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# Final Report to LRP Panel: the Square Kilometre Array

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## ABSTRACT

The Square Kilometre Array (SKA), an exciting new world observatory that will enable transformational science at metre and centimetre wavelengths for years to come, is rapidly becoming reality. Scientific and technological participation in the SKA has been identified as a top priority for the Canadian astronomical community for almost twenty years. This report to the 2020 Long Range Plan Panel (LRPP) summarizes the history of the SKA in Canada and provides an update on the SKA project since the 2015 Mid-Term Review of the 2010 Long Range Plan (LRP), focussing on the first phase of the project (SKA1) scheduled to begin construction early in the next decade. The current state of Canadian participation in the SKA from scientific, technological, and governance standpoints is also discussed. Finally, we provide technical and financial information to support the recommendations regarding Canada's future participation in the project that are discussed in the SKA LRP white paper.

## 1. INTRODUCTION AND EXECUTIVE SUMMARY

The Square Kilometre Array (SKA) is one of the most ambitious astronomy projects on the horizon today, with broad science goals and challenging technical requirements. When constructed, it will be the largest and most powerful general-purpose radio telescope operating from 50 MHz – 15+ GHz for years to come. The SKA will be built in two phases, with the first phase (SKA1; Fig. 1) representing ∼10% of the full facility (SKA2). SKA1 will do transformational science by virtue of its combination of sensitivity and angular resolution relative to current and planned facilities. The SKA1 design is now mature, and construction is set to begin early in the next decade. This final report, requested by the Long Range Plan Panel (LRPP) to help assess the current Canadian astronomy landscape, focusses on SKA1 and supercedes the initial report submitted to the panel a few months ago.

Canada has a long history of significant scientific and technological contributions to the SKA, and Canadian leadership was instrumental in the early days of the project. Canadian participation in the SKA has been highly ranked by two previous Long Range Plan (LRP) prioritizations and their subsequent Mid-Term Reviews (MTRs), which have enabled sustained leadership in the project for the past two decades. A brief history of the SKA project in Canada through the lens of the LRP process from 2000 – 2015 is given in §2.

The SKA project has evolved significantly since MTR 2015, particularly in terms of SKA1 design, timeline, and governance. SKA1 is transitioning from a pre-construction to a construction phase, with construction projected to begin in 2021 and full operations getting underway towards the end of that decade. An update of the global SKA project since MTR 2015 is given in §3.

Canada is poised to play leadership roles in SKA1 science and technology. Our scientific community has significant strengths in pulsars, magnetism, transients, low-frequency cosmology, galaxy evolution, multi-messenger astronomy and planetary system formation, and Canadians have the potential to play world-leading roles in corresponding SKA1 Key Science Projects (KSPs) and PI programs. Our key SKA1 technological capabilities include the design and fabrication of correlators and beamformers, low-noise amplifiers (LNAs) and digitisers as well as signal processing monitor & control; these technologies provide a suite of possible in-kind contributions to offset construction costs. Canada also has the computing platform and archive development expertise to host an SKA Regional Centre (SRC) that will be needed to scientifically exploit SKA1 data. The recent history and current status of SKA-related science and technology in Canada is given in §4.1–§4.3.

Canada currently contributes to SKA governance through its membership in the Square Kilometre Array Organisation (SKAO) responsible for the SKA1 design, and is an Observer of the Council Preparatory Task Force (CPTF) of the Inter-Governmental Organisation (IGO) that will oversee SKA1 construction and oper-

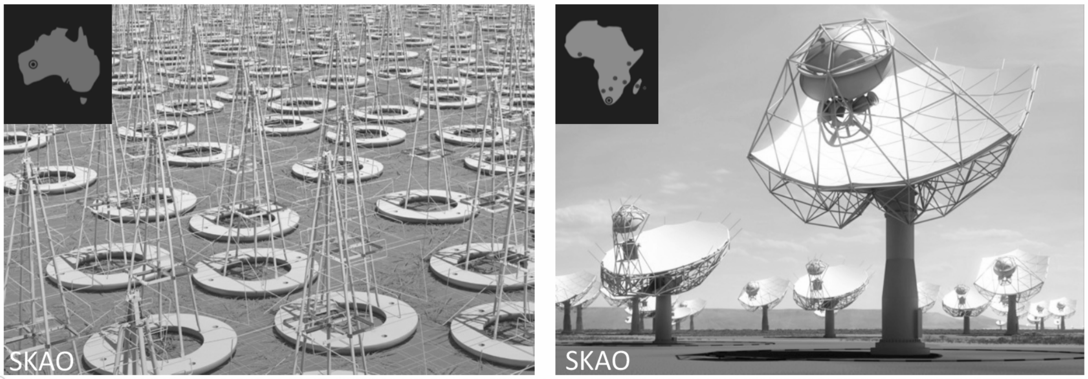

**Figure 1.** Artist's conception of SKA1-Low antennas (left panel) and SKA1-Mid dishes (right panel) with their approximate locations in Australia and South Africa shown by the inset sketches. Image credit: SKAO.

ations. An estimate of scientific leadership opportunities afforded by SKA1 Key Science Projects (KSPs) during normal operations suggests that a Canadian participation level of 6% in SKA1, adopted as a benchmark in recent years, remains commensurate with our scientific capacity and ambitions. A summary of the recent history and current status of SKA governance in Canada as well as a discussion of the construction, operations and SRC costs from 2020 – 2030 for a 6% participation are given in §4.5.

SKA1 is happening now, and continued Canadian engagement with the project will require participation in the construction and operations phases. The future prospects for Canada and the SKA from 2020 – 2030, that build directly on the history and current status of the project detailed in this report, are described in the SKA White Paper (WP) submitted for LRP 2020 (Spekkens et al. 2019). We summarize the central themes explored and recommendations therein in §5.

## 2. CANADA, THE SKA, AND THE LRP: HISTORY

As an early international leader in very large radio telescope design and one of 6 signatories to a 1997 MOU to collaborate on technology development for what would eventually become the SKA (Ekers 2012), Canada's history with the project is both long and significant. This long-standing participation is a consequence of the high scientific and technological priority assigned through LRP planning processes over the last two decades. A compilation of SKA-related recommendations by all previous LRP and Mid-Term Review (MTR) panels is given in Table 1. This section summarizes the history of Canada and the SKA through the LRP lens, focussing on LRP 2010 through MTR 2015.

### 2.1. *LRP 2000 – LRP 2010*

LRP 2000 (Pudritz et al. 2000) recommended that Canada join the SKA and a Very Large Optical Telescope (VLOT) project with equal priority. This recommendation was re-iterated by MTR 2005 (Seaquist et al. 2005), although it was recognised that VLOT access through the Thirty Meter Telescope (TMT) project was likely to precede SKA construction. SKA-related technological development and prototyping were ranked among the highest priority moderate-sized projects in both LRP 2000 and MTR 2005. It was estimated that \$10M (LRP 2000) – \$30M (MTR 2015) CAD would be required from 2000 – 2010 to fulfill these recommendations; correspondingly, Canada was participating in the SKA project at the ∼\$2.5M CAD/yr level by the end of that decade.

LRP 2010 (Pritchet et al. 2010) recognised the potential for the SKA's sensitivity and resolution to afford far-reaching advances on a number of pressing scientific questions regarding dark energy, gravity, galaxy evolution and planetary formation, as well as the potential for Canada to become a technological leader in the project given the follow up by NRC-HIA on previous LRP+MTR recommendations. Canadian participation in the SKA was ranked as the top priority following VLOT by the 2010 LRPP, with related R&D as the highest-priority medium-scale project from 2010 – 2020. LRP 2010 estimated that \$15M CAD would be required for detailed SKA design and engineering in that decade, and that Canadian participation in the SKA at a level commensurate with its standing in the partnership at the time (∼ 10%) would require construction funds of ∼\$60M CAD for SKA1.

### 2.2. *2011 – MTR 2015*

Significant developments in the SKA project and in Canada's SKA participation ensued from 2011 – 2015. The Square Kilometre Array Organisation (SKAO) was established 2011 to move the project into a pre-construction design phase. Canada joined the SKAO in 2012, agreeing to deliver €8M (2012 Euro) of in-kind work in the Central Signal Processor (CSP), the Dish Consortium (DSH) and Phased Array Feed (PAF) element consortia (∼8% of the total consortium pre-construction

**Table 1.** Past LRP-related recommendations regarding the SKA

| Document | Recommendation |
|---|---|
| LRP2000 | **3:** The LRPP strongly recommends that the Canadian Large Adaptive Reflector (LAR) concept be carried forward into prototypes for key component (phase B) studies. This study should be one of the highest priorities among moderate size projects. |
| LRP2000 | **6:** The LRPP recommends that Canada position itself now for entry into the construction of SKA as well as VLOT. |
| LRP2000 | **7:** The LRPP strongly recommends the enhancement of the correlator and receiver groups within NRC. This should be one of the highest priorities among moderate size projects. |
| MTR2005 | **7:** The MTRP strongly reaffirms the original LRPP recommendation that Canada position itself to play a leadership role in the international SKA initiative. |
| MTR2005 | **8:** The MTRP strongly recommends that the Phase B Study, leading to a design of the LAR, be supported to ensure its successful and timely completion for the selection of the design of the SKA by the international SKA consortium. The Phase B Study should be at the highest priority level among moderate size projects. |
| MTR2005 | **9:** The MTRP recommends that NRC-HIA plan to participate in the construction of prototype components of the SKA once the decision on the SKA technology has been made. This could be either an antenna element based on the LAR design, if this design is adopted by the SKA project, or other components based either on the work of the Phase B Study or on other expertise in radio astronomy instrumentation. |
| LRP2010 | **16:** The LRPP reaffirms the importance and very high priority of Canada's participation in the SKA, which it anticipates will become the top priority following VLOT. Canada should continue its current path in the engineering design and prototype development of SKA elements, leading to participation in the pre-construction design phase, and should continue to seek opportunities to build components where Canada has experience and an international reputation. SKA R&D is the highest priority medium-scale project over the next decade. The decision as to how and when Canada should enter the construction phase of SKA should await further reviews of SKA project development, a more accurate cost estimate, better understanding of international prospects, and a better knowledge of timing for funding a construction start. |
| MTR2015 | **8:** The MTRP re-iterates the very high importance of Canada's technological and scientific participation in the next generation of radio telescope facilities. With TMT construction funds committed, access to the capabilities provided by SKA1 in the next decade is the top priority for new funds for ground-based astronomy. The MTRP re-iterates the high priority of mid and low-frequency radio R&D, and in particular the development of key technologies for SKA1 tender and procurement. |
| MTR2015 | **9:** The MTRP strongly recommends that Canada enter into negotiations to join the intergovernmental organization that will oversee SKA1 construction and operations starting in 2017. An alternative to a treaty may be needed for Canada to join SKA1; this alternative must not significantly compromise Canada's role in SKA1 governance, access, or construction tender and procurement. |

activity costs). The decision to site SKA1-Low (and, at the time, SKA1-Survey) in Australia and SKA1-Mid in South Africa was made in 2012, while the UK was chosen to host SKA Headquarters in 2015. A cost cap of €650M (2013 Euro) was imposed on SKA1 construction (see §3.2 for how construction is defined) in 2013 by the SKAO Board of Directors. Design reviews and the identification of design-driving Highest Priority Science Objectives (HPSO) (Braun et al. 2014) were undertaken in 2014 (see §3.2), and a re-baselining in 2015 finalized the design baseline for SKA1-Low and SKA1-Mid (and deferred SKA1-Survey) while preserving these science goals (see §3.1). The 2000-page updated SKA Science Book was published in 2015, and by that time Canadian astronomers had joined almost all of the SKA Science Working Groups (SWGs) and were playing leadership roles in SKA Pathfinder facility surveys. It was also becoming clear by that time that SKA governance would likely transition to an Inter-Governmental Organisation (IGO) for construction and operations. ACURA constituted the AACS in 2015 to advise it and NRC on the needs of university astronomers during the design, pre-construction and construction phases of the SKA.

MTR 2015 (Thacker et al. 2015) recognised that the SKA1 science case is well-aligned with Canadian research interests and areas of considerable Canadian expertise, noting the potential for leadership in pulsar searches and timing experiments to carry out strong-field gravity tests, radio continuum and polarimetry surveys to measure cosmic magnetism, transient studies to explore the variable radio universe, and both resolved and unresolved atomic gas surveys as a probe of galaxy evolution and cosmology. It also noted the superiority of SKA1 relative to existing or forthcoming instruments for pulsar searches, cosmic magnetism and galaxy surveys, as well as the complementarity between SKA1 and CHIME for pulsar timing. MTR 2015 concluded that Canada's leadership role in SKA engineering design and prototype development, in particular its correlator, low-noise amplifier (LNA) and digitizer technology, had forged strong partnerships with industry to directly improve SKA1 performance and position Canada to compete for tender and procurement of SKA1 construction contracts.

The 2015 MTRP re-reiterated the very high importance of scientific and technological participation in next-generation radio telescope facilities such as SKA1, citing access to SKA1 capabilities as the top priority for new ground-based astronomy construction funds. MTR 2015 re-affirmed the LRP 2010 assessment that the SKA1 construction funding required was ∼\$60M CAD, which could feasibly be provided by an ensemble of in-kind Canadian technology contributions. Accordingly, the development of key technologies for SKA1 tender and procurement was highly prioritized. The 2015 MTRP also strongly recommended that Canada enter into negotiations to join the SKA1 IGO, stipulating that alternatives to treaty membership must not significantly compromise Canadian governance, access, or construction tender and procurement.

## 3. SKA PROJECT UPDATE

There has been a tremendous amount of activity within the SKA project since the 2015 MTR. This section summarizes the recent history and current status of the SKA1 design (§3.1), projected construction and operations timelines (§3.2) and costs (§3.3), and project governance (§3.4).

### 3.1. *SKA1 Design Baseline*

The 2014 design reviews and 2015 re-baselining exercises undertaken by the SKAO finalized the SKA1 Design Baseline, and it remains the design and construction benchmark today. Illustrations of SKA1-Low and SKA1-Mid are shown in Fig. 1, and their projected sensitivities and survey speeds relative to other facilities are shown in Fig. 2. Because of its global research significance, the SKA1 Baseline Design has had "landmark" status within The European Strategy Forum on Research Infrastructures (ESFRI) since 2016 (ESFRI 2018); this honour is rarely bestowed, and is an indication of the very high profile of the SKA in Europe.

The SKA1-Low Design Baseline comprises 512 stations each with 256 antennas, providing continuous frequency coverage from 50 MHz – 350 MHz and a maximum interferometric baseline of 65 km (Dewdney et al. 2016). Averaged over the LOFAR band, SKA1-Low will have 1.25 times the Low Frequency Array (LOFAR) resolution, 8 times its sensitivity and 135 times its survey speed (see Fig. 2). The SKA1-Mid Design Baseline comprises $133 \times 15$ m dishes as well as the $64 \times 13.5$ dishes from the MeerKAT SKA Pathfinder working in concert from 350 MHz – 15+ GHz, with a maximum interferometric baseline of 150 km (Dewdney et al. 2016). The frequency range spanned by SKA1-Mid is divided into several bands, of which 3 are part of the Design Baseline: Band 1 will contiguously span 350 MHz – 1.05 GHz, Band 2 will contiguously span 950 MHz – 1.76 GHz, and Band 5 will span 4.6 GHz – 15.3 GHz in $2 \times 2.5$ GHz sub-bands. Bands 3, 4 and the upper end of Band 5 will be deployed as upgrade paths[1]. When averaged over the overlapping JVLA bands, the SKA1-Mid Design Baseline will have 4 times the resolution of the Jansky Very Large Array = Expanded Very Large Array (JVLA) in its A configuration, 4 times its point-source sensitivity and 60 times its survey speed (see Fig. 2).

Much of the SKA design work in the last decade has taken place within 12 design element consortia, involving $\sim$ 600 scientists and engineers from around the world and a total cost of ~€ 200M. The SKA1 Design Baseline relies on 9 of these consortia, and the progress of each one towards element Critical Design Review (CDR) is illustrated in Fig. 3. Seven consortia have successfully completed CDR and related closeout activities (green circles in Fig. 3); remaining development work has been transferred to SKAO and these consortia have been dissolved, including the Canada-led CSP

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[1] We note that the digitiser system and the rest of the signal chain will be ready to handle these signals at the onset of operations, with a minimum amount of work; the upgrade paths require only funding, not technology development.

