operational efficiency.*

Observatory annual reports provide a number of examples of initiatives undertaken by observatories to reduce costs and improve overall efficiency. Examples of these initiatives include:

- ***Improved energy efficiency and reduced energy costs:*** In 2013, a photovoltaic system (for solar power) was installed on the roof of the CFHT headquarters building in Waimea to

[9] The 2011 evaluation further noted that the research standard of Canadian universities is 10Gb/s, however, as of July 2013 the CANARIE network connecting the Canadian research community is capable of up to 100 Gb/s (CANARIE, 2013).

offset approximately 40% of energy use. Further, conventional fluorescent lamps were replaced with LED lamps throughout the building (CFHT, 2013, p. 20).

- ***Gemini Transition Program:*** Following the withdrawal of the UK and a reduction of approximately 20% ($7.4 million) in its operating budget, Gemini launched a Transition Program in 2013 to introduce cost savings activities while sustaining operations. According to Gemini's 2015 Annual Report, the observatory has achieved spending reductions of $6.5 million from its 2012 budget. These savings are the result of three activities: reduction in staff (from 212 FTEs in 2011 to 178 FTEs in 2015); reduction in non-labour expenses (such as supplies, travel and computers); and implementation of projects that support operations with a smaller staff or achieve additional yearly savings (including reducing data archive costs, increasing visitor observing, and energy savings) (Gemini Observatory, 2015, pp. 18–21).

4.2.6 HAA's ability to influence decision-making processes in the governance of Canada's offshore telescopes

Key Finding 30: *HAA staff participate in various observatory boards and committees, and are consequently directly involved in the decision-making processes of international telescopes supported by Canada.*

As mentioned in Section 3.1.1, HAA has been a member of numerous boards and committees across the five observatories reviewed by this evaluation. HAA was a member of the Board and the Finance/Budget Committee for all five observatories. In fact, key informants noted that HAA's GM and an HAA Director were Chairs of the Finance/Budget Committees at Gemini and CFHT. These committees are responsible for approving and reviewing observatory budgets. Further, HAA's GM was Chair of the SKAO Board and is currently the Vice-Chair of the Thirty Meter Telescope International Observatory (TIO). HAA is also a member of the Audit Committees at the CFHT, TIO and SKAO and, as such, is involved in examining financial statements and reviewing external audit reports. As a result, HAA is directly involved in the decision-making processes regarding observatory operations, planning and finances. Finally, key informants pointed to HAA representatives on the ALMA Board, noting that:

- the HAA representative on the ALMA Board is currently servicing as Vice-Chair (an important role for setting and controlling the agenda and workings of the Board).
- an HAA representative is the Chair of the ALMA Budget Committee.

5. CONCLUSION

Overall, the evaluation found that HAA is aligned with the LRP2010 which ensures that the Portfolio's activities and investment priorities meet the needs of the Canadian astronomy community. Additionally, HAA is perceived as playing a critical role in representing the interests of the Canadian astronomy community internationally through its involvement in existing and future observatories. HAA's facilities at DAO and DRAO are unique in Canada, providing core capabilities and expertise in observatory instrumentation and infrastructure development.

HAA has performed well and has made significant impacts by supporting Canada's offshore observatories as well as other telescopes around the world. This support has been mainly through HAA's involvement in the governance of international observatories, the provision of financial support and the development of world-class instruments and technologies. HAA has collaborated with industry on various instrumentation projects, resulting in positive impacts for partnering companies. While HAA has been effective at meeting its objectives during the evaluation period, evidence suggests that the Portfolio has encountered operational challenges which may impact HAA's ability to fulfill its mandate.

The areas of greatest concern are related to IT. In particular, limited network capabilities at the CADC have impacted HAA's ability to provide access to telescope data. Further, as the observational data collected by observatories becomes increasingly complex, particularly with next-generation telescopes, the need for HPC and improved data management capabilities was identified as a critical issue that must be addressed if the CADC is to remain a key player in astronomical data archiving and processing. The evaluation noted that since the transfer of HAA's IT infrastructure to SSC, HAA has experienced challenges in its ability to plan, implement and acquire new equipment and networking capacity. Additional challenges included procurement delays, lengthening timelines for staffing actions, and limitations in IT desktop support.

