MTR Update on Square Kilometre Array

1 What is the SKA?

The Square Kilometre Array (SKA) is an ambitious and exciting project to build a next generation radio telescope system to enable transformational discoveries across astrophysics:

- Probing the Cosmic Dawn – Imaging and tomography of the Epoch of Reionization to understand the transition of the universe from completely neutral to the largely ionized state seen today.
- Galaxy Evolution, Cosmology and Dark Energy – Providing a complete inventory of galaxy assembly, while simultaneously using baryonic acoustic oscillations as a precision probe of Dark Energy.
- The Origin and Evolution of Cosmic Magnetism – Tracking the evolution of magnetism in galaxies, in clusters, and in the intergalactic medium over cosmic time.
- Strong Field Tests of Gravity – Establishing a pulsar timing array to detect nano-Hz gravitational waves, and testing General Relativity in the strong field limit using pulsar/black hole binaries.
- The Cradle of Life - Detection of organic and pre-biotic molecules in interstellar space, and direct imaging of Earth-like planets forming around other stars.

These experiments require a telescope system with 50 times the sensitivity of the Jansky Very Large Array, currently the world's most powerful radio telescope.

A project of the scale of the SKA requires the collaborative efforts of a number of countries. In 2011 the SKA Organization (SKAO) was formed to move the project into a pre-construction design phase. Canada is one of the 10 full-member countries of the SKAO, which also includes Australia, China, Germany, India, Italy, Netherlands, New Zealand, South Africa, Sweden and the UK.

The SKA will be developed in a phased manner, first with the design and deployment of "SKA1", a subset (~10%) of the full "SKA2" that will be realised at a later date. A large frequency range is required by the key science drivers, potentially demanding three different telescope technologies – an aperture array for low frequencies (50 – 350 MHz), an array of dishes for frequencies above 350 MHz, and a subset of these dishes outfitted with phased-array feeds for surveys requiring very large fields-of-view.

The SKA will be located at two sites, in Australia and South Africa, both of which provide superb conditions for radio astronomy. Two SKA precursors have been constructed on the Australian site: the Australian SKA Pathfinder telescope (ASKAP), a 36-element array of 12-m dishes outfitted with phased-array feeds, and the Murchison Widefield Array (MWA), an array of 128 low-frequency tiles. A third SKA precursor is at the South African site: MeerKAT, a 64-element dish array with single-pixel feeds. The MWA has been fully operational since 2012, while ASKAP and MeerKAT are in their commissioning stages and are moving toward early science programs.

Two aspects of the SKA Science Case have been targeted for the initial deployment of SKA1, namely:

- Understanding the role of hydrogen in the Universe from the "Dark Ages" to the present day, and

- Detecting and timing of millisecond pulsars in order to test theories of gravity (including General Relativity and quantum gravity), to discover gravitational waves from cosmological sources, and to determine the equation of state of nuclear matter.

To address these focussed science requirements the current baseline design comprises three components:

- SKA1-Low: an aperture array of ~250,000 dipoles covering 50 – 350 MHz, in Western Australia.
- SKA1-Mid: 190 dishes from 0.35 to 14 GHz with single-pixel receivers, in the Karoo, South Africa
- SKA1-Survey: 96 dishes from 0.35 to 4 GHz using phased-array feeds, located in Western Australia.

The design work in the SKA1 pre-construction is aimed at realising these components, within a cost cap of €650M.

2 SKA1 Pre-Construction.

The vision of the SKA is exciting, ambitious and challenging, and is stimulating significant research and development in a number of areas where high performance at low cost will be paramount for delivery of the SKA. This R&D has been on-going around the globe over the past decade, and is now being captured in a formal system engineering process within SKA1 pre-construction.

The pre-construction phase began in earnest in 2013 when the design and costing of the three components of SKA1 commenced. This work has been completed in ten design consortia that comprise industry, national laboratories, and university partners spread throughout the member countries. This effort amounts to a contributed value in excess of €97M. The design requirements for the initial design work were derived from a baseline design of the three telescopes. The resulting designs to realise the baseline design will be formally assessed at the preliminary design reviews (PDRs) scheduled for Q4 2014/ Q1 2015.

The principal boundary condition for SKA1 is the construction cost cap of €650M. The initial costings derived by the design consortia are in excess of this, and the immediate goal following the PDRs is to establish a re-baselined design for the SKA1 within this cost cap. This may change the scope of the three telescope systems currently under consideration, but will be optimized to provide the highest-priority SKA1 science goals. Following the selection of the SKA1 design in 2015, the proposed schedule is as follows:

- 2016 - Critical Design Reviews of SKA1 detailed design
- 2017 - Tender and procurement of SKA1 construction
- 2018 – Start SKA1 construction, start detailed design of SKA2
- 2020 – Early SKA1 science
- 2023 – Complete SKA1 construction, full SKA1 science
- 2024 – Start SKA2 construction (duration depends on scope of SKA2)

3 Canada and the SKA

Canada was one of the six countries that formed the initial SKA consortium in 2000, and has participated in the SKA concept design and preparatory phase for over a decade.