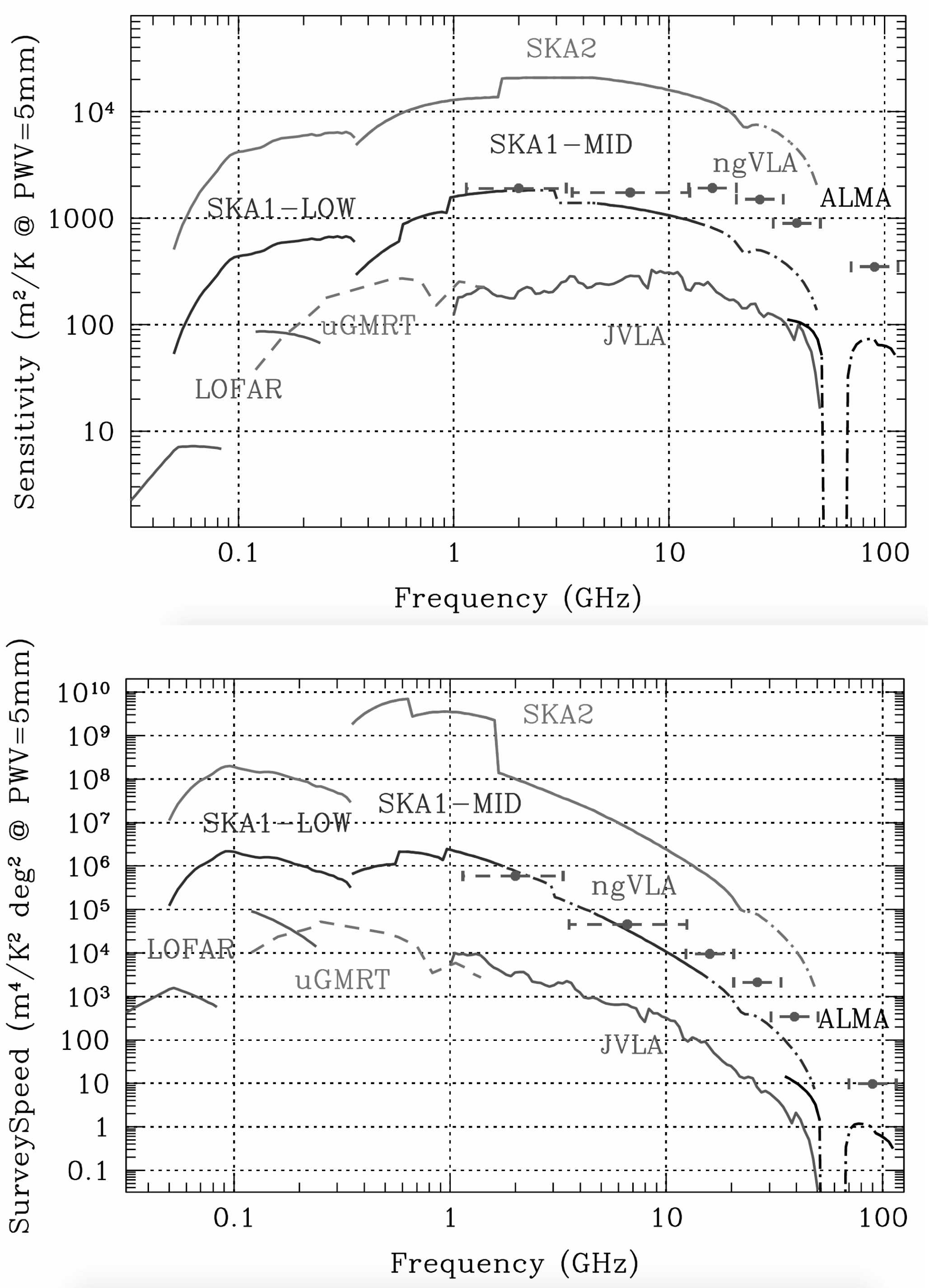

**Figure 2.** Anticipated SKA1 sensitivity (top panel) and survey speed (bottom panel) as a function of frequency in comparison to existing facilities as well as to the anticipated ngVLA performance. For all facilities, sensitivity is defined as $A_{eff}/T_{sys}$ where $A_{eff}$ is the effective area and $T_{sys}$ is the system temperature, while survey speed is defined as $(A_{eff}/T_{sys})^2 \times FOV$ where $FOV$ is the field-of-view. The SKA1 numbers correspond to the Design Baseline (Braun et al. 2017), and the dot-dashed lines indicate upgrade paths (see text). The ngVLA numbers correspond to the reference design (Selina et al. 2019). Note that the highest frequency ngVLA point assumes PWV= 1 mm, while the corresponding ALMA curve corresponds to PWV= 5 mm. Image credit: SKAO.

**Figure 3.** Illustration of SKA1 consortia and their progress towards CDR. Green circles indicate consortia for which CDR + closeout is complete; those consortia have been dissolved. The CSP consortium led by Canada (see §4.2) is highlighted. Orange circles represent consortia for which CDR is complete but closeout is ongoing. The orange arc around DSH indicates an upcoming CDR (scheduled for Q2 2020). System CDR is scheduled for Q4 2019. Image adapted from SKAO infographic, which reports up-to-date CDR information (Carbon Creative & SKA Communications 2019).

(see §4.2). At the time of writing, LFAA has completed CDR and closeout activities are underway (orange circle in Fig. 3). The only outstanding element CDR is that for DSH (orange arc in Fig. 3), which has been scheduled for Q2 2020 to provide enough time for prototyping lessons learned to be incorporated into the design and for outstanding Intellectual Property (IP) issues to be resolved. SKA1 system CDR is scheduled for Q4 2019.

### 3.2. *SKA1 Construction and Operations*

With a mature Design Baseline and the CDR process nearly complete, the construction timeline for SKA1 is becoming more concrete. A representation of that timeline that focusses on scientific milestones is shown in Fig. 4. The timeline is anchored by an anticipated construction start in Q2 2021, which assumes an IGO treaty ratification duration of 12 months (see §3.4) and a construction tender and procurement duration of $\sim$ 18 months. Science commissioning will start as soon as the first dish or station is on-site in 2023.

The deployment of antennas during SKA1 construction will be staged into four Array Assemblies (AAs), and the timeline for major SKA1 science milestones is tied to the availability dates for AA2 (= 64 SKA1-Low stations, 64 SKA1-Mid dishes; the minimum array of stations or dishes that is scientifically competitive with current

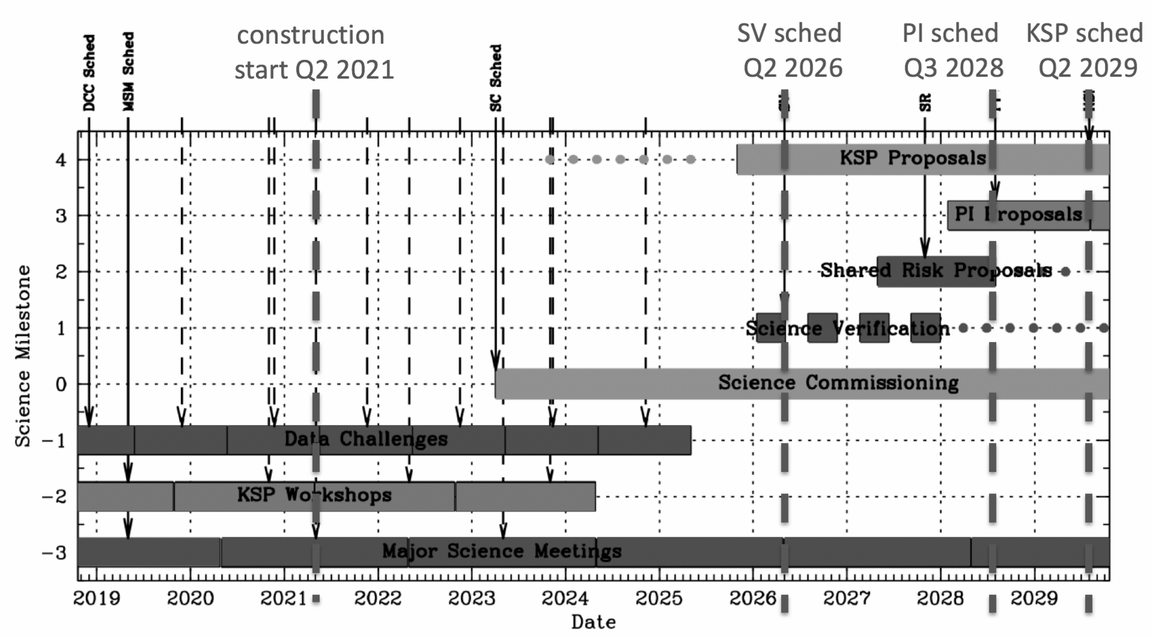

**Figure 4.** Projected SKA1 science milestone timeline adopting the most recent construction start estimate of Q2 2021 (leftmost red vertical line) and a construction duration of 7 years. Other red vertical lines highlight the anticipated time at which of Science Verification (SV), Principal Investigator (PI) and Key Science Projects (KSP) observations would be scheduled from left to right respectively. Image adapted from SKAO infographic.

facilities) and AA4 (= completed SKA1 arrays). Science verification will start 9 months after the completion of AA2 to allow for component testing, and is anticipated in 2026. Shared risk observations with the full complement of SKA1-Mid dishes and SKA1-Low stations are expected to begin in late 2027, 3 months after the completion of AA4.

The vast majority ($\gtrsim 95\%$) of the available observing time on SKA1 will be reserved for participating countries. The balance of observing time allocated to PI projects compared to that earmarked for the of execution large programs – called Key Science Projects (KSPs) by SKAO – will be finalized during the construction phase. However, a rough breakdown between the two can be gleaned from the Highest-Priority Science Objectives (HPSO; Braun et al. 2014) that resulted from an SKAO prioritization of community ambitions. The list of HPSO is given in Table 2 (Braun et al. 2014), where they have been grouped according to the Science Working Group (SWG) under which they fall but are otherwise listed in arbitrary order. HPSOs informed the development of the SKA1 Level 0 Science Requirements (Braun et al. 2015) among other factors; they are representative of community ambitions for SKA1, and are likely to require KSP-like allocations to accomplish (Braun et al. 2015; see also §4.5)[2]. A consideration

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[2] There is therefore no direct counterpart to ALMA's Level 1 Science Goals (NRAO 2019a) within the SKA1 design framework, but the L0 Science Requirements (Braun et al. 2015) come closest while the HPSOs are SKAO-prioritised but non-binding community ambitions. KSPs resemble ALMA Large Programs (NRAO 2019b), but it is reasonable to assume that the KSPs that are proposed will bear some resemblance to the HPSOs.

**Table 2.** SKA1 Highest Priority Science Objectives (HPSO)$^a$

| SWG | Science Objective |
|---|---|
| CD/EoR | Physics of the early universe IGM: I. Imaging |
| CD/EoR | Physics of the early universe IGM: II. Power spectrum |
| Pulsars | Reveal pulsar population and MSPs for gravity tests and GW detection |
| Pulsars | High-precision timing for testing gravity and GW detection |
| Atomic Gas | Resolved HI kinematics and morphology of $M_{HI} \sim 10^{10}\,\mathrm{M}_{\odot}$ galaxies out to $z \sim 0.8$ |
| Atomic Gas | High spatial resolution studies of the ISM in the nearby Universe |
| Atomics Gas | Multi-resolution mapping studies of the ISM in our Galaxy |
| Transients | Solve missing baryon problem at $z \sim 2$ and determine the dark energy equation of state |
| Cradle of Life | Map dust grain growth in terrestrial planet forming zones at a distance $d = 100\,\mathrm{pc}$ |
| Magnetism | Resolved all-sky characterisation of the interstellar and intergalactic magnetic fields |
| Cosmology | Constraints on primordial non-Gaussianity and tests of gravity on super-horizon scales |
| Cosmology | Angular correlation functions to probe non-Gaussianity and the matter dipole |
| Continuum | Star formation history of the universe: I+II. Non-thermal and thermal processes |

Note—*a*: HPSO are grouped by SWG (see Table 5) but are otherwise listed in arbitrary order.

of the baseline KSP-like surveys required to accomplish the HPSOs leads to 50%−75% of SKA1 time being reserved for KSPs and the remaining 25% − 45% being reserved for PI programs (see Appendix A for a specific example of plausible KSP distributions over a decade of operations).

The construction timeline in Fig. 4 anticipates that PI projects will be scheduled for observations with SKA1 starting in 2028 with the onset of full operations, while the KSP proposal process will kick off in late 2025 and KSPs will be scheduled starting in 2029. A number of scientific activities are planned to prepare the community for SKA1 observations and data, including major science meetings (such as “Fundamental Physics with the Square Kilometre Array” in 2017, jointly hosted by the University of Toronto and the University of Cape Town), KSP Workshops (most recently held in March 2019 at SKAO Headquarters) and Science Data Challenges (the first of which took place from November 2018 – April 2019). These initiatives are also indicated in the construction and operations timeline in Fig. 4.

The raw data rates, processing speeds and calibrated data volumes implied by the SKA1 Design Baseline and anticipated observing modes are enormous: SKA1-Low and SKA1-Mid will stream 7.2 Tb/s and 8.8 Tb/s of raw data into the CSP, respectively, which in turn will feed $\sim 5$ Tb/s into the Science Data Processor (SDP) that will use $\sim 250$ Pflops to produce $\sim 600$ Pb/yr of calibrated data products. A tiered model for data and science support, similar to that employed by CERN, has therefore been adopted for SKA1 (Bolton et al. 2018; Scaife, A 2018). Storage and processing resources associated with and funded by the observatory itself will be highly constrained in order to keep up with operational demands, and are expected to be limited to that required simply to calibrate raw datasets. Any further processing and subsequent science extraction by users will require significant, outside computing and storage resources in the form of SKA Regional Centres (SRCs) The number of SRCs that is currently anticipated to handle the global science processing and archive+interface needs for SKA1 is of order 5. A variety of initiatives are underway to develop this capacity in time for SKA1 science commissioning, such as the European AENEAS (AENEAS 2019; recently superceded by ESCAPE [SKAO 2018]) the Eridanus Asia-Pacific collaboration, and the Canadian Initiative for Radio Astronomy Data Analysis (CIRADA) (see §4.3).

### 3.3. *SKA1 Costs and Deployment Baseline*

There are 3 basic elements to the cost of SKA1 (excluding science data processing and storage, which requires separate SRC funding; see §3.2) during the construction phase:

1. The cost of procuring and constructing the facilities in Australia and South Africa;
2. The cost of construction activities at SKA Headquarters; and
3. The cost of early operations and business-enabling functions ramping up to full operations by the end of construction.

For consistency with previous cost definitions as well as the most recent numbers released by the SKAO Board of Directors (Césarsky 2019a), this report will follow the historical SKAO convention of defining “construction” to comprise the first element, and “operations” to encompass the second two elements.

SKA1 construction is currently cost-capped at €650M in 2013 Euros, or €691M when inflation-adjusted to 2017 Euros. In 2017, a review of the SKA1 design called the Cost Control Project (CCP) was undertaken to explore and capitalise on a range of cost-saving measures designed to ensure the delivery of an instrument within the cost cap. While some cost savings were identified that do not compromise the Design Baseline, a significant outcome of the CCP was the definition of a “Deployment Baseline” for SKA1. While the Design Baseline remains the design and construction goal for SKA1, the Deployment Baseline corresponds to as much of the Design Baseline as can be afforded at the time of construction (the latter can be recovered later given the scalable nature of interferometers).

The final Deployment Baseline will be defined in the SKA1 construction proposal, but an estimate was made during the 2017 CCP given the available costing and anticipated scientific impact of possible cost-saving measures on the project. A comparison between the Design Baseline and this estimated Deployment Baseline is given in Table 3. The scientific assessment from the CCP concluded that the 2017 Deployment

**Table 3.** SKA1 Design and 2017 Deployment[a] Baselines

| **Telescope** | **Design Baseline** | **2017 Deployment Baseline**[a] |
|---|---|---|
| **SKA1-Mid** | | |
| No. dishes | 133 | 130 |
| Max. baseline | 150 km | 120 km |
| No. Band 1+2 Feeds | 133 | 130 |
| No. Band 5 Feeds | 133 | 67 |
| Pulsar search | 500 nodes | 375 nodes |
| **SKA1-Low** | | |
| No. stations | 512 | 476 |
| Max. baseline | 65 km | 40 km |
| Pulsar search | 167 nodes | 125 nodes |
| **Common** | | |
| Compute power[b] | 260 PFLOPs | 50 PFLOPs |

Note—*a*: most recent estimate given available costing. A bottom-up cost review is scheduled for Q2 2020. *b*: Compute is projected to refresh to Design Baseline 3-5 years after deployment.

Baseline will provide transformational science capabilities, albeit with reduced science returns relative to the Design Baseline.

By definition, the total construction cost of the 2017 Deployment Baseline is capped at €691M (2017 Euros), while the most recent estimated cost of the Design Baseline is $\gtrsim$30% higher at €914M (2017 Euros; Césarsky 2019a). Note that the increased Design Baseline cost estimate relative to earlier numbers (most recently €816M in 2017 Euros from Césarsky 2018) stems from both revised element costing and an increase in the contingency estimate, which is now being generated by SKAO using an industry-standard 80% probability of success metric endorsed by the Board of Directors. Operations costs for the Baseline Design and 2017 Deployment Design in the decade following the start of construction are expected to roughly equal the construction cost of the Deployment Baseline. The operations costs for the Design Baseline and 2017 Deployment Baseline will be similar because the difference between them is mainly computing hardware (see Table 3). During regular operations, the total operations costs of SKA1 have been estimated to be €92M/yr (2017 Euro; Césarsky 2019b).

It is important to note that the Design Baseline and operations costing will evolve very soon, as will the definition of the final Deployment Baseline. The SKAO is developing a Cost Book using the same bottom-up Work Breakdown Structure (WBS)-based costing methodology as other large science projects (e.g. LIGO, DKIST, LSST and TMT). Costs associated to risks are fully included in this methodology. A series of 6 construction planning workshops that began in late 2018 will deliver a Design

Baseline Cost Book in Q2 2020. The production of this Cost Book will also be informed by System CDR planned for December 2019. The Cost Book will then be subjected to a full external review to a panel of international experts, and a recommendation for the final Deployment Baseline will be made shortly thereafter.