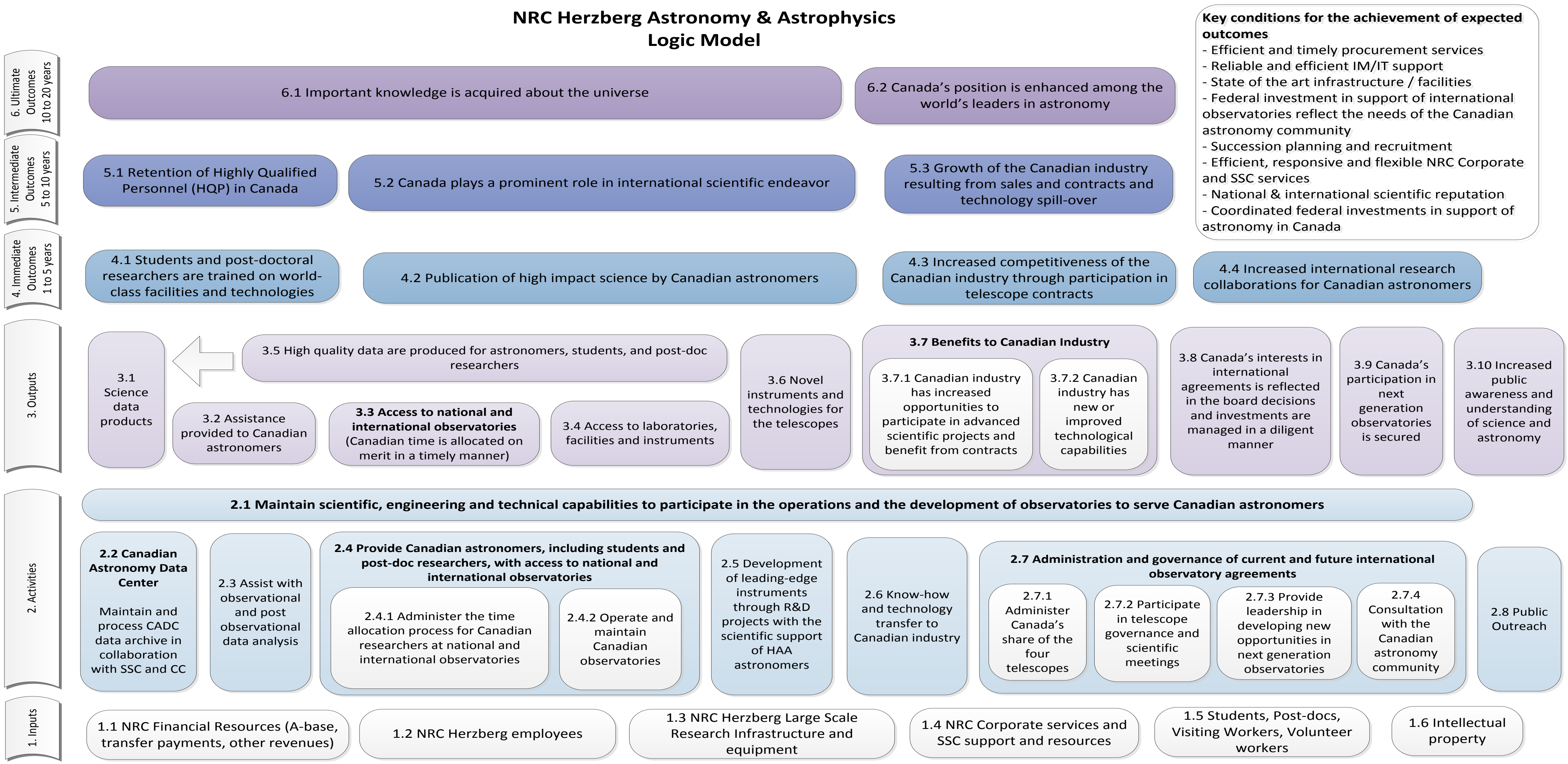
Through its ongoing involvement in next generation observatories, including SKA and TMT, HAA appears to be well positioned to continue to achieve impacts in the future.

