

# An MTR Overview of Canadian Submillimetre/millimetre Facilities

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## 1. Introduction

The wavelengths known as “submillimetre/millimetre” (SMM; 0.1-10 mm) comprise an important observational window for studying our cosmic origins. In this White Paper, we provide an overview of the present state of SMM astronomy in Canada and offer a strategy to maintain Canada’s scientific leadership in this important regime. This document complements other White Papers on SMM facilities prepared for the 2015 Mid-Term Review, i.e., the James Clerk Maxwell Telescope (JCMT; Wilson et al.), the Cerro Chajnantor Atacama Telescope (CCAT; Fich et al.), and the Atacama Large Millimetre/submillimetre Array (ALMA; Scott et al.), by describing how these facilities relate to each other. This White Paper is effectively an update of “A Roadmap for Canadian Submillimetre Astronomy” (Webb et al. 2013; available at <http://xxx.lanl.gov/abs/1312.5013>).

Canada’s history in SMM astronomy began in 1987, with its entry (through NRC) into the JCMT partnership with the UK and Netherlands. Participation in JCMT was a critical success for Canadian astronomy. Canadians were involved in many of JCMT’s highest-impact results. Also, experience gained with JCMT led Canadians to become major users of other SMM observatories worldwide and in space. Of the latter, Canadians were notably involved (through CSA) in the recent successful BLAST, *Planck*, and *Herschel* missions. Canada further built on its SMM history when it joined ALMA through NRC in 2003, and Canadians have led ~12 successful ALMA projects since Early Science observing began in 2011. NRC formally withdrew from JCMT at the end of September 2014 along with the UK<sup>1</sup>, but Canadian use of the facility will continue at least in the near term. Looking to the future, a coalition of Canadian universities has joined the CCAT partnership (with U.S. and German universities). This coalition has recently proposed to CFI for funding a major share of CCAT construction.

## 2. Single-dish Facilities: Wide-Field Imaging and Spectroscopy

Single-dish telescope access is a critical requirement for success in SMM astronomy. Indeed, it is important that Canada maintain its participation in a large single-dish SMM telescope. Though angular resolutions are typically moderate e.g., 15” for JCMT at 850  $\mu\text{m}$  and 4” for CCAT at 350  $\mu\text{m}$ , SMM single-dish data provide ‘big picture’ results that are key to understanding physical processes on all relevant scales. Single-dish telescopes with wide format detectors are particularly good for mapping large fields at high sensitivity, allowing significant coverage of populations of targets. They provide valuable prerequisite information needed for effective follow-up studies at higher angular resolutions with interferometers. (An analogy is using CFHT with Megaprime to locate optical targets for follow-up observations with TMT.) Note that, unlike optical, infrared, and radio telescopes, existing single-dish SMM telescopes have *not* mapped the entire sky at moderate angular resolutions.

The importance of large-area mapping in the SMM is especially true for cosmological and Galactic science. In the case of cosmology, detailed statistical analyses require extremely large samples that can only be obtained by mapping many square degree fields on the sky. Additionally, rare sources, such as strong gravitational lenses require dedicated large-area searches, which can then be followed up with detailed interferometric observations. For Galactic science, molecular clouds subtend many square degrees on the sky. The process of star formation is dominated by the flow of mass and momentum, modulated by magnetic fields and turbulence, within molecular clouds down to the scale of pre-stellar cores and proto-stars. Finally, the distribution of star formation across the Galaxy requires many square degree surveys along the Galactic Plane.

### 2.1 JCMT

JCMT (see Figure 1) has been Canada’s workhorse single-dish SMM facility for over 25 years, providing data to a community of SMM astronomers that has grown around the telescope. Indeed, several generations of Canadian graduate students and postdocs have been trained at this facility. From 1987 to 2014, Canada had a 25% share in JCMT observing time. With a 15-m diameter primary reflector, JCMT remains the world’s largest single-dish submillimetre telescope. The telescope and enclosure have been maintained in excellent condition, and its instrumentation and software have remained at the cutting edge. The present suite of instruments include the

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<sup>1</sup> The Netherlands withdrew from the JCMT partnership earlier, in March 2013.

revolutionary SCUBA-2 “camera” for observing continuum emission at 850  $\mu\text{m}$  and 450  $\mu\text{m}$  and the HARP focal-plane heterodyne array for observing line emission at 325-275 GHz (i.e.,  $\sim 850 \mu\text{m}$ ). These two wide field-of-view instruments have been used extensively over the past five years to conduct the extensive JCMT Legacy Survey (JLS) projects, a suite of seven peer-reviewed large-scale observing programs that probe a wide variety of phenomena, from the detection of debris disks around nearby stars to the distributions of submillimetre galaxies at high redshifts. Note that most of the JLS projects were significantly re-scoped in 2012 to fit into the remaining few years of known JCMT operations. As of this writing, most of the seven JLS projects are complete or nearly complete, i.e., having used all allocated observing time.