While current costing remains uncertain, the steady increase in the estimated Design Baseline construction cost relative to the cost cap suggests that the final Deployment Baseline will be less capable than the 2017 Deployment Baseline defined in Table 3. The SKAO has suggested that recruiting new members to the project may help close the gap between the Design Baseline and cost cap, something it has successfully done since the cost cap was adopted in 2013 (see Table 4).

The details of the procurement model that will be employed to construct SKA1 will be determined by the Inter-Governmental Organisation (IGO) that will oversee construction and operations (see §3.4), but a range of models from fully allocative to fully competitive have been discussed. The framework that has been endorsed (Césarsky 2019a) is a hybrid allocative model, in which the default position would be competitive procurement but where allocations could be formally requested. This model has the potential to accommodate both cash procurements and in-kind contributions as well as to reconcile work-return aspirations by participating countries. A non-binding request for information (RfI) was issued in Q1 2018 in order to gauge tender and procurement interests for SKA1 Design Baseline elements. The responses received suggest that a workable distribution of aspirations among participating countries can be plausibly expected with satisfactory fair work return (FWR) – the fraction of contributed funds spent in one's own country – for all. A procurement model that encourages competition for elements of high interest has also been discussed.

### 3.4. *SKA Governance*

Design and pre-construction activities within the SKA project in the last decade have been overseen by the Square Kilometre Array Organisation (SKAO), a not-for-profit private company limited by guarantee in the UK. The Director-General of the SKAO is Phil Diamond, and the organisation currently employs $\sim 90$ full-time equivalent staff (FTE) (Césarsky 2019a). Table 4 lists the current member countries of the SKAO, the year that they joined and the adhering organisation. The last year has been active from the perspective of recruiting SKA partners, with the addition of three new countries (France, Spain and Germany) to increase the total number of SKAO members to 13.

The SKAO is guided by a Board of Directors chaired by Catherine Césarsky (SKAO 2019a), and comprises two members from each adhering organisation. Independent scientific and technical advice from the international astronomical community is provided to the SKAO and its Board by an 18-member Science and Engineering Advisory Committee (SEAC). Concepts for a global SKA Regional Centre (SRC) net-

**Table 4.** Current SKAO Members and IGO signatories

| Participating Country | Membership Year (SKAO) | Adhering Organisation to SKAO |
|---|---|---|
| *Australia* | 2011 | Department of Industry, Innovation and Science |
| Canada | 2012 | National Research Council of Canada (NRC) |
| *China* | 2012 | Ministry of Science and Technology |
| France | 2018 | National Center for Scientific Research |
| Germany | 2019 | Max Planck Society |
| India | 2015 | National Centre for Radio Astrophysics |
| *Italy* | 2014 | National Institute for Astrophysics |
| New Zealand [a] | 2012 | Ministry of Economic Development |
| *Portugal* [b] | | |
| *South Africa* | 2011 | National Research Foundation |
| Spain | 2019 | Ministry of Science, Innovation & Universities |
| Sweden | 2012 | Onsala Space Observatory |
| *The Netherlands* | 2011 | Netherlands Organisation for Scientific Research |
| *United Kingdom* | 2011 | Science and Technology Facilities Council |

Note—Countries in italics are Founding Members of the IGO (SKAO 2019b). *a* New Zealand has confirmed that it will not participate in SKA1 IGO (SKAO 2019c). *b*: Portugal is an IGO Founding Member but not an SKAO member.

work were initially developed by an independent SKA Regional Centre Coordination Group (SRCCG), but this group was superceded in 2019 by a new SKA Regional Centre Steering Committee (SRCSC) that is a partnership of emerging SRCs and the SKAO.

The recent focus of the SKAO has been oversight of the element consortia CDRs (see §3.1) and preparations for System CDR in Q4 2019. Outstanding design work following element and System CDR is being undertaken by the SKAO during a ∼year-long "Bridging Phase" between pre-construction and construction.

SKAO activities are limited to pre-construction, and stewardship of the SKA project will transition to a different organisation for construction and operations. The final act of the SKAO will therefore be to deliver detailed construction and operations proposals to that new entity, which is anticipated to take over the project in Q4 2020 (Césarsky 2019a). It is estimated that the post-System CDR work within the SKAO required to develop the construction and operations proposals that will be delivered to the IGO will require a significant increase in staff to the SKAO in its waning year, and recruitment is ongoing.

The construction and operations of SKA1 will be undertaken by an Inter-Governmental Organisation (IGO) called the SKA Observatory[3] that is established by a treaty convention. An IGO, which is the governance structure that underlies CERN and ESO, differs fundamentally from a company in that it provides sovereign protection to the organization and to its employees. A signing ceremony for the IGO Treaty Convention and Final Record was held in March 2019 (SKAO 2019b), and the seven countries that have insofar signed the Convention are the IGO Founding Members, highlighted in italics in Table 4. In August 2019, The Netherlands became the first country to ratify the Treaty Convention (SKAO 2019d), following its commitment of €30M of construction funding earlier in the year (SKAO 2019e).

The IGO will come into existence once 5 signatories have ratified the Convention, which is anticipated to occur by Q3 2020 (Césarsky 2019a). Countries that join the IGO after the first year can only do so via an accession process to be negotiated with the IGO Council that will be formed once the Convention is ratified. Among the SKAO member countries in Table 4, only New Zealand has indicated that it will not participate in SKA1 construction and operations (SKAO 2019c).

Since funding commitments towards SKA1 construction and operations were decoupled from treaty negotiations early in the process, the IGO will exist before financial commitments (and their corresponding payment schedules and contribution definitions) are in place, and the first major task of the IGO at its inaugural meeting will be to approve a budget for its first year of operations (anticipated to be 2021; Césarsky 2019a). It should also be noted that SKA1 was decoupled from SKA2 in the IGO Treaty Convention, and therefore joining the IGO to build and operate the former does not imply a commitment to the latter.

Since the IGO Council comes into force only once the Convention is ratified 5 Founding Members, a Council Preparatory Task Force (CPTF) was formed at the Convention signing that represents the interests of the IGO in the interim. The CPTF is comprised of the countries that have indicated their willingness to join the IGO, and will be the body involved in the transition process that will see the SKAO absorbed by the IGO. The CPTF held its inaugural meeting in March 2019, and the focus of its activities will be the development of a funding schedule, the establishment of principles governing Associate Membership, and the finalisation of key documentation such as procurement strategy and IP policy (Césarsky 2019b).

The most significant governance milestone in the history of the SKA project is the upcoming transition from the SKAO and its Board of Directors to the IGO and its Council, which is unprecedented for a scientific infrastructure project (the closest comparison is ESS). In 2016, the SKAO Board constituted a Strategy and Business Development Committee (StratCom) to develop elements of the business case

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[3] Because of the significance of the SKA Observatory being an IGO in the Canadian context (see §4.4) and because this acronym is different from "SKAO", we refer to the SKA Observatory as "the IGO" throughout.

for SKA1 as well as to advise in IGO negotiations. The current working assumption is that formal transition processes will be completed in Q3 2020, and that the IGO will become fully operational in Q4 2020 (Césarsky 2019a). A Joint Working Group for Transition (JWGT), comprising members of both the SKAO Board and the IGO CPTF, has been created to coordinate the transition activities between the two organisations. The JWGT is co-chaired by the SKAO Board and CPTF chairs (Catherine Césarsky and Patricia Kelly, respectively), and the SKAO representative on the JWGT is Filippo Zerbi (Césarsky 2019b).

## 4. CANADA AND THE SKA: UPDATE

Since the high prioritization of access to SKA1 capabilities and related R&D recommended by MTR 2015 (§2.2), Canadian engagement in SKA1 science and technology development has remained strong across the university, government and industry sectors. An overview of Canada and the SKA can be found on the Canadian SKA website: http://www.skatelescope.ca. This section provides an update on Canadian participation in the SKA from scientific (§4.1), technological (§4.2 and §4.3) and governance (§4.4) standpoints. The appropriate participation level for Canada in the SKA1 Design Baseline is also discussed (§4.5).

### 4.1. *Canadian SKA Science*

Canadian researchers have the scientific expertise to contribute to achieving almost all of the Highest-Priority Science Objectives (HPSOs; see Table 2) for SKA1. Science planning and assessment activities for the SKA project take place within 11 Science Working Groups (SWGs). A list of current Canadian SWG members, highlighting the co-chairs of those groups in the last 5 years, is given in Table 5. Canadian SKA-related science activities were highlighted in reports to MTR 2015 and to NRC in 2017, and were also discussed during three recent meetings: “Canada and the SKA” (Toronto) in December 2015, “Canadian Radio Astronomy: Surveying the Present and Shaping the Future” (Montreal) in September 2017, and “Canadian Radio Futures II” in May 2019. Canadian cm- and m-wave radio astronomy has significant strengths in pulsars, magnetism, transients, low-frequency cosmology, galaxy evolution, gravitational waves and planet formation, and Canadians have the potential to play world-leading roles in corresponding SKA1 Key Science Projects (KSPs) and PI programs. We summarize each of these aspects of Canadian SKA science below. Throughout, all references to SKA1 performance and scientific potential refer to the Design Baseline (§3.1.

**Pulsars:** Pulsar searching and timing for gravity tests and gravitational wave (GW) detection are two SKA1 HPSOs (Table 2). One goal is to discover extremely relativistic systems, possibly including pulsar–black-hole binaries, with which to test the predictions of general relativity with ever-higher precision and to develop new tests of the Cosmic Censorship conjecture and the No-hair theorem for black holes. This will be accomplished by wider-area pulsar surveys, which will also deepen our understanding of the pulsar population and the Milky Way, followed by precision timing with all available sensitivity (Shao et al. 2015). Another major goal is the detection and characterization of low-frequency gravitational radiation from supermassive black-hole binary systems (Janssen et al. 2015). This will require long-term, sensitive monitoring of the most stable millisecond pulsars across the sky.

Canada is home to world-leading radio pulsar groups which attract trainees from all parts of the globe. Canadian astronomers have a long history of involvement in radio pulsar surveys at Parkes (e.g. Stairs et al. 2005), Green Bank (e.g. Archibald et al. 2009) and Arecibo (e.g. Parent et al. 2019) as well as leadership in the study of relativistic binaries (e.g., Stairs et al. 2004; Breton et al. 2008; Fonseca et al. 2014). Ingrid Stairs (UBC) is a member of the pulsar search and timing projects on the MeerKAT pathfinder telescope[4].

They are also participants in the NANOGrav collaboration, which is aiming to make a detection of low-frequency gravitational waves within the next decade using millisecond pulsar timing (e.g., Arzoumanian et al. 2018a,b), and in the International Pulsar Timing Array consortium, where they are already working with their likely SKA collaborators. With the imminent development of Canadian expertise in tracking and modelling interstellar medium variations with CHIME (Ng 2018), Canadian pulsar astronomers are well-positioned to play a leading role in pulsar timing with SKA1. For pulsar searches, SKA1 will be superior to other current or planned facilities. For pulsar timing, SKA1 will provide by far the greatest sensitivity in the Southern hemisphere. CHIME (and possibly ngVLA) along with existing large single-dish telescopes such as Arecibo and the Green Bank Telescope in the North will be complementary. The sensitivity of SKA2 will eventually be necessary to extract the highest-precision science from the pulsars found even with SKA1. Canadians are well-positioned to take on leading roles in the KSPs that will carry out transformational science with SKA1; in particular, Ingrid Stairs at UBC is the co-lead on the 2015 SKA Science Book chapter on testing gravity with pulsars using the SKA (Shao et al. 2015; see Fig. 5), and recently served as co-chair of the pulsar SWG (Table 5).

**Cosmic Magnetism:** We cannot understand the Universe without understanding magnetic fields, which are ubiquitous in interstellar and intergalactic space. Magnetic fields contribute significantly to the total pressure of interstellar gas, are essential for the onset of star formation, and control the density and distribution of cosmic ray particles in the ISM. Cosmic magnetism is an important science drivers for SKA1, and a resolved all-sky characterization of magnetic fields in the ISM and IGM is an HPSO (Table 2).

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[4] Stairs is also the PI for the ASKAP Survey Science Project (SSP) COAST, which is currently dormant because tied-array beam development was de-prioritized by CSIRO.

**Table 5.** Canadian Scientific Participation in SKA Science Working Groups

| Science Working Group | Current Canadian Participants |
|---|---|
| Cosmology | Bond, Halpern, Pen, Sanghai, Shaw, Sigurdson |
| Cradle of Life | Matthews, Boley, Di Francesco, Plume, ***Johnstone*** |
| CD & EoR | Pen |
| Extragalactic Continuum | Baum, Hlavacek-Larrondo, Wall |
| Extragalactic Spectral Line | Robishaw, Rosolowsky |
| HI Galaxy Science | Abraham, Ferrarese, Spekkens, Tulin |
| Cosmic Magnetism | Brown, Gaensler, Kothes, Robishaw, Stil |
| Our Galaxy | Johnstone, Joncas, Kothes, ***Rosolowsky***, Rupen, Sivakoff |
| Pulsars | Graber, Sanghai, Smith, ***Stairs*** |
| Transients & Exploration of the Unknown | Kaspi, Sholz, Sivakoff, ***Rupen*** |
| VLBI Working Group | Bartel, Bietenholz, Rupen |

Note—Individuals in bold italics have co-chaired the corresponding SWG in the last 5 years.

Magnetic fields do not themselves radiate, and therefore the magnetic sky is difficult to explore. Linearly polarized synchrotron emission is generated by the interaction of cosmic ray electrons with the magnetic field and carries the imprint of the magnetic field direction at the point of origin. The plane of polarization is changed by Faraday rotation as the synchrotron emission propagates through regions where magnetic field and free thermal electrons are present. While the synchrotron emission measures the strength and direction of the magnetic field in the plane of the sky, Faraday rotation completes its three-dimensional view by providing information on the field component along the line of sight. For typical interstellar magnetic fields Faraday rotation is only detectable at cm radio wavelengths and therefore radio polarimetry is the most powerful probe of astrophysical magnetic fields. In addition, the Zeeman effect provides an independent measure of strong magnetic fields in dense cold gas clouds.

The main project to study cosmic magnetism with SKA1 will be an all-sky rotation measure (RM) survey, which will produce an RM catalogue of unprecedented size for compact polarized extragalactic sources (Johnston-Hollitt et al. 2015). This dataset will provide an RM grid over the sky at spacings of a few arcmin between compact polarized extragalactic sources for SKA1, which results in a total of 7 – 14 million extragalactic RMs (see Figure 6). SKA2 will produce an RM grid with an average separation of just $20'' - 30''$ between polarized extragalactic sources, delivering a total of more than a billion RMs is expected. Those RM grids will be a powerful tool to probe foreground magnetic fields on many scales and at many redshifts including in our own Milky Way: they will reveal not only the large-scale magnetic field in the disk and halo, but also probe small-scale magnetic fields in interstellar clouds (Van

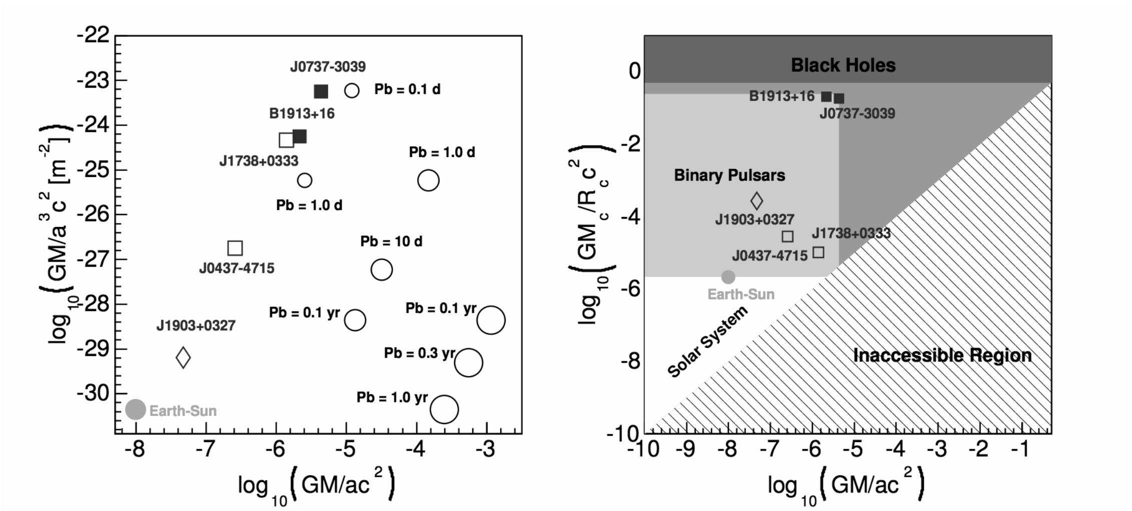

**Figure 5.** Locations of pulsars in the parameter space for quantifying the strength of a gravitational field (left), and the compactness of the gravitating companion star versus that of the orbit (right). Figure from Shao et al. (2015).

Eck et al. 2019), boundary surfaces (Costa & Spangler 2018), and high-velocity clouds (Betti et al. 2019).