6. MANAGEMENT RESPONSE

Recommendation	Response and Planned Action(s)	Proposed Person(s) Responsible	Timelines	Measure(s) of Achievement
The Vice-President's Office (VPO) of Emerging Technologies – National Infrastructure and Future Technologies, in consultation with HAA, should consider establishing a formal consultation process to allow the Canadian astronomy community to provide strategic advice on the Portfolio's scientific activities and priorities.	Accepted. NRC will investigate appropriate mechanisms for obtaining advice on a regular basis from the astronomy community and will develop a proposed process early in FY 2017-18.	VP GM	May 2017	A consultation mechanism allowing the community to provide feedback on HAA strategic directions is developed and implemented.
HAA should continue to work with partners to expand outreach and awareness activities.	Accepted. HAA will continue to work in concert with partners to expand outreach activities. A new model to optimise use of the Centre of the Universe will be explored.	GM	June 2017	A plan for local outreach to the community is put in place.
HAA, in collaboration with other NRC Portfolios and NRC Business Management Support (BMS), should explore opportunities to leverage competencies and astronomy-related technologies.	Accepted. HAA with support from the VPO of Emerging Technologies – National Infrastructure and Future Technologies and BMS will engage into discussions with the broader NRC community and ensure that competencies and intellectual property held at HAA are known and shared.	GM	October 2017	Discussions have taken place and competencies and IP originating at HAA are introduced to other NRC Portfolios.
HAA should identify the reasons why Canadian PIs are not allocated observing time commensurate with Canada's financial support to ALMA operations and take the appropriate measures identified, as needed.	Accepted. HAA will work with the Canadian astronomy community and with the National Science Foundation to understand why the allocation of ALMA time to Canadian astronomers within the allocation of ALMA time to the North American Consortium has not been proportional to Canada's share of the North American Contributions and will attempt work to remove any impediments to Canadian access.	GM	September 2017 (for Cycle 5 ALMA proposals)	Impediments to Canadian access are identified, and an action plan to overcome these is developed and implemented, as needed.

Recommendation	Response and Planned Action(s)	Proposed Person(s) Responsible	Timelines	Measure(s) of Achievement
HAA, in collaboration with KITS, should continue to undertake efforts to find a solution related to the IT equipment upgrades and high speed networking capacity issues at the CADC.	Accepted. NRC will continue to work to find a solution to ensure that CADC services to clients are not impacted.	GM CIO	September 2017	Discussions with KITS and SSC have taken place, and solutions with appropriate timelines are identified.

APPENDIX A: HAA LOGIC MODEL



APPENDIX B: METHODOLOGY

This section presents a detailed description of the evaluation methodology, including the evaluation design and approach, the challenges and limitations encountered during the evaluation, and the data collection methods.

Evaluation Design

The evaluation was carried out in accordance with the NRC's approved evaluation plan and TBS policies. The last evaluation of NRC-HAA took place in 2011. The timing of the evaluation was also determined by the legal requirements of the Financial Administration Act which indicate that the evaluation of HAA's contribution to international observatories needed to be completed no later than November 2016.

The questions addressed by the evaluation are presented in Table 7. The evaluation questions were developed following a review of key program documents and in consultation with HAA management and the VP, Emerging Technologies. It should be noted that a complete and in-depth assessment of the performance of NRC's internal services was not within the scope of the evaluation.

Table 7: Evaluation Issues and Questions

Evaluation Issues	Evaluation Questions
Relevance – Continued need for program	1. To what extent is the HAA Portfolio aligned with the current needs of Canadian astronomy researchers? 2. To what extent is the current delivery model for the administration and operations of Canada's telescopes appropriate to meet the needs of the Canadian scientific astronomy community? ▪ Are there alternative delivery models that could better serve the needs of the Canadian scientific astronomy community? ▪ What are the conditions required for such an alternative model to meet Canada's legal, regulatory and operational requirements?
Relevance – Alignment with government and NRC priorities	3. To what extent is the HAA Portfolio aligned with federal priorities and NRC strategic objectives? ▪ What have been the impacts of NRC's transition to a Research & Technology Organization (RTO) model on HAA's activities and strategic priorities?
Relevance – Alignment with federal roles and responsibilities	4. To what extent are HAA's activities and strategic outcomes consistent with federal roles and responsibilities?
Performance – Effectiveness	5. To what extent has HAA been successful at providing Canadian astronomers with access to: ▪ national and cutting-edge international telescopes; and ▪ science data products (i.e., CADC)?
	6. What have been the scientific impacts stemming from the national and

Evaluation Issues	Evaluation Questions
	international telescopes operated and administered by HAA?
	7. What have been HAA's contributions to the development of novel instruments and technologies in support of Canada's current and future telescopes? ▪ What have been the industrial impacts of the novel instruments and technologies developed by HAA?
	8. To what extent and in what ways has HAA supported Canadian universities with regards to the training of students and post-doctoral researchers?
	9. To what extent has HAA contributed to strengthening Canada's position among the world leader in astronomy?
Performance – Efficiency and Economy	10. To what extent is HAA administered in a cost-effective and efficient manner? ▪ What have been the factors that facilitated or hindered HAA's ability to manage its resources in a cost-effective and efficient manner?