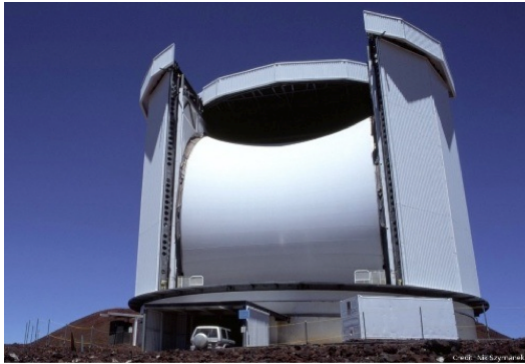


Figure 1: The James Clerk Maxwell Telescope (JCMT) atop Mauna Kea, HI. Credit: Nik Syzmanek

NRC participation in JCMT on behalf of Canada until September 2014 specifically enabled Canadian use of SCUBA-2 for three full years, largely to conduct the JLS projects. Nevertheless, significant untapped scientific potential remains in SCUBA-2, HARP, and the other current JCMT instruments, e.g., RxA3, RxWD. Two additional instruments specifically built by Canadian universities, FTS-2, the SCUBA-2 Fourier transform spectrometer, and POL-2, the SCUBA-2 polarimeter, remain to be commissioned. These instruments also have significant scientific potential but need commissioning time and software development.

The East Asian Observatory (EAO), a new coalition of observatories in China, Taiwan, Korea, and Japan, is planning to take over JCMT operations at the end of January 2015. Realizing the need for access to a large single-dish SMM telescope, the UK and Canada are also working to partner with EAO in JCMT. Discussions about Canada’s role in the new partnership are ongoing; please see the JCMT White Paper by Wilson et al. for details. An important point that must be stressed here, however, is that Canadian support has been identified for only two years. Though plans for new large projects are already being discussed within the new partnership, including Canadians, the viability of the Canadian funding model after 2017 is unclear.

## 2.2 CCAT

CCAT (see Figure 2) will be a 25-m diameter single-dish SMM telescope located near ALMA in Chile. The high-altitude ( $\sim 5600 \text{ m}$ ) site of CCAT is excellent, allowing routine observations of shorter SMM wavelengths. CCAT’s large primary diameter and its site’s typically low precipitable water vapour levels will yield high instantaneous observational sensitivities. Furthermore, CCAT will observe the same sky as ALMA, improving its ability to obtain the ‘big picture’ for follow-up observations with ALMA. Its future instrument directions include long- and short-wavelength SMM continuum cameras, a low-resolution multiplexed spectrometer, and a focal-plane heterodyne array. The CCAT operational model is likely driven by large surveys rather than individual PI projects, though decisions on survey priorities and wider data access have not been finalized.

Given its potential, CCAT was identified as one of the top three priorities for a medium-scale ground-based observatory in the 2010 Canadian Long Range Plan, and remains a top priority within our SMM community. CCAT was also identified as the top priority by the U.S. Astro2010 decadal survey as the highest priority in a similar, mid-sized, ground-based category. CCAT is presently a partnership between universities in the U.S. (Cornell, Colorado), Germany (Köln, Bonn), and Canada (McGill, McMaster, Calgary, Toronto, UBC, Waterloo, Dalhousie, Western, Lethbridge, SMU). The U.S. Associated Universities Incorporated (AUI) organization is also providing logistical assistance to the CCAT project. Canadians have already begun collaborations to build its first generation of instruments. The target for CCAT first light observations is presently  $\sim 2020$ .

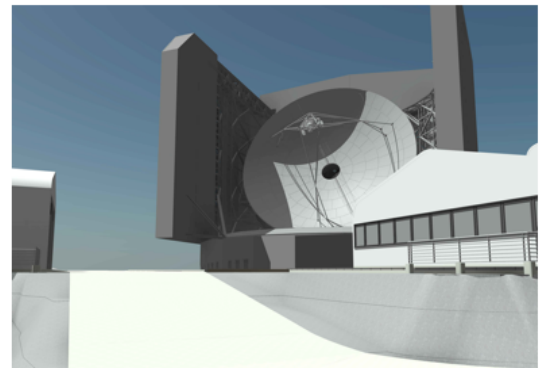


Figure 2: Rendering of the Cerro Chajnantor Atacama Telescope (CCAT) in Chile. Credit: the CCAT Consortium

Though some private funding has been obtained for CCAT construction, as of yet no U.S. or Canadian public funding has been identified; please see the CCAT White Paper by Fich et al. for details. The above coalition of Canadian universities submitted a CFI proposal for the Canadian share of CCAT construction funding (\$30M) in

summer 2014, and a decision is expected in spring 2015. Though funding CCAT construction is presently challenging, the high priority within the community and significant scientific potential of CCAT make it the future for short-wavelength SMM single-dish astronomy.