Canadians have long been leaders in the field of cosmic magnetism. Examples of key recent Canadian contributions in cosmic magnetism and polarimetry include the largest ever catalogue of extragalactic rotation measures (Taylor et al. 2009), the best map of Galactic Faraday rotation (Oppermann et al. 2012), the best data set currently available for mapping the large-scale structure of the Milky Way's magnetic field (Van Eck et al. 2011), and fundamental new processing algorithms such as the polarisation gradient (Gaensler et al. 2011; Herron et al. 2017), polarisation stacking (Stil & Keller 2015) and real-time ionospheric Faraday correction. Canadians are leading almost all the major ongoing or pending worldwide radio polarisation surveys, and there is also heavy Canadian involvement in other surveys with a significant polarisation component. In particular Bryan Gaensler (U. Toronto) leads POSSUM, one of 9 ASKAP Survey Science Projects (SSPs). SKA1 is anticipated to be a superior instrument for magnetic field studies relative to other current or planned facilities. The chapter in the inaugural 2005 SKA Science Book on cosmic magnetism was led by Bryan Gaensler at U. Toronto, and three Canadians hold core membership in the SWG on cosmic magnetism (Table 5). There is a strong expectation that Canada will be in a position to play a leadership role in a KSP on cosmic magnetism.

**Transients:** A growing number of Canadian astronomers are making important contributions to time-domain astronomy, particularly in the study of compact objects such as gamma-ray bursts, magnetars, neutron stars, novae, supernovae, X-ray binaries, and the still-enigmatic fast radio bursts (FRBs). At radio frequencies, Canadians are leading high-impact studies of both "fast" coherent transients that are typically studied using techniques similar to that for pulsar timing, and "slow" incoherent tran-

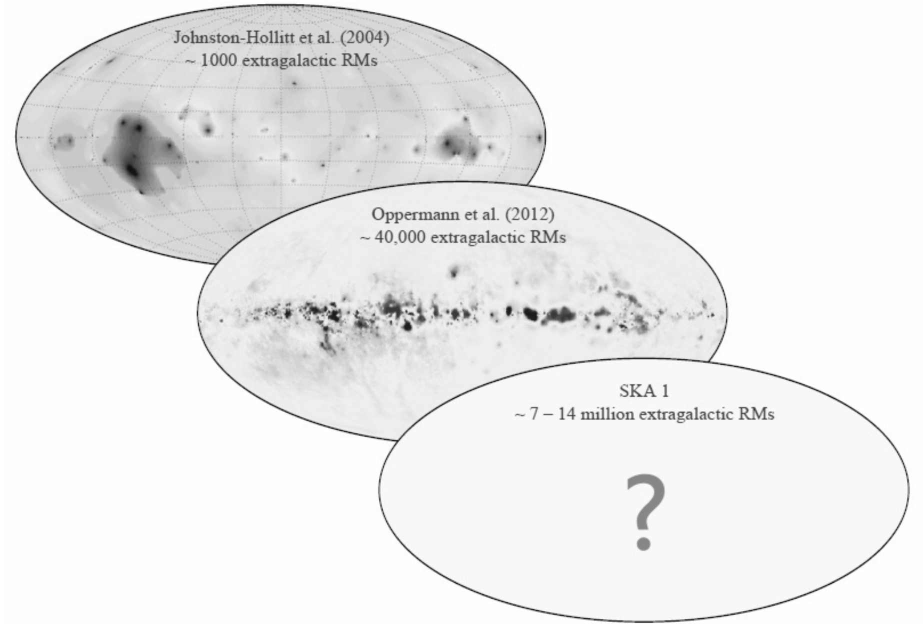

**Figure 6.** Recent developments of rotation measure (RM) maps of the entire sky (Johnston-Hollitt et al. 2004; Oppermann et al. 2012) and the prediction for the SKA1 (Johnston-Hollitt et al. 2015). Image credit: (Johnston-Hollitt et al. 2015).

sients that are typically studied using imaging techniques on timescales longer than ∼seconds. Technical advancements that now allow both techniques to be used at the same time will ensure that SKA1 serves both communities.

The large samples of FRB detections already being detected with CHIME will inform expectations for the number of FRBs to be detected with SKA1-Mid and SKA1-Low (FOV$= 21\,\mathrm{deg}^2$ at 110 MHz).

Since incoherent synchrotron emitters tend to be more rapidly variable at higher radio frequencies, SKA1-Mid, potentially in concert with SKA1-Low, will be of great interest to Canadian astronomers. Combining SKA1 data with similar data from optical and X-ray all-sky monitors will provide a daily view that connects the physics of accretion disks and the launching of relativistic jet, while coordinated observations across the electromagnetic spectrum will provide a seconds-timescale view of the same physics. For example, Canadians recently developed a new model for jet ejections to explain rapid radio-millimeter lightcurves tracked during the 2015 outburst of V404 Cygni, with broader implications for X-ray binaries and super-massive black holes, including Sgr A*.

Canadians are strongly represented in the Transients SWG for SKA1, a group which is currently chaired by Michael Rupen at NRC. Canadian are therefore likely to be in a position to take on leadership roles in transient-focussed KSPs or PI programs on SKA1.

**Low-frequency cosmology:** Measurements of redshifted 21-cm emission from neutral hydrogen provide a wealth of cosmological information across a wide range of

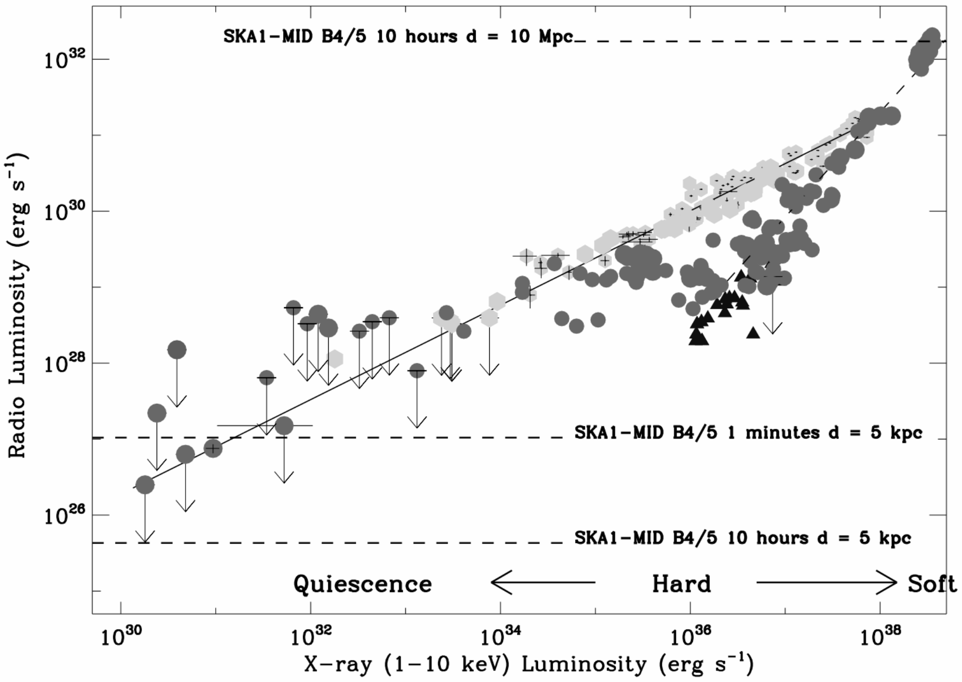

**Figure 7.** Radio and X-ray (1-10 keV) luminosities for Galactic accreting binary black holes in the hard and quiescent states for typical sources (green points), outliers (red points), and neutron star binaries (black points), as well as predicted SKA1-Mid sensitivities. Figure from Corbel et al. (2015).

redshifts. Constraints on cosmology, cosmic dawn (CD) and the epoch of reionization (EoR) are the focus of several HPSOs for SKA1 (see Table 2).

Canada is already a world leader in cosmological observations of redshifted 21-cm emission at $z \lesssim 2.8$, and the theoretical and experimental expertise that has been developed can be readily extended to the frequencies that are relevant to SKA1-Low. At $z \lesssim 2.8$, measurements of aggregated 21-cm emission from neutral hydrogen in galaxies via intensity mapping yield maps of large-scale structure. These maps encode baryon acoustic oscillations (BAO), which have a characteristic length scale that can be used as a standard ruler for charting the expansion history of the universe, in turn letting us measure the basic parameters of cosmology (Bull et al. 2015). The technique of intensity mapping was pioneered by Canadian researchers who made the first detection (Chang et al. 2010; Fig. 8), and CHIME (Bandura et al. 2014) is a groundbreaking, Canadian-led experiment that is capitalizing on this technique in order to shed light on the properties of dark energy. Canada is also playing a leading role in HIRAX (Newburgh et al. 2016), which shares the same science goals as CHIME but is located in the southern hemisphere and has a complementary instrumental approach. Instrumentation development for these projects has fostered dynamic partnerships between universities and national facilities such as DRAO.

At redshifts of $5 < z < 27$, measurements of 21-cm emission probe CD and the EoR, potentially elucidating the physical processes governing the first luminous objects ig-

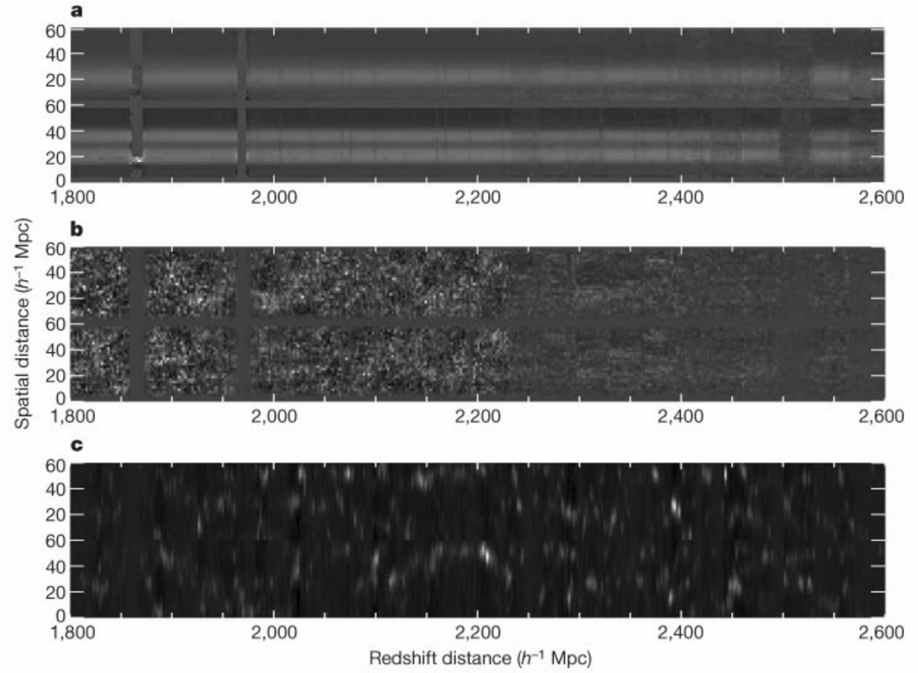

**Figure 8.** GBT radio flux (a) and brightness temperature (b) and optical galaxy density from DEEP2 (c) used in the first intensity mapping detection. Figure from Chang et al. (2010).

niting in the universe. Mapping the patchy structure resulting from reionization may allow us to constrain the details of star formation rates and the first galaxies, properties of X-ray sources and the first black holes, and the general topology of reionization (see *e.g.* Pritchard & Loeb 2012). Canada is already making key contributions to EoR research through the HERA (DeBoer et al. 2017) and MWA (Tingay et al. 2013) experiments, which are SKA precursors. The primary scientific deliverable of HERA is a high signal to noise measurement of the 21-cm power spectrum across a broad range of redshifts encompassing CD and the EoR. Leadership for this effort resides in Canada, with Adrian Liu serving as Power Spectrum Lead within the collaboration. Students and postdocs at McGill are currently heavily involved in delivering forthcoming upper limits on spatial fluctuations from HERA, and will continue to do so through the first detections and characterizations. Canada is additionally involved with MWA through the University of Toronto, with Bryan Gaensler serving as the representative on the MWA Board of Partners.

Canada is in a position of unique strength to play a leadership role in future SKA1-Low observations of CD through an existing portfolio of experiments measuring globally averaged 21-cm emission at these high redshifts. Globally averaged measurements offer information that is highly complementary to fluctuation measurements, giving us valuable insight into the thermal history of the universe and associated energy injection processes. Canada is already playing a key role in the EDGES (Bowman et al. 2018), PRI$^{\mathrm{Z}}$M (Philip et al. 2019), and SARAS2 (Singh et al. 2018) experiments, and the lessons learned from these observations will be crucial for informing the path forward for SKA1-Low.

**Galaxy evolution:** SKA1-Mid will make key advances in our understanding of how galaxies form and evolve, ranging from our own Milky Way to high-redshift radio galaxies, and four of the HPSOs in Table 2 focus on how galaxy star formation, structure and evolution.

Canadians have long-standing expertise in using cm-wave radio observations to understand the structure and evolution of galaxies. Research in this field divides broadly into HI spectral line and radio continuum observations, and Canadians have exploited both to understand the interstellar medium and the interplay between gas and star formation. Seminal early work in our own Galaxy was enabled by the Canadian Galactic Plane Survey (CGPS; Taylor et al. 2003); these detailed Milky Way studies continue today (Beuther et al. 2016, e.g.) and have also been extended into the Local Volume through high-resolution studies of the disk-halo connection (Irwin et al. 2019) and the galactic baryon cycle probed by HI (Dobbs et al. 2019). These local ISM studies are complemented by work at high redshift to understand the interplay between AGN activity, star formation and evolution in massive galaxies (O'Dea 2016).

Canadians are also leaders in exploiting gas content to probe how environment drives galaxy evolution. Statistical studies of gas content as a function of morphology and environment enabled by wide-field single-dish HI surveys remain among the most comprehensive of their kind (Brown et al. 2015, 2017), while deeper HI searches have explored the impact of galactic and group environments on satellite galaxies (Spekkens et al. 2014; Spekkens & Karunakaran 2018). Canadians have developed expertise in using interferometric radio maps to understand how galaxy clusters in both the nearby and distant universe form and evolve Gendron-Marsolais et al. (2018); Trudeau et al. (2019), as well as how those clusters affect the star-forming disks of gas-rich galaxies (Mok et al. 2017). By contrast, the HI disks of isolated galaxies are good tracers of dark matter halo structure, and Canadian researchers made several novel theoretical (Benítez-Llambay et al. 2017; Oman et al. 2019), observational (Dutton et al. 2007; Kuzio de Naray et al. 2012), and technical (Wiegert & English 2014; Kamphuis et al. 2015; Sellwood & Spekkens 2015) contributions to this field. Kristine Spekkens at RMC is the only international Executive Committee member of the 100+ researcher WALLABY SSP team on the ASKAP pathfinder, and leads its technical working group on resolved galaxy kinematics.

SKA1-Mid will be the first facility to map the atomic hydrogen distributions in galaxies over cosmic time, probing the evolution of the galactic baryon cycle and angular momentum assembly Blyth et al. (2015). Deep radio continuum observations will also probe faint radio halos of galaxy clusters both near and far Cassano et al. (2015) to constrain how they form and evolve. SKA1 will also revolutionize our view of the baryon cycle in the Milky Way (McC ????) and nearby galaxies (de Blok et al. 2015). Canadian astronomers are contributing to SWGs that focus broadly on galaxy evolution as probed by the Milky Way, nearby galaxies and the high-redshift galaxy distribution. Canadians are well-represented on the Extragalactic Continuum, Extragalactic Spectral Line, HI Galaxy Science and Our Galaxy SWGs, the latter recently chaired by Erik Rosolowsky at U. Alberta (see Table 5). Canadian interests in galaxy evolution probed by HI and the radio continuum fit well within the broader context of the country's multi-wavelength expertise in this field.

**Multi-Messenger Astronomy:** The LIGO/Virgo discovery of gravitational waves and electromagnetic radiation from the neutron star merger event, GW170817, has opened the new era of 'multi-wavelength, multi-messenger astrophysics. This now-exploding field is born post-SKA1 HPSOs and the SKA science book, but it has significant overlap with the 'Transients and Exploration of the Unknown' theme. Furthermore, there is significant Canadian expertise in high-energy astrophysics across the country, and particularly in the studies of neutron stars, black holes and supernovae which are the promising suspects for GW events.

Radio astronomy has played (and will continue to play) a key role in understanding GW events. Radio follow-up observations of GW170817 were taken with 16 facilities, including SKA precursors (ASKAP and MWA). These are equipped with a large field of view needed to efficiently monitor GW transients given the large positional error circle of LIGO/Virgo sources. The JVLA particularly played a key role, given its sensitivity and high angular resolution in the 1–10 GHz range, in detecting the radio afterglow which is shedding light on the physics of the neutron star merger and the interaction between the kilonova ejecta and its surroundings.

Canadian astronomers have played a significant and leadership role in the initial discovery and follow-up multi-wavelength observations and interpretation of GW170817, placing Canada at the forefront of this newly born and fast-exploding field. In particular, Maria Drout, Bryan Gaensler, Darryl Haggard and CITA researchers co-authored the first 2017 publication announcing the multi-wavelength campaign (Abbott et al. 2017), and Maria Drout from U. Toronto led the light curve analysis in the optical and infrared demonstrating the key role this event plays in r-process nucleosynthesis (Drout et al. 2017). Additional leadership and ongoing efforts include follow-up imaging and spectroscopic studies in the X-ray band (Haggard et al. 2017; Ruan et al. 2018; Safi-Harb et al. 2018) and the development of kilonova and kilonova remnant models (e.g., Fernández et al. (2017); Safi-Harb et al. (2018)). Currently, follow-up multi-wavelength ToO programs are being carried out by a Canadian consortium spread across the country, bringing the observational and theoretical communities together, fostering new international collaborations, and opening a new window for future, exciting discoveries.