The evaluation of HAA was conducted by an independent evaluation team from the NRC Office of Audit and Evaluation. The work of the evaluation team was supported by an Evaluation Advisory Committee (EAC) to provide advice and input on key deliverables.

In order to maximize the possibility of generating useful, valid and relevant evaluation findings, the evaluation used a mixed methods approach, allowing for triangulation (i.e., convergence of results across different lines of evidence) and complementarity (i.e., using complementary research methods to provide different perspectives when examining various facets of complex issues). The methods employed in the study as well as challenges and limitations are described below.

Methods

This evaluation employed both qualitative and quantitative research methods, including:

- Literature and document review
- Analysis of administrative and performance data
- Survey of Canadian telescope users
- Key informant interviews
- Case studies

Literature and Document Review

Internal and external documentation was reviewed, synthesized and integrated into the evaluation to provide contextual and historical information, and to complement other lines of evidence in assessing relevance and performance. Internal documents included HAA strategic planning reports, business plans and implementation plans, as well as NRC Departmental Performance Reports (DPR) and Reports on Plans and Priorities (RPP). External documents included CASCA publications, such as the LRP2010 and LRP2010 Mid-Term Review, as well as publications and reports prepared by Canada's offshore telescopes.

Analysis of Financial, Administrative and Performance Data

Financial, administrative and performance data were reviewed to provide information on program outputs and impacts, and to contribute to the analysis of resource utilization. Administrative and performance data were provided by HAA staff while financial data was provided by NRC Finance Branch.

Data consulted included subscription and publication rates for Canada's offshore observatories, Portfolio expenditures and revenues, as well as HR statistics.

Survey of Canadian Telescope Users

A survey of users of Canada's national and international observatories was conducted. The survey sample included Canadian astronomers who applied for time on the telescopes between 2011 and 2015. More specifically, the survey targeted Canadian astronomers with a faculty position in a Canadian postsecondary institution, students at a Canadian postsecondary institution, and post-doctoral researchers. The survey population did not include HAA researchers.

The survey assessed users' experience in terms of access and collected information about Canada's performance in astronomy since 2011. More specifically, respondents were asked a series of questions to assess the time allocation process administered by the observatories, to describe the scientific impacts that resulted from their access to the telescopes, and to identify Canada's contributions to the field of astronomy over the last five years.

The web survey was offered in both French and English and was administered by NRC's Communications and Corporate Relations Branch (CCRB) using web-based software (FluidSurveys). The survey was available for three weeks. An initial email invitation and two reminder emails were sent by the HAA General Manager during the survey period.

Overall, invitations were sent to a total of 306 individuals, of which 11 did not identify themselves as direct users of national and international ground-based telescopes and were therefore not included in the survey sample. As a result, the final sample was 295. A total of 95 respondents completed the survey, for a response rate of 32 percent.

A survey report analyzing the results was prepared. Where possible, the results of the survey were compared to those obtained in the survey conducted as part of the previous evaluation in 2011.

It should be noted that results from the survey indicate that one of the questions was not formulated clearly. When asked about whether HAA staff provided them with valuable advice when preparing their proposals for observing time, most respondents who did not agree with this statement answered the following three options: "Neither agree nor disagree", "Don't know", or "Not applicable". The survey question should have asked about the support provided not only by HAA but by the observatories as well. In this regard, it was brought to the attention of the evaluation team during the analysis of survey results that the advice is usually provided directly by the observatories or by external committees. In the case of CFHT, for example, HAA provides support to the observatories to employ Canadian Resident Astronomers with the understanding that such staff provide an informal point of contact for Canadian applicants and users of the CFHT. For Gemini, the feedback is provided by the National Gemini Office that is administered by HAA employees, as per the Gemini partnership agreement.

Key Informant Interviews

Internal and external stakeholders were consulted to collect qualitative evidence with regards to the relevance and performance of NRC-HAA. The information gathered through the qualitative, semi-structured interview process was based on personal experience, opinions and expert knowledge. This information was important for contextualizing performance data and other statistics.

Interviews were conducted either in-person or by telephone. Each interview lasted approximately 30 to 90 minutes and was conducted using an interview guide. The interview guides were adjusted to each key informant group, ensuring that questions were relevant to each group. All key informants received a copy of the interview guide in advance of the interview.