### 2.3 Single-dish summary

To serve its own large and active SMM community and make best use of its considerable investments in ALMA, Canada requires significant access to a single-dish SMM telescope. In the near-term, Canada must continue its partnership in JCMT. At present, however, the total value of Canada's contributions is TBD. Hence, the size of our share in PI-led projects and the scope of our participation in future large projects or surveys are also TBD. Moreover, the Canadian contribution to JCMT operations will be exhausted in only two years, i.e., early 2017. In the longer term, Canada must transition smoothly from JCMT to CCAT. A significant interruption will negatively affect the ambition, scope, and momentum of research in the Canadian SMM community. The exact date of the JCMT-CCAT transition, however, is unclear. CCAT is presently targeting first light in ~2020, though funding challenges may require that goal to slip. In addition, a source of long-term operational funding from Canada for CCAT is needed. Should CFI decline the present CCAT construction proposal, Canada must remain in JCMT over an even longer timescale, until CCAT is finalized. At any rate, ***new and stable funding for national participation in SMM single-dish facilities must be identified.*** If not, Canada's participation in SMM science will be severely curtailed, and its current estimable global standing in such science will wither.

## 3. Interferometric Facilities: Narrow-Field Imaging and Spectroscopy

Interferometer access is also a critical requirement for success in SMM astronomy. Interferometers are needed to determine details of structure in such targets that are unattainable by any single-dish telescope. Importantly, interferometers are needed to observe SMM emission on small angular scales equal to those probed by optical/IR telescopes, i.e., sub-arcsecond resolutions or less, to address a large host of astrophysical questions.

### 3.1 ALMA



Figure 3: The Atacama Large Millimetre/submillimetre Array (ALMA) in Chile. Credit: ALMA (ESO/NAOJ/NRAO)

ALMA (see Figure 3) consists of three telescope arrays: i) a “12-m Array” of fifty 12-m diameter antennas that can be separated by ~15 km for higher-resolution observations; ii) a “Compact Array” of twelve 7-m diameter antennas fixed to a maximum separation of 33 m for lower-resolution observations; and iii) a “Total Power Array” of four 12-m diameter antennas which provide low spatial frequency (single-dish) data for combination with the other arrays. The arrays are used separately, but the latter two are used exclusively to obtain data complementary to 12-m Array data, and are not used independently for large-scale surveys of SMM emission. ALMA is located in northern Chile at an altitude of ~5000 m, and can presently observe emission from 84 GHz to 950 GHz<sup>2</sup>.

Its dry location, large numbers of antennas, and modern receiver and correlator technologies make ALMA a transformational instrument for exploring the SMM universe at unprecedented sensitivities and resolutions. Accordingly, the Long Range Panel in 2000 recommended Canada join the ALMA project as its highest ground-based observational priority. Today, Canada is partnered in ALMA with 19 other countries; Canada shares in the North American fraction of all ALMA time (~34%) with the United States and Taiwan.

Science operations with ALMA began in late 2011 during the first Cycle of Early Science observing, with a limited number of available antennas (16), baseline lengths (up to 400 m), receiver bands (4), and commissioned correlator modes (7). Indeed, ALMA capabilities have grown with each successive ALMA Cycle, and the next (Cycle 3) is expected to offer 40 antennas with seven receivers and baselines up to 15 km in length. Canadians have used ALMA successfully in the first few Cycles, e.g., as PIs of ~12 high priority projects. Notably, time for high priority ALMA projects is extraordinarily difficult to obtain, with ~1000 proposals on average being submitted per Cycle worldwide in response to the three proposal calls so far, and an average oversubscription rate greater than 5. Projects led by Canadian PIs have been receiving about 3% of available ALMA time in the first

<sup>2</sup> Plans are currently underway to extend ALMA's frequency range down to ~35 GHz, i.e., ALMA Band 1.



few Cycles, i.e., approximately the same percentage as Canada's contribution to ALMA operations costs. Given this extreme demand, it is presently difficult to plan student dissertations or postdoctoral projects around ALMA data. Moreover, students and postdocs cannot get hands-on experience and training with ALMA.