The improved sensitivity of LIGO/Virgo and upcoming LIGO-India and Japans KAGRA facilities will necessitate improved sensitivities in the radio in the coming decade, placing SKA1 at the forefront for GW science. This will present us with nearly 10 times increase in resolution over the JVLA and about 100 times increase in survey speed (between 1 and 10 GHz). SKA1 will be also complementary to the ngVLA at higher frequencies. Given the importance of multi-wavelength and multi-messenger (including neutrino) follow-up for this science, SKA1 will pay a key synergetic role advancing the field on many fronts for decades to come.

**The Formation of Planetary Systems:** Studies of planets and their formation have been revolutionized in the last decade, due to both space missions such as *Kepler* leading to an exponential increase of the number of known exoplanets, and due to the rise of the ALMA, which is finally allowing detailed observations of dust and gas in protoplanetary disks surrounding young stars, where planets are thought to form ('cradles of life'). Following the astonishing image of HL Tau revealing a multi-ring dust structure potentially linked to young planets carving their path in the disk (ALMA Partnership et al. 2015), ALMA is now routinely producing spectacular images at scales of a few AU, revealing that many, if not all disks contain substructures directly related to dust growth and planet formation (van der Marel et al. 2019).

The revolutionary ALMA images also pose many new questions: the mm-sized dust grains traced at mm wavelengths may not tell the full story of dust growth, as their emission tends to become optically thick, in particular in the inner part of the disks: longer wavelength observations tracing the cm-sized grains at $\sim$10 GHz will provide actual answers on the efficiency of dust and planetesimal growth in the terrestrial regimes $0.1 - 5\,\mathrm{AU}$ from the host stars (Testi et al. 2015). SKA1 will play a crucial role in obtaining detailed images of the inner planet-forming regions at wavelengths inaccessible by ALMA at high resolution. Furthermore, at lower frequencies the free-free emission of ionized gas close to the star begins to dominate the cm flux, which is thought to originate from disk winds predicted by disk dissipation models (Pascucci et al. 2012).

However, the current lack of spatially resolved observations of the inner disk at cm wavelengths implies that this process is entirely unconstrained. The evolution of the disk, in particular dissipation processes and time scales, continues to be a mystery, while it is of utmost importance to connect disk properties with exoplanet demographics, exoplanet composition and planet-disk interaction processes such as migration, gap clearing and core accretion. SKA1 is expected to deliver the first images of disk winds that provide clues on the disk dissipation process (Pascucci et al. 2018). Finally, SKA1 opens up a spectral window for detection of complex organic molecules, the precursors of biomolecules and building blocks of life, in the planet-forming regime in disks, which are generally produced in ices and non-thermally desorbed at low temperatures in the 1-15 GHz regime (Testi et al. 2015).

Although planet formation is a relatively young field of research, Canada has a growing expertise in this exciting new discipline: with a solid historic background in

**Table 6.** Canadian SKA-related R&D Contributions and Partners since 2015

| Technology | Government/ University Partners | Industry Partners |
|---|---|---|
| Correlators/beamformers | NRC | MDA, Intel |
| LNAs and digitisers | NRC, U. Calgary, McGill | Nanowave, MDA,<br>Canadian Circuits |
| Signal processing monitor & control | NRC, U. Calgary, UBC, U. Alberta, CANARIE | Rackforce |
| Phased-array feeds (PAFs) | NRC, U. Calgary | MDA |
| Composite reflectors | NRC | SEDsystems, Minex Eng. |

both star formation and exoplanets, experts in Solar System and debris disks, and recent hires in planet formation experts in Victoria, Canadian astronomy has all the ingredients to become one of the world leaders in this HPSO for SKA1, following its important contributions to ALMA which has started to revolutionize this field.

### 4.2. *Canadian SKA Technology*

The high prioritization of key technology development for SKA1 tender and procurement was a strong recommendation of the 2015 MTRP (see §2). Canada has remained a world leader in this development through effective partnerships between government, academia and industry. A summary of Canadian SKA-related R&D since 2015 is given in Table 6; a major goal of this development is to create a “basket of opportunity” for Canadian in-kind contributions to SKA1 and other facilities. Canadian key technologies to emerge from SKA R&D in the last 5 years relate to correlators and beamformers, low-noise amplifiers (LNAs) and digitisers, signal processing monitor & control, phased array feeds (PAFs), and composite dishes. Canada has also shown leadership in developing the computing and storage resources that will be needed for SKA science data processing and access via an SKA Regional Centre (SRC). A brief update on each of these technology aspects is below.

**Correlators and Beamformers:** NRC led the Central Signal Processing (CSP; see Fig. 3) element consortium that was responsible for designing the SKA1-Mid correlator/beamformer, SKA1-Low correlator/beamformer, pulsar search engine(s) and pulsar timing. In addition to overall consortium coordination, NRC led the SKA1-Mid correlator/beamformer design that resulted in the TALON-DX processing board pictured in Fig. 9 in collaboration with Intel. In response to the CCP (see §3.3), NRC developed the Frequency Slice Architecture for the TALON-DX that delivered the SKA1 Design Baseline at a ∼€ 20M cost savings relative to initial estimates. CSP achieved a major milestone in late 2018 by completing its CDR, which passed with “no action” (the only consortium to have received this high rating), marking the end of nearly six years of development work. CDR closeout is complete and the CSP consortium has since dissolved; NRC is currently working with the SKAO on Bridging Phase activities. Correlator/beamformer technology makes up the bulk of NRC's "basket of opportunity" for SKA1 tender and procurement.

**LNAs and digitisers:** NRC cryogenic LNAs and direct-conversion digitisers are being developed for the SKA1-Mid Band 1 (0.35–1.05 GHz) and Band 2 (0.95–1.76 GHz) single-pixel feeds (SPFs) within the DSH element consortium. The LNA development builds on earlier work for ALMA and MeerKAT with Nanowave, MDA and Canadian Circuits, while the digitiser design arose from technology developed for CHIME at McGill and a high-speed digitiser design by U. Calgary. The digitiser development work has resulted in the mid-frequency single pixel feed receiver/digitiser (SPFRx) design, which has undergone a recent re-design to satisfy CSP and DSH requirements. A full prototype antenna system was deployed at the SKA1-Mid site in South Africa by DSH, which along with reflector IP issues has pushed out the DSH CDR to Q1 2020 (see §3.1 and Fig. 3). NRC activities within DSH are therefore ongoing, and preparations for CDR are underway. LNA and digitiser technology are components of NRC's "basket of opportunity" for SKA1 tender and procurement.

**Signal processing monitor & control:** NRC, the CADC and CANARIE contributed to the SDP and TM element consortia through development work on SKA1-Mid signal processing monitor & control, in collaboration with a group of Canadian universities. In particular, NRC supported the development of standards for the local monitor & control software architecture, while CADC led the work on science archive interfaces and Virtual Observatory services (discovery and access) as well as components of the SDP Delivery System. Both SDP and TM have completed CDR and related closeout activities, and the consortia have been dissolved. Signal processing monitor & control is a component of NRC's "basket of opportunity" for SKA1 tender and procurement.

**PAFs:** NRC has worked on both room-temperature and cryo-cooled PAFs with U. Calgary and industry partner MDA, initially contributing to the PAF sub-element design within the DSH Consortium. The deferral of SKA1-Survey that resulted from the 2015 SKA1 re-baselining exercise (see §2) has downgraded the priority of related R&D from the SKA perspective, although development work aimed at Band 4 (2.8-5.2 GHz) is ongoing under the SKA Advanced Instrumentation Programme (AIP).

**Composite reflectors:** Through 2015, NRC led the dish structure sub-element development through the DSH Consortium, and for a time NRC rim-supported composite antennas were the recommended design for SKA1-Mid. Late that year a panelised metal reflector design from Germany and China was recommended for SKA1 over the NRC one, removing NRC from DSH dish structure work and ceasing SKA1-specific R&D. However, NRC has continued its composite reflector research work at higher

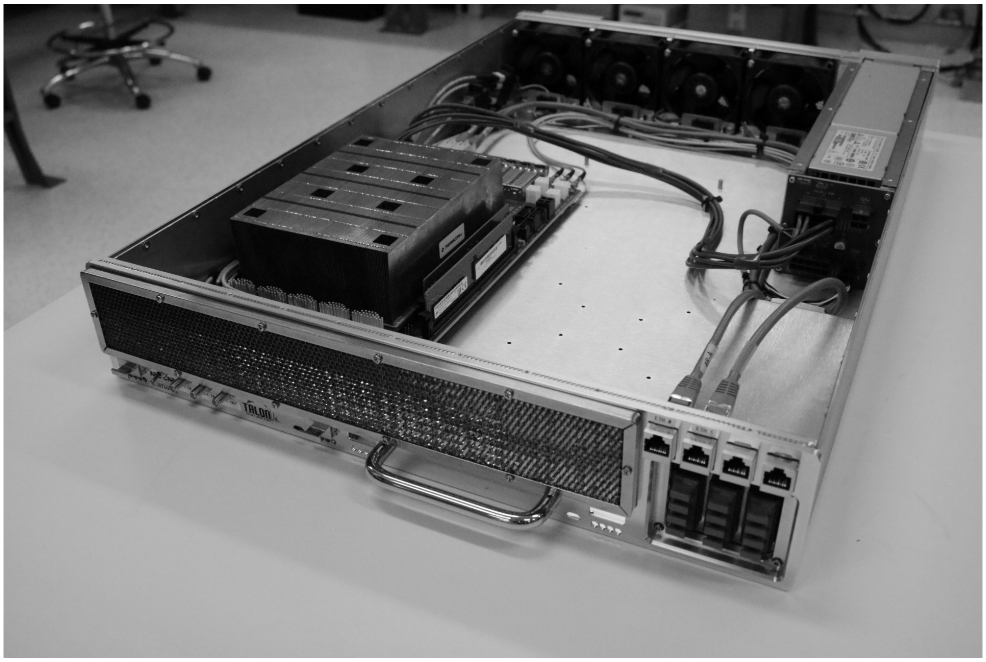

**Figure 9.** A close-up of the TALON-DX processing board and the TALON Line Replaceable Unit (LRU), developed by NRC in collaboration with Intel. Image credit: Michael Pleasance, NRC.

frequencies, resulting in designs with potential uptake by other large projects such as ngVLA.

### 4.3. *A Canadian SRC*

An important outcome of the 2015 "Canada and the SKA" conference as well as 2018 discussions regarding the desirable Canadian participation level in SKA1 (see §4.5) was a strong consensus that a Canadian SKA Regional Centre (SRC) is needed to serve the scientific data processing, storage and user support needs of the Canadian astronomical community (see §3.3), as opposed to a model in which those services are purchased elsewhere. Scientific computing platform and archive development is a Canadian strength, and CADC/CANFAR have the capability to play a leading role in the development of SRC architectures and implementations in collaboration with the scientific community. A Canadian SRC would leverage this leadership to deliver computing, storage, and user support tailored to the needs and ambitions of the Canadian community, providing agency over its capacity to scientifically exploit SKA1.

Since that time the Canadian SKA Regional Centre Advisory Committee (CSRCAC) (see §4.5) has been working to define the scope and possible implementations of a Canadian SRC, and has now developed a realistic, bottom-up estimate of related requirements. The CSRCAC has worked closely with CANARIE, Compute Canada and NRC to establish real-world estimates for the costing of computing hardware, networking and FTE capacity that will be required to operate an SRC. The costing amounts are derived from ongoing roll-outs of infrastructure in Canada and reflect the total cost of ownership of those systems. These are the most detailed and sophisticated costing estimates of SRC operations to have yet been produced within the project, and a description of the methodology is in Appendix B.

The CSRCAC estimates account for PI and KSP networking, processing and online storage costs, near-line storage costs for the SKA1 archive in compliance with SRC network guidelines (Bolton et al. 2018; Scaife, A 2018), 5-year processing refresh costs and continuous storage refresh costs, and staffing costs to provide user support for both observers and archive users. A processing ramp-up to full operations in the next decade is also embedded in the estimate, with processing hardware purchased and science commissioning processing/storage beginning in 2022 and the capacity to support the science compute load of full operations in 2028. The calculations in Appendix B indicate that the bulk of the global SRC costs, will be driven by on-line storage requirements (near-line, long-term storage is an order of magnitude cheaper), with support staff (if Canadian employment standards and remuneration are adopted), processing, and networking costs contributing the rest.

Some of the capabilities that will be needed for a Canadian SRC are being developed by the newly-established Canadian Initiative for Radio Astronomy Data Analysis (CIRADA, PIs Bryan Gaensler from U. Toronto and Erik Rosolowsky from U. Alberta), a consortium of six Canadian universities funded by a $10.3M CAD CFI grant to develop science-ready data products for ASKAP, CHIME and the VLA Sky Survey (VLASS. The tools and infrastructure that CIRADA is developing to produce science-ready data products for direct application to VLA, CHIME and ASKAP surveys are a stepping stone towards the infrastructure that will be needed to support a Canadian SRC. Opportunities for a unifying Canadian astronomical data strategy that provides compute, data, and software resources across a variety of observational facilities including SKA1 was identified by CSRCAC as an area for exploration for LRP 2020 (Kavelaars et al. 2019).

## 4.4. *Canadian SKA Governance*

Table 7 summarizes Canadian individuals in SKA governance positions over the last 5 years, with italics indicating positions currently held. Within Canada, the ACURA Advisory Council on the SKA (AACS) advises ACURA and NRC regarding the SKA project, and the Canadian SKA Regional Centre Advisory Committee (CSRCAC) has been working to define the scope of potential Canadian SKA Regional Centre (SRC) contributions (see §3.2 and §4.3).

Canada currently contributes to the governance of the SKA project through its membership in the Square Kilometre Array Organisation (SKAO). NRC is the adhering organisation, and Luc Simard and Michael Rupen are first and second Nominated Representative Members for NRC (see §3.4 and Table 4). Canada is represented on

**Table 7.** Canadian SKA Governance Since 2015

| Body | Voting Canadian Members |
|---|---|
| **Within Canada:** | |
| AACS (voting) | Aldridge, Bartel, Dobbs, Fry, Gaensler, *Hlavacek-Larrondo*, Jagula, *Johnstone*, *Joncas*, Kaspi, *Rosolowsky*, Safi-Harb, *Sivakoff*, *Spekkens*, Stairs, *Stevens*, Stil, Taylor, Wall |
| CSRCAC | *Gaudet*, Irwin, *Kavelaars*, Kaspi, Pen, *Rosolowsky (chair)*, Taylor |
| **Within the SKAO:** | |
| Representative NRC Members | Fahlman, *Simard (first)*, *Rupen (second)* |
| SKAO Board | Fahlman, Gaensler, *Rupen*, *Spekkens* |
| StratCom | *Fahlman* |
| SEAC | Dougherty, Gaensler, Spekkens, *Stairs* |
| SRCCG / SRCSC | *Gaudet* |
| **Within the IGO:** | |
| CPTF Observer | *Simard* |

Note—Individuals in italics are current members.

the SKAO Board by a (voting) NRC Director and a (non-voting) Science Director, who are currently Michael Rupen from NRC and Kristine Spekkens from RMC respectively (SKAO 2019a). Other Canadians on key SKAO committees (see §3.4) include Greg Fahlman from NRC as a Strategy and Business Development Committee (StratCom) member, Ingrid Stairs from UBC as a Science and Engineering Advisory Committee (SEAC) member, and Séverin Gaudet as an SKA Regional Centre Steering Committee (SRCSC) member. The governance goals of the SKAO in the next 12 months are ambitious, and include overseeing System CDR completion and closeout as well as developing the SKA1 Cost Book, final Deployment Baseline and construction/operations proposals for approval by the IGO (see §3.4). Canadian engagement and input is particularly important as the SKAO completes these critical tasks, and we are well-positioned to contribute.

With the anticipated transition in global project leadership from the SKAO to the Inter-Governmental Organisation (IGO) (Césarsky 2019a), the SKAO's governance role is becoming increasingly limited. Key policies for SKA1 construction and operations such as the funding schedule, IGO participation models beyond Full Membership, tender and procurement and IP policy are being developed by the Council Preparatory Task Force (CPTF) for approval by the IGO Council once it comes into force (see §3.4). Canadian participation in the IGO is complicated by laws stipulating that governmental approval via a Memorandum to Cabinet must be obtained before treaty negotiations can be entered; at present, no Canadian organisation has that authority[5]. Recently, NRC was directed by the government to explore IGO membership options for Canada. Luc Simard from NRC is the Canadian Observer on the CPTF along with representatives from several other countries interested in IGO membership (see Table 7). While this is a positive step towards participating in SKA1 construction and operations, there is currently no mechanism for Canada to inform policy or process during those phases.

It is possible for Canada to accede to the IGO if governmental approval is obtained; alternatively, Canada could participate in SKA1 construction and operations via some form of Associate Membership or other agreement to be negotiated with the IGO. Details regarding the accession process to Full IGO Membership as well as alternative participation models are being developed by the CPTF, and bilateral discussions with the CPTF regarding possible mechanisms for Canada are ongoing.