Overall, a total of 31 interviews were conducted with NRC and NRC-HAA staff, external stakeholders, representatives from Canada's offshore observatories, and international experts. Interviewees were selected in consultation with HAA management and the EAC. To encourage participation, the HAA General Manager sent an email to potential interviewees inviting informing them of the evaluation and inviting them to participate. The evaluation team followed up with key informants to confirm their participation and to schedule an interview.

A summary of the key informant groups consulted as part of this evaluation is presented in Table 8.

Table 8: Summary of key informant interviews

Interviewee category	n
NRC-HAA management and staff	13
External members of the astronomy community	6
Other federal government departments and agencies	2
Telescope directors	4
Industry partners	3
International astronomy experts	3
Total	**31**

Case Studies

A series of four case studies were conducted as part of the evaluation to illustrate the types of projects and activities undertaken by HAA in support of international observatories, as well as to gain a better understanding of the Portfolio's role in astronomy research and instrumentation development and the impacts resulting from HAA projects, including identifying factors and conditions that facilitate or impede the achievement of impacts. The case studies involved a review of project-level documents and interviews with project proponents, including HAA staff, representatives from international observatories, and representatives from postsecondary institutions and industry involved in the project.

A brief report summarizing the findings was prepared for each case study project.

The four case studies included in the evaluation, and the number of key informants consulted, is presented in Table 9.

Table 9: Summary of case study interviews

Case study	n
ALMA Band 3 Receiver	5
Gemini Planet Imager (GPI)	4
Pan-Andromeda Archeological Survey (PAndAS)	4
WIDAR Correlator for the EVLA	5
Total	**18**

Challenges and limitations

The evaluation encountered certain limitations and challenges that must be taken into consideration when interpreting the findings. These challenges and limitations are common in most evaluations conducted within the federal government. In order to alleviate any adverse impacts on the evaluation findings, various mitigation strategies were identified. Table 10 presents the limitations and challenges, their potential impact on the project, as well as the mitigation strategies used to minimize their effects.

Table 10: Evaluation limitations, challenges and mitigation strategies

Limitations and challenges	Impact on evaluation project/findings	Mitigation strategies
The evaluation was not able to provide an assessment of the level of satisfaction of CADC users.	Due to limited resources, the evaluation did not survey or interview CADC users to quantify and qualify levels of satisfaction with services.	The evaluation relied on data provided by the Portfolio as well as perspectives of internal and external key informants, including observatory partners and Canadian astronomers, who use CADC services.
The evaluation identified some limitations to the reliability of NRC Corporate KPIs (i.e., indirect costs as proportion of total expenditures).	Data on the Portfolio’s indirect expenditures do not include administrative costs associated with services provided by NRC Corporate (e.g., HR, BMS, ASPM, and Communication).	The reliability issues associated with the NRC corporate KPIs were documented to ensure that the evaluation findings are interpreted with caution.

APPENDIX C: OVERVIEW OF INTERNATIONAL TELESCOPES SUPPORTED BY CANADA

Table 11: Overview of Canada's Offshore Telescopes

Telescope:	CFHT	JCMT	Gemini	ALMA	TMT
Location:	Summit of Maunakea, Hawaii	Summit of Maunakea, Hawaii	(North) summit of Maunakea, Hawaii (South) Cerro Pachón, Chile	Chajnantor Plateau, Atacama Desert, Chile	Summit of Maunakea, Hawaii (Planned location; construction not completed)
Type / Specialization:	Optical-InfraRed (3.6-meter)	Sub-millimeter (15 meter)	Optical-InfraRed (twin 8-meter)	Millimetre & Sub-millimetre	Optical ((near-ultraviolet to mid-infrared (30-meter)
Start of Funding Agreement:	1974	1989	1993	2008	2015
Date Telescope became operational	1979	1987	2000 / 2001 (North / South)	2013	Not yet constructed
Canada's share	42.5%	0% (Formerly was 25%)	19.88%[10]	2.8% (7.25% of North American share 37.5%)	TBD: Estimated 15%
Partners	France (42.5%) and the State of Hawaii (15%)	No longer applicable	United States: 69.84% Canada: 19.88% Brazil: 6.96% Argentina: 3.32%	Europe (37.5%) North America (37.5%) East Asia (25%) In cooperation with the Republic of Chile	United States (25%) Japan (20%) China (10%) India (10%) University of Hawaii (7.5%) 15% is currently unsubscribed and is available for additional partners

10 This proportion is Canada's current share as of January 1, 2016. It should be noted that partner shares in Gemini have changed over the evaluation period.