Extraordinary steps have been taken to ensure ALMA is accessible to the wider astronomical community, especially those with no previous experience in SMM astronomy. Nevertheless, Canada's success with ALMA so far is at least in part attributable to its historical access to JCMT. Interferometer proposals necessarily require some indication of the bigger picture, i.e., relevant flux densities and the spatial scales over which they are distributed, to request the appropriate time. Since ALMA and JCMT can view 65% of the total sky in common, JCMT has certainly provided (and will continue to provide) significant amounts of such data. In addition, JCMT has provided the important training ground for Canadian astronomers to gain hands-on experience with SMM observing, which can provide another important advantage in proposals. Access to JCMT also has made Canadians valuable members of teams led by people from countries with no such similar access. CCAT will in future cover 100% of the same sky as ALMA and provide further excellent training opportunities and collaborative value for Canadians. Hence, *Canada's continued success with ALMA may depend on its access to large single-dish SMM telescopes.*

### 3.2 NGVLA

The Karl G. Jansky Very Large Array (VLA; see Figure 4) is the end result of the "Expanded Very Large Array" (EVLA) project, a significant upgrade to the observational capabilities of the Very Large Array operated in New Mexico by the U.S. National Radio Astronomy Observatory (NRAO). The VLA can now observe from 1-50 GHz<sup>3</sup>, and the highest of these frequencies overlap with the longest SMM wavelengths (~10 mm). It consists of twenty-seven 25-m antennas with maximum baselines of ~36 km. To partner with the U.S. in ALMA, Canada and the NRAO formed the North American Partnership in Radio Astronomy (NAPRA), allowing Canadians access to NRAO facilities, including the VLA.



Figure 4. The Karl G. Jansky Very Large Array on the Plains of San Agustin in New Mexico. Credit: AUI/NRAO

Though Full Operations of the new VLA began relatively recently (in early 2013), discussions about further upgrades to the facility began in late 2014. Notably, a "next generation" VLA, e.g., with more antennas and longer baselines, could provide at the longest SMM wavelengths high sensitivities and resolutions approaching those planned for the SKA. With Canada's present involvement in NAPRA, Canadians should keep an eye to future scientific, software, and instrument opportunities to contribute to this project. A workshop to discuss this topic will occur in Seattle, WA on 04 January 2015 and the organizers have specifically sought Canadian participation in the workshop.

### 4. SMM Instrumentation

Canadian access to both single-dish and interferometer telescopes is also critical to keep Canada at the forefront of SMM instrumentation. For ALMA, Canada (through NRC) supplied the suite of 72 receiver cartridges for its Band 3 (84-116 GHz; 3 mm), one of the first four such Bands available to ALMA users and a key band for calibration. The Band 3 team largely drew from experience gained building receivers for JCMT, including RxB3 and RxA3. Based on this background, ALMA represents a key opportunity for continued Canadian instrument development, advancing our valuable expertise in this area. For example, members of the ALMA Band 3 team are contributing to the development of new ALMA Band 1 receivers (in a project led by Taiwan). In addition, Canadians are studying development possibilities for focal-plane array receivers for the Total Power Array antennas and improvements to Band 3 receiver design. Moreover, Canadians are also currently exploring key software developments related to ALMA. Note that partnerships in JCMT and CCAT will allow Canada to develop new instrumentation for those facilities as well. Finally, we note that Canadians designed and built the revolutionary ACSIS spectral correlator for JCMT and the WIDAR correlator for the VLA.

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<sup>3</sup> Frequencies lower than 1 GHz are also observable with the VLA but only over certain bands.

## 5. Summary of Strategy

In this document, we advocate for continued Canadian involvement in SMM astronomy. This involvement requires access to both single-dish telescopes and interferometers, since both are needed to get as clear a picture as possible of SMM emission in the sky. For single-dish facilities, Canada will have access in the near-term to the JCMT and in the long-term to CCAT. Canada should determine new and stable operational funding for these facilities, allowing a smooth transition from JCMT to CCAT once the latter begins operations. As Canada's role in the JCMT led to strong Canadian involvement within BLAST, *Planck*, and *Herschel*, it is expected that continued support of the JCMT and CCAT, especially in their pathfinder roles, will open doors for increased Canadian participation in future balloon and space missions (e.g., SPICA; see White Paper by Naylor et al., FIRI). For interferometric facilities, Canada has access to ALMA and the VLA, both of which have begun to thrive as they enter their respective full operations phases. By sheer demand, however, Canada cannot expect the same access to these interferometers as they can enjoy with significant shares in single-dish telescopes. Such shares provide key information for effectively using interferometers, allow Canadian students and postdocs to be well trained, and enable key Canadian instrumental expertise to be retained.