The IGO Treaty Convention and Final Record do not distinguish between the scientific or technological access and leadership rights of Full Members and those of countries that participate through Associate Membership or other agreements (ref here). It is therefore possible for Canada to negotiate for full scientific and technological rights if an alternative to Full IGO Membership is sought. Given the significant scientific leadership potential of the Canadian community (§4.1) as well as the potential for key technical contributions that deliver return on SKA1 construction funding investment (§4.2), this approach aligns well with Canadian ambitions.

### 4.5. *Canadian SKA1 Participation*

Canadians have sought to participate in the SKA at the 5% –10% level since the beginning of the project. In recent years, 6% was adopted as the nominal Canadian share of SKA1[6], a value that is intermediate to our current contribution of ∼5% of the SKAO budget and our ∼8% contribution to the total cost of pre-construction activities across the various element consortia (see §3.1). Several lines of reasoning suggest that a participation level in the range of $6\% \pm 2\%$ is appropriate for the Canadian community, such as our expertise and capacity to lead anticipated Key Science Projects (KSPs, see §4.1 and below), the percentage of SKA Science Book authors who are Canadian, the value of potential Canadian technological contributions to SKA1 (see §4.2), and the relative sizes of the astronomical communities of SKAO member countries as judged by their IAU participation (see Table 4). In 2018, the appropriate Canadian participation level in SKA1 was again discussed during two telecons to which ∼30 Canadian radio astronomers called in. The strong consensus from those discussions was that ambitions for a 6% share of SKA1 should be maintained.

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[5] Canada did not participate in drafting the IGO Treaty Convention or Final Record, though it did observe the process by invitation of the negotiating parties.

[6] Recall that participation in SKA1 is decoupled from that in SKA2 (§3.4); the discussion here pertains exclusively to the former.

To further explore how well a 6% participation level aligns with Canadian scientific ambitions for SKA1, the first detailed estimates of leadership opportunities for SKA1 KSPs over a decade of full operations were carried out (see Appendix A). Starting from assumptions regarding SKA1 operations, the distribution of KSP durations and their management structure, the total number of available leadership positions (KSP leads, executive members, working group leads, and team members) across the project were estimated. Further introducing the concept of SKA1 science leadership "currency", three different science leadership scenarios for a 6% participation in SKA1 were explored: a Proportional scenario where leadership is directly proportional to the participation level, a Top-Heavy scenario where more currency is spent on KSP leads, and a Bottom-Heavy scenario where more currency is spent on team membership. The resulting leadership opportunity estimates are shown in Fig. 10.

It is important to note that assumptions regarding telescope operations, time allocation and KSP project structure – none of which have yet been determined for SKA1 – underpin the science leadership estimates presented in Fig. 10; these numbers are necessarily preliminary. Nonetheless, the approach adopted and estimates produced in Appendix A are the most sophisticated for SKA1 to date, and represent a reasonable benchmark against which to compare Canadian scientific ambitions.

Canada is a world leader in studies of pulsars, cosmic magnetism and transients, as well as in low-frequency cosmology (see §4.1). Our multi-wavelength expertise in galaxy evolution, mulit-messenger astronomy and planetary system formation in which radio observations play a critical role is also a key strength. It is therefore reasonable to conclude that over a decade of full SKA1 operations, Canadians will lead a medium/large (ie. 5000–10000 hours) KSP in each of pulsars, magnetism, transients and cosmology, while there is also potential for Canadians to hold $\sim 5$ KSP exec positions or working group chairships in pulsars, magnetism, transients, cosmology, galaxies, multi-messenger astronomy, and planets. The breadth of our engagement in SKA SWGs (Table 5) additionally suggests that each of the $\sim$100 KSP science teams assembled undertaken with SKA1 in a decade will include at least a few Canadians. These numbers are well-matched to the 6% Proportional scenario illustrated by the left histograms in Fig. 10 (a further breakdown is in Table 10).

Further flexibility over Canadian KSP participation is gained by "spending" the "currency" secured through a 6% participation differently from straight proportionality, either emphasizing leadership (the Lead-Heavy scenario illustrated in the middle of Fig. 10), team membership (the Lead-Light scenario illustrated on the left in Fig. 10), or some other combination. Whether or not some kind of SKA1 currency will be developed and how it will be valued remain to be seen, but these scenarios illustrate that a range of possibilities exist should Canadian aspirations evolve as SKA1 operations get underway. Overall, Fig. 10 and Appendix A demonstrate that a 6%

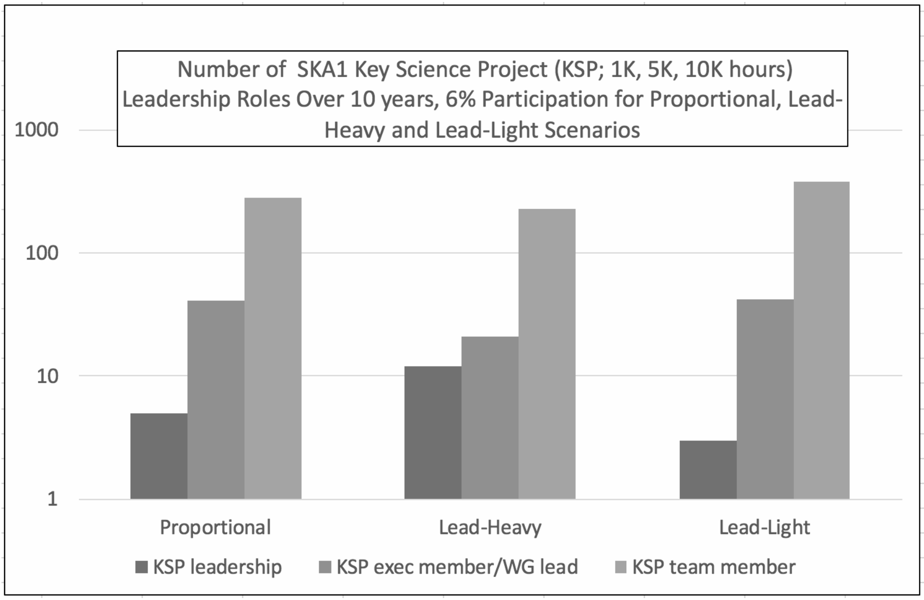

**Figure 10.** Canadian SKA1 KSP leadership opportunities over a 10-year period for a 6% participation level and different scenarios emphasizing KSP leadership (Lead-Heavy) or membership (Lead-Light) relative to a straight proportionality of available position (Proportional). See Appendix A for details.

participation level in the SKA1 Design Baseline remains broadly well-matched to the scientific leadership ambitions of the Canadian netre and centimeter radio community.

If Canada does participate in the SKA1 Design Baseline at the 6% level, then the latest available costing and schedule (§3.2 and §3.3) imply that construction funding of order (€ 918M × 0.06 × 1.46 CAD/€ ∼) $80M CAD (2017 CAD) will be required in the next decade as well as commensurate operations funding for a total estimated construction and operations cost of $160M CAD (2017 CAD) from 2021 – 2030. Contributions to a staged observatory development fund that grows to a project-wide € 20M (2017 €) by the onset of full operations have also been included in this number. This number is ∼ 25% higher than the rough estimates presented in LRP 2010 and MTR 2015 because of cost estimate increases in the Design Baseline. It is important to recall that considerable uncertainties on construction and operations costs remain; the bottom-up cost review that will be carried out at the end of Q2 2020 (see §3.3) will increase the accuracy and reliability of these estimates. Operations costs are particularly uncertain at the present time, but current estimates suggest that Canada's contribution to full operations beyond 2030 for a 6% participation level would be ∼ $8M CAD/year.

In addition to construction and operations funding, Canada will need to contribute to the global SKA Regional Centre (SRC) network that will supply the requisite processing, storage and user support to scientifically exploit SKA1 (see §3.1). Realistic Canadian SRC costing estimates are now available from the CSRCAC (see §4.3 and Appendix B), and the cost for a 6% participation level is anticipated to be $45M CAD

(2017 CAD) from 2021 – 2030 including processing, storage, networking, and staffing costs. In this model the first hardware is purchased and minimal processing/storage is carried out in 2022, with processing/storage/support capacity ramping up to handle full operations by 2028. Averaged over 5 years of full operations (ie. one processing hardware refresh cycle), the expected annual SRC cost beyond 2030 would be ∼ $5M CAD/year, with considerable uncertainties due to rapidly evolving techniques, technologies and costs in the compute sector.

The total estimated cost for participation in SKA1 Design Baseline construction and ramp-up to full operations, at a 6% level commensurate with Canadian scientific ambitions for that facility, is therefore ($160M + $45M =) $205M CAD (2017 CAD).

## 5. CONCLUSIONS AND WHITE PAPER RECOMMENDATIONS

This report to the LRPP has focussed on the recent history and current status of the SKA in Canada from scientific, technological and governance standpoints. Technical and financial information regarding Canada's future participation in the project has also been provided in support of the LRP 2020 White Paper (WP) (Spekkens et al. 2019). While the task of looking forward falls within the purview of that document, some closing comments regarding these future prospects as well as the WP recommendations are included here for completeness.

SKA1 design, technology and governance have matured tremendously over the last decade into a project on the cusp of construction (see §3). It is clear that 2020 – 2030 will be monumental years for the SKA. Uncertainties in the SKA1 timeline (Fig. 4) and deployment (see §3.3) do remain, but the observatory is undeniably transitioning out of the pre-construction phase. The international momentum of the project is significant. *SKA1 is happening*, and Canada at last has the opportunity to reap the scientific benefits of our decades-long scientific, technical and governance contributions to the project.

Canadians have a long history of important scientific and technological contributions to the SKA, guided by its high prioritization through two decades of LRPs and MTRs (see §2). That scientific and technological leadership persists today within a vibrant and world-leading Canadian cm and m-wave radio astronomy community (see §4). If Canadian participation in the SKA is to continue, then *this is the decade in which a commitment to build SKA1 will be needed, and this is the decade in which construction, operations and computing funds will need to flow.* Important related decision points will be required early in the next decade, and likely within a year or two. LRP 2020 will therefore determine the future of the SKA in Canada now, through 2020 – 2030, and beyond.

The SKA LRP 2020 WP (Spekkens et al. 2019) will make the case for Canada's continued scientific and technological participation in the SKA project. It will argue that SKA1 will make transformational advances in our understanding of the Universe in a number of important areas, that Canadians are poised to play scientific and technical leadership roles in many of them, that the scientific and technological return on investment is high, and that participation in the SKA will position Canadian astronomy for future opportunities in the decades to come. While a detailed justification of these statements is beyond the scope of this report, their backbone is evident from its contents. For completeness, then, the recommendations for Canada's future participation in the SKA project from the WP are below.

**Recommendations: Canada and the SKA from 2020 – 2030**

**1. Canada should participate in the construction and operations phases of SKA1.** SKA1 Design Baseline construction, operations and a staged technology development program should be funded at a 6% level, commensurate with Canadian scientific ambitions. This commitment is estimated to cost $160M CAD over the period 2021 – 2030.

**2. Canada should participate in the SKA regional centre (SRC) network to ensure community access to the processing, storage and user support required to scientifically exploit SKA1.** The cost of this participation at a level commensurate with Canadian scientific ambitions, and in accordance with SRC network guidelines, is estimated to be $45M CAD over the period 2021-2030 in addition to construction and operations funding. To meet its SKA1 compute needs, Canada should leverage its established strength in scientific computing platforms and archive development by hosting a Canadian SRC.

**3. The membership model through which Canada participates in the Inter-Governmental Organisation (IGO) that will build and operate SKA1 should provide full scientific and technological access as well as leadership rights for Canadian researchers and industry.** An agreement for Canadian participation in the IGO should be finalized as early as possible in the next decade in order to maximize our impact on the construction phase as well as to maximize opportunities for technological tender and procurement.

## 6. ACRONYMS

**AA:** Array Assembly

**AACS:** ACURA Advisory Council on the SKA

**ALMA:** Atacama Large Millimeter Array

**LRU:** Line Replaceable Unit

**ACURA:** Association of Canadian Universities for Research in Astronomy

**AENEAS:** Advanced European Network of E-infrastructures for Astronomy with the SKA

**AGN:** active galactic nucleus

**AIP:** Advanced Instrumentation Programme

**AIV:** Antenna Integration and Verification

**ALMA:** Atacama Large Millimeter Array

**ASKAP:** Australian SKA Pathfinder Telescope

**BAO:** baryon acoustic oscillations

**CADC:** Canadian Astronomy Data Centre

**CANFAR:** Canadian Advanced Network for Astronomical Research

**CCP:** Cost Control Project

**CERN:** European Organization for Nuclear Research

**CHIME:** Canadian Hydrogen Intensity Mapping Experiment

**CIRADA:** the Canadian Initiative for Radio Astronomy Data Analysis

**CDR:** Critical Design Review

**CD:** cosmic dawn

**CFI:** Canadian Foundation for Innovation

**CGPS:** Canadian Galactic Plane Survey

**CITA:** Canadian Institute for Theoretical Astrophysics

**COAST:** Compact Objects with ASKAP: Surveys and Timing

**CPTF:** Council Preparatory Task Force

**CSP:** Central Signal Processor

**CSIRO:** Commonwealth Scientific and Industrial Research Organisation of Australia

**CSRCAC:** Canadian SKA Regional Centre Advisory Committee

**DKIST:** Daniel K. Inoue Solar Telescope

**DSH:** the Dish Consortium

**DRAO:** Dominion Radio Astronomy Observatory

**ESCAPE:** European Science Cluster Astronomy & Particle Physics ESFRI Research Infrastructures

**EoR:** epoch of reionization

**ESFRI:** The European Strategy Forum on Research Infrastructures

**ESO:** European Southern Observatory

**ESS:** the European Spallation Source

**EVLA:** Expanded Very Large Array = Jansky Very Large Array

**FRB:** fast radio burst

**FTE:** full-time equivalent staff

**FWR:** fair work return

**KAGRA:** Kamioka Gravitational Wave Detector

**KSP:** Key Science Projects

**GBT:** Green Bank Telescope

**GoC:** Government of Canada

**GW:** gravitational wave

**HERA:** Hydrogen Epoch of Reionization Array

**HIRAX:** Hydrogen Intensity and Real-time Analysis eXperiment

**HPSO:** Highest Priority Science Objectives

**IAU:** International Astronomical Union

**IGM:** intergalactic medium

**IGO:** Inter-Governmental Organisation

**IP:** Intellectual Property

**ISM:** interstellar medium

**JVLA:** Jansky Very Large Array = Expanded Very Large Array

**JWGT:** Joint Working Group for Transition

**LAR:** Canadian Large Adaptive Reflector

**LFAA:** the Low Frequency Aperture Array consortium

**LIGO:** Laser Interferometer Gravitational wave Observatory

**LNA:** low-noise amplifier

**LOFAR:** Low Frequency Array

**LRP:** Long Range Plan

**LRPP:** Long Range Plan Panel

**LSST:** Large Synoptic Survey Telescope

**MDA:** MacDonald Dettweiler & Associates

**MOU:** Memorandum of Understanding

**MSP:** milli-second pulsar

**MTR:** Mid-Term Review

**MTRP:** Mid-Term Review Panel

**MWA:** Murchison Widefield Array

**ngVLA:** Next-Generation Very Large Array

**NRC:** National Research Council of Canada

**NRC-HIA:** Herzberg Institute for Astrophysics (now NRC-Herzberg)

**PAF:** Phased Array Feed

**PI:** Principal Investigator

**POSSUM:** Polarization Sky Survey of the Universe's Magnetism

**PWV:** precipitable water vapour

**RfI:** request for information

**RMC:** Royal Military College of Canada

**RM:** rotation measure

**SDP:** Science Data Processor

**SEAC:** Science and Engineering Advisory Committee

**SKA:** Square Kilometre Array

**SKAO:** Square Kilometre Array Organisation

**SPF:** single-pixel feed

**SPFRx:** mid-frequency single pixel feed receiver/digitiser

**SRC:** SKA Regional Centre

**SRCSC:** SKA Regional Centre Steering Committee

**SRCCG:** SKA Regional Centre Coordination Group

**SSP:** Survey Science Project

**StratCom:** Strategy and Business Development Committee

**SV:** Science Verification

**SWG:** Science Working Group

**TM:** Telescope Manager

**TMT:** Thirty Meter Telescope

**ToO:** Target of Oppportunity

**UBC:** University of British Columbia

**VLA:** Very Large Array

**VLOT:** Very Large Optical Telescope

**WALLABY:** Widefield ASKAP L-Band Legacy All-Sky Blind Survey

**WBS:** Work Breakdown Structure

**VLASS:** VLA Sky Survey

**WP:** White Paper

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# APPENDIX

## A. SCIENCE LEADERSHIP OPPORTUNITIES FOR SKA1 KEY SCIENCE PROJECTS: A CANADIAN CASE STUDY

This appendix (circulated to SKAO in August 2019 as a stand-alone memo) estimates science leadership opportunities for SKA1 Key Science Projects (KSPs) over a decade of full operations, focussing on possibilities for a 6% participation level typically discussed in the Canadian context. Starting from assumptions regarding SKA1 operations, the distribution of KSP durations and their management structure, the total number of available leadership positions (KSP leads, executive members, working group leads, and team members) across the project is estimated. Further introducing the concept of SKA1 science leadership "currency", three different science leadership scenarios for a 6% participation in SKA1 are explored: a Proportional scenario where leadership is directly proportional to the participation level, a Top-Heavy scenario where more currency is spent on KSP leads, and a Bottom-Heavy scenario where more currency is spent on team membership. These scenarios produce different distributions of leadership opportunities, with the number of KSP leads varying by a factor of four and the other roles varying by a factor of ∼two between them. Science leadership currency is a potentially useful construct for enabling scientific return on SKA1 investment that is tailored to the interests and expertise of participating countries. If a currency is adopted, its valuation will be an important factor for the IGO Council to consider because it may influence the range of KSPs ultimately undertaken. While the primary goal of this appendix is to inform the Canadian astronomical community as part of its 2020 Long Range Plan prioritization process, it is hoped that the methodology and outcomes are also useful to other SKA stakeholders.