Telescope:	CFHT	JCMT	Gemini	ALMA	TMT
Executing Agency	CFHT Corporation (a not-for-profit corporation)	Currently the East Asian Observatory (EAO). Formerly operated by United Kingdom's Science and Technology Facilities Council.	The National Science Foundation (NSF) is the executive agency. However, the Association of Universities for Research in Astronomy (AURA) manages the organization as authorized through an agreement with the NSF.	The Joint ALMA Observatory (JAO) provides the unified leadership and management of the construction, commissioning and operation of ALMA.	TMT International Observatory
Duration of agreement	The current agreement began February 1, 2015 and continues until January 2019. Although there is no fixed termination date; dissolution is provided for in by-laws.	Canada withdrew effective September 2014.	Current agreement began January 1, 2016 and lasts until December 31, 2021. The prior agreement was scheduled to end December 31, 2015.	The ALMA Trilateral Agreement signed between the NSF, the National Institutes of Natural Sciences of Japan (NINS) and the European Southern Observatory (ESO) expires no sooner than December 31, 2021. NRC and NSF have entered into a Contributions Agreement (CA) reflecting Canada's commitments under the NRC-NSF MOU signed in 2003. The current term of the CA extends to December 31 2020, with NRC notice of intent to extend or	TBD

Telescope:	CFHT	JCMT	Gemini	ALMA	TMT
				terminate the CA provided to the NSF by December 31, 2019.	
Annual operating budget	As of 2014, CFHT's total budget is approximately $7.2 million and includes the following: • Staffing: $4.9 million • Base facilities and operations: $620,485 • Observatory facilities and operations: $618,684 • General administrative expenses: $437,771 • Transfer to reserve: $390,000 • Science: $81,215 • Instrumentation: $79,634 • Outreach: $55,516	Not Available	As of 2015, Gemini's total budget is approximately $33.5 million and includes the following: • Operations and maintenance: $31.3 million • Instrument Development Fund: $2.2 million • Facilities Development Fund: $46,564	(All figures in USD) 2015 total: $69.2 million Chilean operations (Joint ALMA Observatory): $39.3 million For the above two totals, the North American share is 37.5% Offsite expenses (North America): $10.9 million	Not Applicable
Total employees	~44	Not Available	~165	Not Available	Not Applicable

Note: SKA is not included in the table as the project is still in its early stages and not enough information is available.

APPENDIX D: EVALUATION FRAMEWORK

Evaluation question	Document review	Data review	Key informant interviews	Case studies	Survey of telescope users
1. To what extent is the HAA Portfolio aligned with the current needs of Canadian astronomy researchers?	✓	✓	✓	✓	✓
2. To what extent is the current delivery model for the administration and operation of Canada's telescopes appropriate to meet the needs of the Canadian scientific astronomy community? 2.1 Are there alternative delivery models that could better serve the needs of the Canadian scientific astronomy community? 2.2 What are the conditions required for such an alternative model to meet Canada's legal, regulatory and operational requirements?	✓		✓		
3. To what extent is the HAA Portfolio aligned with federal priorities and NRC strategic objectives? 3.1 What have been the impacts of NRC's transition to a Research & Technology Organization (RTO) model on HAA's activities and strategic priorities?	✓	✓	✓		
4. To what extent are HAA's activities and strategic outcomes consistent with federal roles and responsibilities?	✓		✓		
5. To what extent has HAA been successful at providing Canadian astronomers with access to national and international telescopes and science data products (i.e., CADC)?	✓	✓	✓		
6. What have been the scientific impacts stemming from the national and international telescopes operated and administered by HAA?	✓	✓	✓	✓	
7. What have been HAA's contributions to the development of novel instruments and technologies in support of Canada's current and future telescopes? 7.1 What have been the scientific and industry impacts of the novel instruments and technologies	✓	✓	✓	✓	✓

Evaluation question	Document review	Data review	Key informant interviews	Case studies	Survey of telescope users
developed by HAA?					
8. To what extent and in what ways has HAA supported Canadian universities with regards to the training of students and post-doctoral researchers?	✓	✓	✓		✓
9. To what extent has HAA contributed to strengthening Canada's position among the world leaders in astronomy?	✓		✓	✓	✓
10. To what extent is HAA administered in a cost-effective and efficient manner? 10.1 What have been the factors that facilitated or hindered HAA's ability to manage its resources in a cost-effective and efficient manner?	✓	✓	✓	✓	✓

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