### A.1. *Introduction*

Canada has a long history of participation in the SKA initiative; it is currently a member of the SKA Organisation (SKAO) and has Observer status on the Council Preparatory Task Force (CPTF). Funding priorities for Canadian astronomy are determined by the Canadian Astronomical Society (CASCA) each decade via the Long Range Plan (LRP)[7], wherein the SKA has been identified as a top priority for the last twenty years. LRP2020[8] is underway now, and the process of assessing future Canadian ambitions for participation in the SKA project has begun.

SKA1 will be a superb survey instrument, and it is anticipated that most of the available observing time will be allocated to the completion of Key Science Projects (KSPs). While scientific merit will play a central role in determining the KSPs that will be undertaken, scientific return on investment by participating countries will also be taken into consideration. As such, an important consideration for the Canadian

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[7] CASCA LRP website: https://casca.ca/?page_id=75
[8] LRP2020 website: https://casca.ca/?page_id=11499

astronomical community is the potential for scientific leadership in the KSPs ultimately undertaken given the expected Canadian participation level. While the SKA1 Operations Plans will ultimately be defined[9] by the intergovernmental organisation (IGO) that will oversee construction and operations, estimates of scientific leadership opportunities for a ∼6% participation level in SKA1 that is typically discussed in the Canadian community will provide valuable input for LRP2020. This appendix provides such estimates[10].

The structure of this document is as follows. In §A.2 the methodology and assumptions that underlie the scientific leadership estimates are explained, including SKA1 operations, KSP durations and management structure, and the valuation of a scientific leadership "currency" for KSPs. The resulting estimates for a 6% participation level given different expenditures of that currency are presented in §A.3, which represents a case study for different scenarios of potential interest to the Canadian astronomical community. §A.4 summarizes the results and discusses the concept of a scientific leadership currency more broadly.

*This appendix makes implicit and explicit assumptions regarding telescope operations, time allocation and KSP project structure that have not yet been determined for SKA1 and that fall within the purview of the IGO. While the hope is that these assumptions are sensible and ultimately useful, they are not final in concept or value.*

### A.2. *Methodology and Assumptions*

The set of assumptions that underlie the science leadership estimates are given in Table 8, and divide into observing and KSP distribution assumptions, KSP management structure assumptions, and scientific leadership currency assumptions. Each one is discussed in turn below.

- **Observing and KSP Distribution:** It is assumed that the overall observing efficiency of SKA1-Low and SKA1-Mid (ie. the fraction of the total time in a year spent carrying out science observations) will be 90%. This efficiency is similar to that for existing large radio observatories such as the VLA but may be optimistic for SKA1, particularly during early operations. In line with initial operations planning within SKAO, it is assumed that 70% of all observing time will be spent on KSPs and that a factor of 2 in observing efficiency will be gained from commensal observations. This focus on surveys at from onset of full operations differentiates SKA1 from facilities such as ALMA, where most of the observing time is spent on PI science. Commensurate with the fiducial survey sizes being discussed within SKA Science Working Groups, "small" 1,000-hour KSPs, "medium" 5,000-hour KSPs, and "large" 10,000-hour KSPs

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[9] The SKA1 Operations Plan is a Tier 3 IGO document.

[10] Only KSP leadership opportunities, and not smaller PI project opportunities, are considered here. It is assumed that scientific return on investment will be straightforward to calculate for PI projects since the number of proposals accepted in a given cycle will be large and since many operational precedents for this model exist.

**Table 8.** Parameter Assumptions

| **Parameter** | Value |
|---|---|
| **Observing and KSP Distribution Assumptions** | |
| Observing Efficiency | 90% |
| Fraction of time spent on KSPs | 70% |
| Commensality Factor | 2 |
| Number of large (10,000 hr) KSPs per year | 1 |
| Number of medium (5,000 hr) KSPs per year | 2 |
| **KSP Management Structure Assumptions** | |
| Number of leads, medium KSP | 2 |
| Number of executive members, medium KSP | 5 |
| Number of working group (WG) leads, medium KSP | 10 |
| Number of team members, medium KSP | 100 |
| Factor by which to scale from medium to small KSPs | 0.5 |
| Factor by which to scale from medium to large KSPs | 1.5 |
| **Scientific Leadership Currency Assumptions** | |
| Leadership value, medium and large KSPs | 1 |
| Leadership value, small KSP | 1/2 |
| Value of exec membership relative to leadership for a KSP | 2/5 |
| Value of WG membership relative to leadership for a KSP | 1/5 |
| Value of team membership | 1/50 |

Note—See §A.2 for details.

are considered. It is assumed that an average of 1 large KSP and 2 medium KSPs will be carried out each year, and that the remainder of the KSPs undertaken will be small. These assumptions imply that in a decade of full SKA1 observations a total of 10 large KSPs, 20 medium KSPs, and 21 small KSPs will be undertaken. The high number of medium and large KSPs relative to small ones reflects an implicit assumption made here that producing transformational SKA1 science will require relatively large amounts of SKA1 time. This seems reasonable given that pathfinder instruments will have already completed surveys of several thousands of hours by the time the KSPs get underway, and is also commensurate with the survey strategies identified by the SKA Science Working Groups (SWGs) to accomplish the High-Priority Science Objectives that are representative of the science that the KSPs will carry out[11]. Indeed, the management structure within the pathfinder survey science teams informs that adopted for KSPs below.

- **KSP Management Structure:** It is assumed that the basic management structure of several large radio surveys being undertaken now (e.g. VLASS on

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[11] See Table 2 of SKA-TEL-SKO-0000007, "SKA Level 0 Science Requirements".

**Table 9.** Case Study Scenarios

| **Scenario** | **Currency Expenditure** | | | |
|---|---|---|---|---|
| | **Lead** | **Exec** | **WG** | **Team** |
| Proportional | 25% | 25% | 25% | 25% |
| Top-Heavy | 50% | 15% | 15% | 20% |
| Bottom-Heavy | 10% | 25% | 25% | 40% |

Note—Currency valuation is in Table 8 and explained in §A.2.

the VLA, Wallaby on ASKAP, MIGHTEE on MeerKAT and others) is representative of that for a medium KSP. The adopted science leadership categories consist of KSP leads, executive committee members, working group (WG) leads, and team members. We broadly define the latter category as the individuals who have proprietary access to the data before it is publicly released. A medium KSP is assumed to have 2 leads, a 5-member executive committee, 10 working groups, and a survey team of 100. The number of leadership positions is assumed to scale with KSP size such that, on average, a small KSP has 50% fewer leadership positions and a large KSP has 50% more leadership positions within its management structure relative to a medium KSP. This management structure combined with the observing assumptions described above produces estimates for the number of leadership positions over a 10-year period across the project as a whole shown in the top portion of Table 10: in aggregate there will be over 90 KSP leads, almost 700 exec members + WG leads, and ∼4500 team members.

- **Scientific Leadership Currency:** It is assumed that scientific return on investment into KSPs will be calculated using a science leadership currency. It is logical to assume that the "valuation" of this currency will balance the relative rarity of a given leadership category against the management workload associated with it. While the concept of a currency has been broadly discussed before, there appears to have been no previous attempt at estimating its valuation. The general approach and specific valuation adopted here is as follows. The basic currency unit is defined to be a medium or large KSP lead (ie. they are valued at 1), and a small KSP lead is valued at 1/2. The values of executive membership, WG leadership, and team membership scale relative to that for the leads of a given KSP, with valuations of 2/5, 1/5, and 1/50 respectively. It should be noted that both this approach and the resulting valuations are based on intuition rather than any concrete precedent (it is unclear that a precedent exists). However, these valuations combined with the KSP distribution and management structure adopted here imply that, across the project as a whole, each leadership category has a roughly equal value (ie. the currency divides

**Table 10.** Results: KSP Science Leadership over 10 Years

| **Observatory-Wide** | | | | |
|---|---|---|---|---|
| **Role** | **Small** | **Medium** | **Large** | **Total** |
| Leadership | 21 | 40 | 30 | 91 |
| Exec Memberships | 53 | 100 | 75 | 228 |
| WG Leads | 105 | 200 | 150 | 455 |
| Team Memberships | 1050 | 2000 | 1500 | 4550 |
| **6% Proportional Participation** | | | | |
| **Role** | **Small** | **Medium** | **Large** | **Total** |
| Leadership | 1 | 2 | 2 | 5 |
| Exec Memberships | 3 | 6 | 5 | 14 |
| WG Leads | 6 | 12 | 9 | 27 |
| Team Memberships | 47 | 94 | 141 | 282 |
| **6% Participation, Lead-Heavy** | | | | |
| **Role** | **Small** | **Medium** | **Large** | **Total** |
| Leadership | 3 | 5 | 4 | 12 |
| Exec Memberships | 2 | 3 | 2 | 7 |
| WG Leads | 3 | 6 | 5 | 14 |
| Team Memberships | 38 | 76 | 114 | 228 |
| **6% Participation, Lead-Light** | | | | |
| **Role** | **Small** | **Medium** | **Large** | **Total** |
| Leadership | 1 | 1 | 1 | 3 |
| Exec Memberships | 3 | 6 | 5 | 14 |
| WG Leads | 7 | 12 | 9 | 28 |
| Team Memberships | 63 | 126 | 189 | 378 |

Note—Scenario definitions are given in Table 9.

equally between KSP leads, exec members, WG leads, and team members), which seems sensible. We return to the interplay between KSP structure and currency valuation in §A.4.

### A.3. *A Canadian Case Study: 6% Participation*

Canada has long made clear its intention to participate in the SKA at a level of $4\% - 8\%$, a range that arises through a number of different considerations of scientific and technological capacity within the community. Canadian expertise in SKA-related science is both deep and broad, and Canadians are members of every SKA SWG. It is therefore anticipated that the Canadian community will have ambitions to take on scientific leadership roles ranging from leads to team memberships in many different KSPs over the course of a decade. A reasonable approach for a Canadian case study is therefore to estimate a plausible range of leadership opportunities for a 6% participation level in SKA1 by scaling from the 10-year project-wide numbers, since this should be representative in the mean.

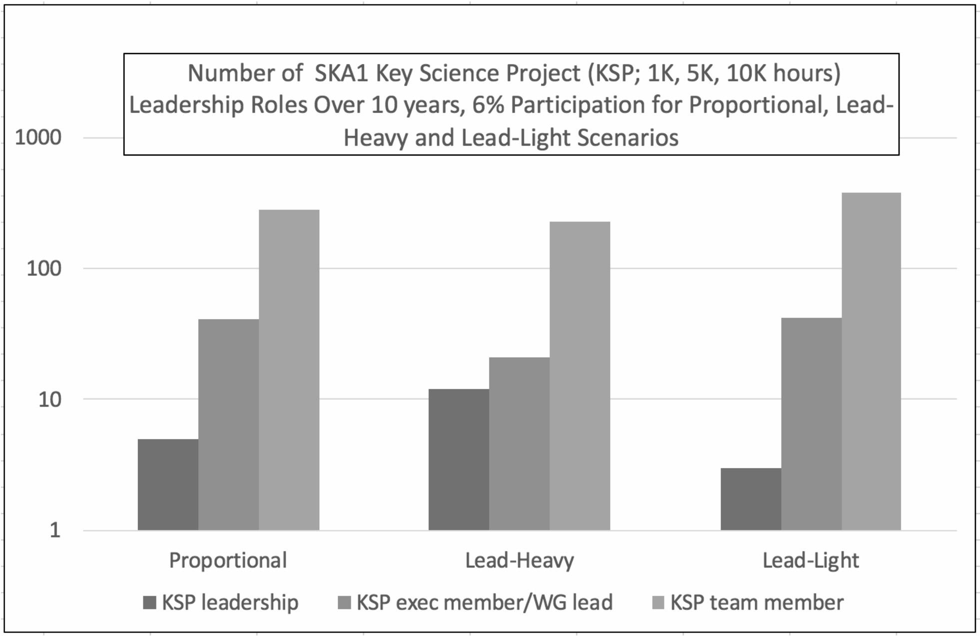

**Figure 11.** Canadian SKA1 KSP leadership opportunities over a 10-year period for a 6% participation level and the Proportional (left), Lead-Heavy (middle) and Lead-Light (right) scenarios summarized in Table 9.

The introduction of the science leadership currency allows for different expenditure scenarios to be examined in the context of a 6% participation level. Table 9 defines the different scenarios considered here, chosen to illustrate a reasonable range of options afforded by the currency construct:

- **Proportional scenario:** participation in each leadership category is simply proportional to the total number (which, given the currency valuation described in §A.2, implies that 25% of the available currency is spent on each of the four leadership categories adopted here);
- **Top-Heavy scenario:** more (50% vs 25%) of the currency is spent on KSP leads largely at the expense (15% vs. 25%) of executive memberships and WG leaderships relative to the Proportional scenario;
- **Bottom-Heavy scenario:** more (40% vs 25%) of the currency is spent on team membership at the expense (10% vs. 25%) of KSP leads relative to the proportional scenario.

To compute the implied number of leadership positions for each of these scenarios over a 10-year period, the (integer) number of leadership positions of a given category is computed starting with the most valuable (ie. KSP leads), and using any leftover currency in categories of less value (ie. exec memberships, then WG leads, then team memberships). This approach ensures that nearly all of the currency is spent in estimating the possibilities for each scenario. The resulting number of leadership roles for each scenario is given in Table 10 and illustrated in Figure 11.

Table 10 and Fig. 11 illustrate that the introduction of a science leadership currency produces a range of leadership possibilities for a 6% participation level: for the scenarios considered here, the number of KSP leads varies by a factor of four, and the combined number of exec members and WG leads as well as the number of team memberships vary by a factor of ∼two. This Canadian case study therefore implies that there is scope for some flexibility in tailoring the spectrum of leadership opportunities to the interests and expertise of the community. Which of the scenarios explored here (if any) are best suited to the Canadian community remains to be seen; this topic will be addressed in the context of LRP2020.

### A.4. *Summary*

This appendix has provided estimates of the available SKA1 KSP science leadership opportunities over a 10-year period using a series of observing, KSP distribution, KSP management structure and science leadership currency valuation assumptions for a 6% participation level characteristic of Canadian ambitions. The Proportional, Lead-Heavy and Lead-Light scenarios considered here produce a range of leadership opportunities in which the number of KSP leads varies by a factor of four and the other leadership roles vary by a factor of ∼two.

While the methodology described in §A.2 certainly oversimplifies the KSP framework that will be established by the IGO Council, the case study in §A.3 suggest that a scientific leadership currency is a potentially useful construct for calculating scientific return on investment for KSPs. Despite its simplicity, the approach adopted here highlights the interplay between the valuation of that currency, which will presumably be in place before KSP proposals are solicited in order for SKA1 partners to understand the commitments of their members, and the KSPs that will ultimately be undertaken, which will presumably balance scientific merit and participation level across the project. The spectrum of KSP sizes and structures that will likely be required to accomplish the HPSOs may therefore be important to consider in valuing the currency; SWGs or the entities that supercede them once the IGO comes into force may be in the best position to provide this input.

Given the range of scientific leadership opportunities that the introduction of a currency affords, it will be beneficial for the Canadian community – with a breadth and depth of expertise and a small anticipated SKA1 participation level – to consider its KSP leadership ambitions and the scenario by which those ambitions can be fulfilled. LRP2020 and the SKA-related recommendations that will emerge from that process provide an opportunity for concrete discussions in this regard. It is hoped that the methodology and outcomes in this appendix help inform those specific Canadian conversations, but also prove useful to a broad cross-section of SKA stakeholders across the project.

## B. A CANADIAN SKA REGIONAL CENTRE

This appendix details the estimates carried out by Canadian SKA Regional Centre Advisory Committee (CSRCAC) members S. Gaudet, J. Kavelaars, and E. Rosolowsky (see §4.5) to define the scope and possible implementations of a Canadian SRC, and has now developed a realistic, bottom-up estimate of related requirements. The CSRCAC has worked closely with CANARIE, Compute Canada and NRC to establish real-world estimates for the costing of computing hardware, networking and FTE capacity that will be required to operate an SRC. The costing amounts are derived from ongoing roll-outs of infrastructure in Canada and reflect the total cost of ownership of those systems. These are the most detailed and sophisticated costing estimates of SRC operations to have yet been produced within the project.

### B.1. *The SKA need for regional centres*[12]

It is currently estimated that the SKA Observatory will generate 700 PB of calibrated science data products each year. This data rate is unprecedented in observational astronomy. The infrastructure for transporting such large data volumes to users around the world, and the computational resources that are required to enable users to turn those data into scientific results, are not within the current planned scope of the SKA project and demand imaginative solutions.

In April 2016, the SKA Board received the report of the Data Flow Advisory Panel (DFAP). The Board endorsed the DFAPs proposed strategy of a collaborative network of SKA Regional Centres (SRCs) to provide the essential functions that are not within the scope of the SKA project: specifically, computational capacity for re-processing and science analysis, provision of an SKA Science Archive, and local user support. The collaborative relationship between the Observatory and the regionally-funded SRCs was suggested to be based on a resource pledging arrangement and governed by Memoranda of Understanding.

A minimum set of requirements for each SRC will be defined, and these (amongst others) will pertain to:

- curation and preservation of SKA and user-generated data products and workflows;
- provision of resources for post-processing, analysis and data visualisation;
- application of SKA data policies and procedures for access to SKA data; user support.

In addition, some SRCs may wish to have their own Communications and Outreach activities.

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[12] This section adapted from "SKA REGIONAL CENTRES: BACKGROUND AND FRAMEWORK", SKA-TEL-SKO-0000706, 2017-06-06

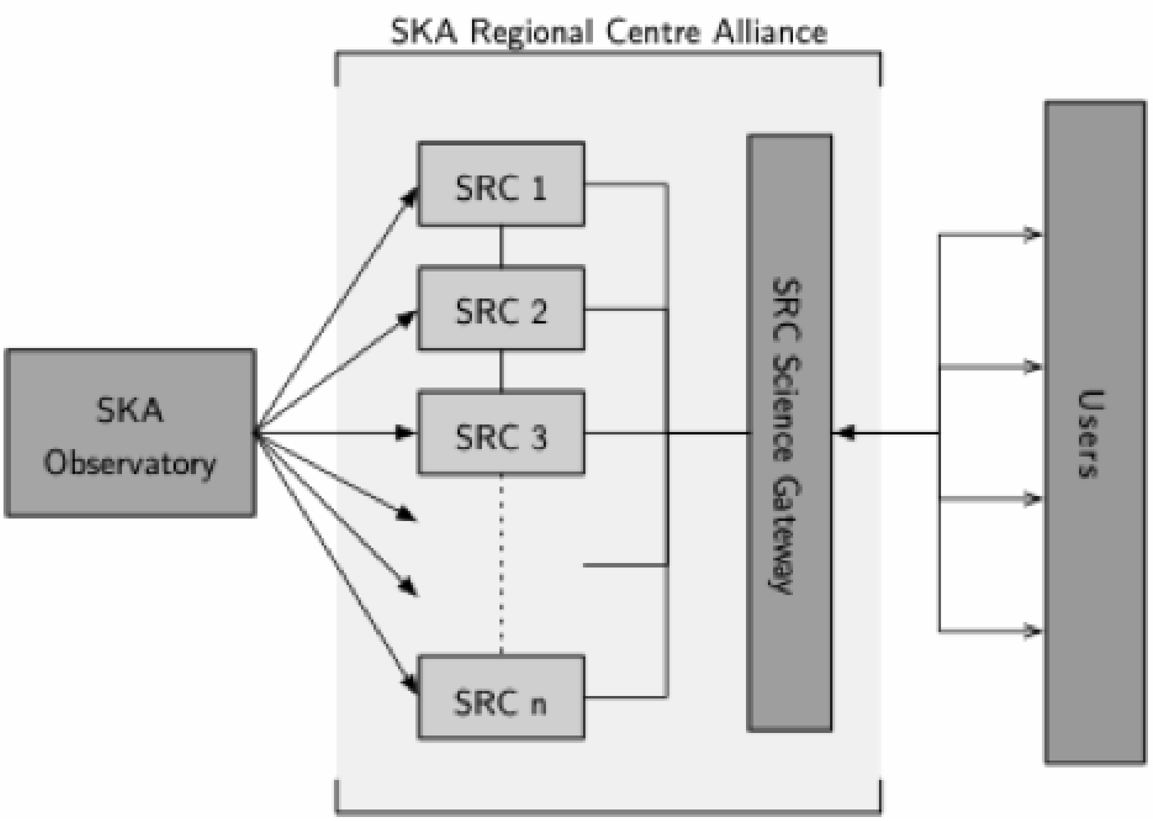

**Figure 12.** A network of SKA Regional Centres (the SRC Alliance) receives science data products from the SKA Observatory. Access to SKA science data products, as well as the tools and processing power necessary to fully exploit the science potential of those products, is provided via a Science Gateway. Access to science data products is irrespective of a SKA users geographical location, or whether their local region or country hosts an SRC.

The SRC Alliance will have two primary, collective, responsibilities: (i) to provide the long-term curation and preservation of SKA and user-generated data products and workflows, and (ii) to provide a common platform to enable the creation of user-generated data products of high science value. The aim is for a SRC Alliance working together for the SKA community as a whole. As with most modern, large scientific projects, the SKA will execute extensive projects over a broad and globally distributed community with common aims. At least the following functionality is anticipated to be required (amongst others):

- the long-term data archive for SKA and user-generated science data products (Observatory data products and advanced data products, respectively);
- sharing of data products, processing resources and workflows between SRCs;
- interoperability, using a common platform and standards, across the SRC Alliance;
- supporting VO services and protocols.

### B.2. *Why Canada Should Host an SRC*

Hosting a regional centre for the SKA is essential for growing and maintaining a broad community of Canadian SKA users. The SKA is regarded as an information and communications technology telescope, where the vast computation and data processing requirements drive the design of the observatory nearly as much as the telescope antennas. A Canadian SRC will directly link Canadian users to their data and enable new computational approaches for using SKA data for scientific discovery.

Development of a Canadian SRC and participation in the SRC network implies some SKA data data will be hosted in Canadian computational facilities, closely connected to high-performance computing resources. In the SRC model, the physical location of the data is not critical for the SKA archive: all users will have global, pooled access to the archive and associated computation to execute their observations. However, if we did not participate in the SRC network, we would have to rely on other regional centres for access to data and computation. Such access would have to be negotiated and paid for as part of the SKA participation, through cash or in-kind contributions.

Participating in the network provides one key advantage: it directly enables new archive users. The SRCs do not provide processing and storage support for these users, leading to a high barrier for scientists who want to use SKA data for computationally intensive analyses but were not on the original proposing teams. Without an SRC, archival users will be more limited in their access to data, which would stunt the growth of the Canadian SKA community. In continuing our participation in the development of the SRC network, we ensure that the implementation of the network will be compatible with our existing (strong) approaches to data and computing in Canada. Such participation will connect the SKA archive with our domestic computing facilities, catalyzing archive use.

### B.3. *What a Canadian SRC Could Do*

The minimum hardware requirements for the SRC will be set by the SRC Alliance. Much like the telescope itself, Canada can commit to participation in the SRC Alliance and will be responsible for providing some share of SKA processing and archiving. In principle, we can participate in a share that is not the same as our participation in the observatory, so we consider three Scenarios, corresponding roughly to 2%, 6% and 8% shares of the requirements of the SRC network.

This minimum participation would be a contribution of storage for archive, computation for observer teams to process their data and the network costs associated with transport of the data through the SKA data network. The minimum cost includes both the hardware initial and refresh costs, operations costs (power) and the staffing required for maintenance of the infrastructure. The requirements are established by the SKA design studies. The minimum model also requires some commitment to the ongoing governance and development of the SRC Alliance and standards, adopting

| Activity | Scenario 1 | Scenario 2 | Scenario 3 |
|---|---|---|---|
| SRC Data Processing Share for PI Projects | 6% | 6% | 8% |
| SRC Archive Hosting Share for PI Projects | 6% | 6% | 8% |
| SRC Data Processing Share for KSPs | ··· | 6% | 8% |
| SRC Archive Hosting Share for KSPs | ··· | 6% | 8% |
| SKA Archive Data Processing | 6% | 6% | 8% |
| Data Transport for SRC Alliance | 100 Gbps | 100 Gbps | 100 Gbps |
| Contributed Effort for SRC Software Development | 1 FTE | 2 FTE | 2 FTE |
| Contributed Effort for SRC Governance | 0.1 FTE | 0.25 FTE | 0.25 FTE |
| Effort for dedicated support to Canadian SKA users | 4.5 FTE | 4.5 FTE | 4.5 FTE |
| Education and Public Outreach | 3% | 3% | 3% |
| Total cost (M$, over 10 years of ramp up) | 24 | 45 | 55 |

**Table 11.** Summary of SRC Activity and Costing for Different Involvement Scenarios

software changes, and ensuring that the Canadian hardware resources are in the SRC network. The SRC model also provides for sufficient Canadian SKA user support for, e.g., help-desk support during the proposal process or providing access to SKA data and computing. We summarize different SRC activities in these Scenarios in Table 11.

The possible SRC activities include:

- Processing and Storage for SKA users – Participation in SRC alliance commits Canada to providing some share of the processing required to generate science-ready SKA data and the storage needed to host the SKA archive. Given the discussion in Appendix A, the Canadian contribution can be steered toward PI science or Key Science Projects, which are nominally divided 30% (PI) to 70% (KSP). In our model, we consider the main priority to be supporting PI users of the SKA. KSPs are likely span multiple partner nations so the KSP processing and archiving could be hosted in other SRCs. The entire SRC network will need to archive 700 PB / year and provide 21.6 PFLOPs of processing. Some fraction of this will be Canada's contribution.

- Data Transport – The SRC Alliance will also need to pay the costs of data transport. We have considered the costs borne by CANARIE for transoceanic networking at 100 Gbps. The SRC network architecture and cost estimates are shown in Figure 13.

- Contributed Effort for SRC Software Development and Governance – In joining the SRC Alliance, Canada would contribute software and personnel time to supporting the work of the international network. This would likely include activities similar to what is already being done by NRC/CADC in preparing for the SKA.

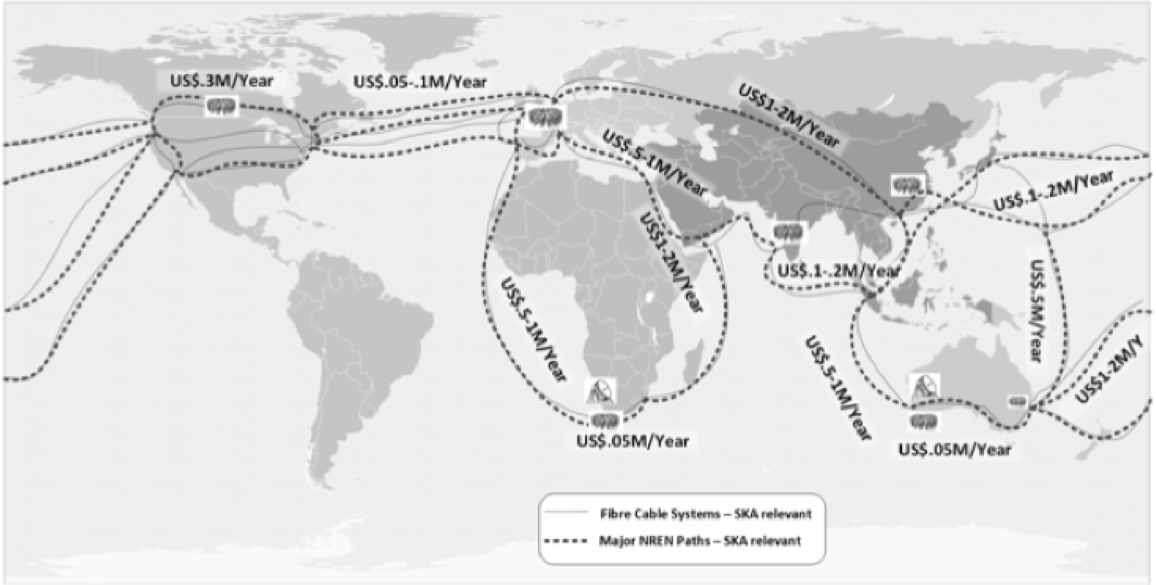

**Figure 13.** SRC Network Configuration and estimated costs of data transport.

- Personnel for Supporting Canadian users of the SKA – This staffing includes Canadian SKA helpdesk staff that support Canadian PIs during the proposal and processing stages of a project. These positions include 2 FTE dedicated to community support through, e.g., the SKA helpdesk and 1 FTE dedicated to facilitating Canadian science (KSP or PI) through dedicated scientific software development that applies high-throughput computing to digest large SKA data sets. The remaining 1.5 FTE are dedicated initially to adapting the SRC software to the Canadian computer resources. Once deployed, the positions will transition to developing software to support Canadian SKA users. These personnel would also guide Canadian users of the SKA archive for carrying out archival science.
- Education and Public Outreach – Even though it is not mandated by the requirements for SRCs, we recommend that a Canadian SRC include support for EPO efforts at a level of 3% of the SRC personnel budget. The Canadian SKA Regional Centre is the natural host organization for SKA-related EPO efforts. Participation in the SKA would mean a major public investment in radio astronomy and it is critical to make the effort to communicate the return on investment back to the public.

We consider a range of support options for a Canadian SRC as laid out in Table 11. The lowest-cost model prioritizes support for Canadian PI users, including the archive and processing capacity to support those project. By maintaining these data domestically, we can connect them to national computing resources for advanced processing. Scenario 1 includes the costs of participating in the SRC but also personnel to ensure Canadian PIs can take advantage of domestic resources.

In Scenarios 2 and 3, we consider the additional hardware required to support KSPs domestically at a level consistent with our national share in the telescope for Scenario 2 or participating with an increased share for Scenario 3.

While the SRC Alliance establishes the minimum requirements, all our models include services that specifically support the Canadian community using the SKA, focusing on effective and novel use of the SKA archive. In doing so the SRC activities become part of a larger Canadian SKA Science Centre, or depending on alignment with respect to other data-intensive telescopes (e.g., LSST), a unified Canadian Astronomy Science Centre (CASC). Apart from the SRC requirements, the CASC would support the user support, software development, and computing resources needed for astronomers outside of the successful proposal teams to use archival data. This additional effort would be targeted at broadening access to the SKA.

We also prioritize leadership within the SRC Alliance based on Canadian strength in the activities that underpin the SRC network, drawn from the work of CADC and university efforts like CIRADA.

### B.4. *Cost Estimate*

Using this suite of activities for the SRC, we have made a cost prediction for these different scenarios. This costing effort was led by Séverin Gaudet at the CADC. The cost model uses constant 2019 dollars. We established costs for storage and processing based operations costs for purchasing and operating this equipment in Canada. These numbers reflect “all-in” costing, which includes preferred vendor pricing, infrastructure operations costs including the purchase of data center hardware (e.g., racks and cabling), power, replacement parts, hardware refresh at the end of its service lifetime, and the personnel required to maintain this hardware. This pricing was established using numbers for the full cost of purchasing and operations for large data and compute centres operated by Compute Canada. This pricing includes quotes subject to non-disclosure agreements with vendors, so we are unable to provide a breakdown of the hardware components. We validated these estimates by comparing to costs estimates for hardware assumed by other SRC development initiatives and to the cost of purchasing and operations of CADC hardware. We note that our cost estimates are higher than other preliminary figures proposed in the SKA consortium because of our “all-in” costing.

We quote an aggregate cost over 10 years of ramp-up starting 7 years before SKA main science operations (taken to be 2028), but our model includes staged purchasing every three years with a decreasing cost for computation and storage reflecting long term trends in computing. To reach the storage quotas required for SKA archiving, we assume that some data will be stored in “nearline” formats, i.e., on tape, so that data are retrieved into active storage on timescales of minutes to hours. For computation, we assume a 30%-70% split between GPU and CPU processing. We assume that paying one FTE for a year requires \$200k inclusive of benefits.

| | 2021-2030 (Cumulative) | 2031-2035 (Annual Average) |
|---|---|---|
| Cost | \$45,400,000 | \$4,940,000 |
| Processing | 9.7 PFLOP-years | 1.7 PFLOPs |
| Online Storage | 237 PB-years | 42 PB |
| Nearline Storage | 654 PB-years | 322 PB |
| Data Transport | 100 Gbps | 100 Gbps |
| Staffing | 53.8 FTE-years | 6.75 FTE |
| Travel | \$1,100,000 | \$126,000 |
| Education/Public Outreach | \$400,000 | \$40,500 |

**Table 12.** Specifications for Recommended Scenario

We thus determine a realistic model for the true cost of operating an SRC in Canada using a conservative pricing approach. The cost of hardware is a driving factor and it could decrease (new technology advances) or increase (supply chain failures) away from our baseline model.

### B.5. *Timeline*

We assume that Canadian SRC activities would commence soon after the Canada formally joins the SKA. Before actual SKA operations, SRC activities would include creating SRC Alliance and developing the software required to integrate the SRCs together. The Canadian SRC would require hardware to serve the SKA needs during construction and commissioning stages and to be ready for full operations in 2028. We assume the first part of SRC operations would begin in 2021 with hardware purchasing commencing in 2022, using data from SKA precursor facilities to develop and test the SRC network.

### B.6. *Recommendation*

We recommend Scenario 2 as a good model for Canadian participation in the SRC. This includes processing and storage for PI and KSP data at a fraction equivalent to the Canadian share of SKA. Given the central role that KSPs will make to driving SKA science, we deem it important that Canada maintain a stake in the storage and processing of the KSP data. We also strongly recommend that the mandated Canadian SRC activities be a part of a larger Canadian SKA Science Centre with additional personnel dedicated to facilitating Canadian SKA science and EPO efforts. We summarize the characteristics of the recommended Canadian SRC Scenario in Table 12. We present the cumulative costs and capabilities for the construction and early science operations of the SKA (2021-2030) and then the steady-state annual average over the following five years during science operations.