Canadian scientists defined the initial SKA science case, and have been major participants in the recent refinement of the science goals of the SKA1 that are now driving the engineering specifications. In addition, Canadian astronomers are playing leading roles in most of the marquee SKA science programs, including tests of gravity, galaxy evolution, cosmic magnetism and Dark Energy. Canada is also contributing significantly to developing the design of SKA1 through four of the ten design consortia, and is conducting R&D in areas of technology where we have significant experience and where we have novel and new approaches that address the performance/cost challenge posed by the SKA.

These contributions are consistent with the support of the community as outlined in the 2010-2020 Long Range Plan (LRP) for Canadian astronomy, which ``*reaffirms the importance and very high priority of Canada's participation in the SKA*". Specifically, the LRP states that "*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.*"

Canada's participation in the SKA is overseen by the ACURA Advisory Council on the SKA (AACS), which includes relevant representatives from universities and industry. The AACS promotes and advances Canadian involvement in the SKA, advises ACURA and NRC on ways to define and attain Canada's goals for SKA participation, and coordinates between universities, NRC and industry on SKA activities, partnerships and associated technology development.

3.1 Canadian contributions to the Pre-Construction Design work.

In joining the SKAO, Canada agreed to deliver €8M of in-kind work to the SKA pre-construction phase. This work is being captured in four of the SKA1 design consortia, and is being driven both by NRC and by the university community. Canadian industry is collaborating in many aspects of this work, and there is industry up-take for some of this R&D. Areas in which Canada is contributing are:

- ***Digital Signal Processing*** – NRC is leading the Central Signal Processing (CSP) consortium, with assistance from industry partner MacDonald Dettwiler & Associates (MDA), Richmond BC, on the design of the correlators and beamformers, and on non-imaging pulsar search and timing processors. The leadership of the CSP consortium builds on NRCs reputation in leading-edge digital system design and delivery, exemplified by the WIDAR correlator delivered to the Jansky Very Large Array.
- ***Composite reflectors -*** Over the past eight years, NRC has developed high-performance, low cost composite reflectors that can be mass produced. This work has matured to an 18mx15m Dish Verification Antenna DVA1, currently under test at NRC DRAO, and is a major effort within the DISH consortium (where NRC is responsible for the Dish Structure sub-element). There is industry interest in this potential game-changing composite reflector technology, and NRC is working with SED

Systems (Saskatoon, SK) on the DVA1 and with GDSatcom Technologies (Richardson, Texas, USA) on delivery of the sub-reflectors for MeerKAT in South Africa.

- ***Low Noise Amplifiers and RF digitizers –*** Cryogenic LNAs have been developed by NRC that achieve world-class noise performance and, in collaboration with Nanowave Technologies (Etobicoke, ON), will be part of the EMSS (Stellenbosch, RSA) L-band and UHF-band receivers on MeerKAT. One of these receiver systems is being tested with the DVA1 at NRC DRAO. In collaboration with NRC, UCalgary has been investigating room-temperature LNAs to reduce operations costs inherent with cryo-cooling. UCalgary is also working on low-power, high-bandwidth ADCs. As part of the DISH consortium work, NRC is responsible for the digitizers for single-pixel feeds. Part of this work has been based on an ADC architecture used by McGill for CHIME.
- ***Phased-array Feeds (PAF) –*** Arrays of receiver systems that deliver a larger field-of-view are a new technology important for the high survey speeds envisaged for SKA1-Survey. NRC is one of a number of groups around the globe working on demonstrating phased-array feeds on dishes, with a specific focus on cryo-cooled PAFs for improved noise performance.
- ***Science Data Processing –*** With daily data volumes to the archives of 10's of TB/s, the SKA is at the vanguard of projects that drive the "grand data challenge". Canada is contributing to this challenge through the UCambridge (UK)–led Science Data Processing (SDP) consortium. Through CANARIE, UCalgary is building a test bed for SDP Data Delivery in collaboration with Rackforce (Kelowna, BC) and with partners in the UK, Netherlands, South Africa and Australia. In addition, NRC CADC is contributing to data archive processing and access, while McGill, UBC, UAlberta and UCalgary are working on data-processing pipeline design.
- ***Telescope Management –*** Building on experience from the EVLA project, NRC is participating in the design of the SKA1 monitor and control system, and on interfaces to the SKA Telescope Manager.

4 Considerations for Canada

The 2010 LRP recommended that "*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*". In 2015, the preliminary design phase, project re-baselining and selection of the design of SKA1 that falls within the cost cap will all take place, addressing many of the conditions set in the 2010 LRP. Outstanding issues still to be resolved are:

- The scale of Canada's fiscal commitment to construction. The expectation is 6%-10% of construction, taking into account the number of member countries, their GDPs and the relative sizes of their astronomy communities. This implies a range of possible contributions from ~€28M to €52M.
- Canada's ability to commit to SKA1 is dependent on the nature of the governance structure of the SKAO, currently under discussion, and on phasing with TMT funding.
- The sub-systems of SKA1 for which Canada should focus its efforts post-rebaselining, and secure a role for Canadian industry. Much depends on the outcomes of rebaselining and the choice of SKA1 design, the nature of the SKA1 procurement process, areas of technology innovation consistent with GoC S&T policy, and the scale of our fiscal commitment to construction.

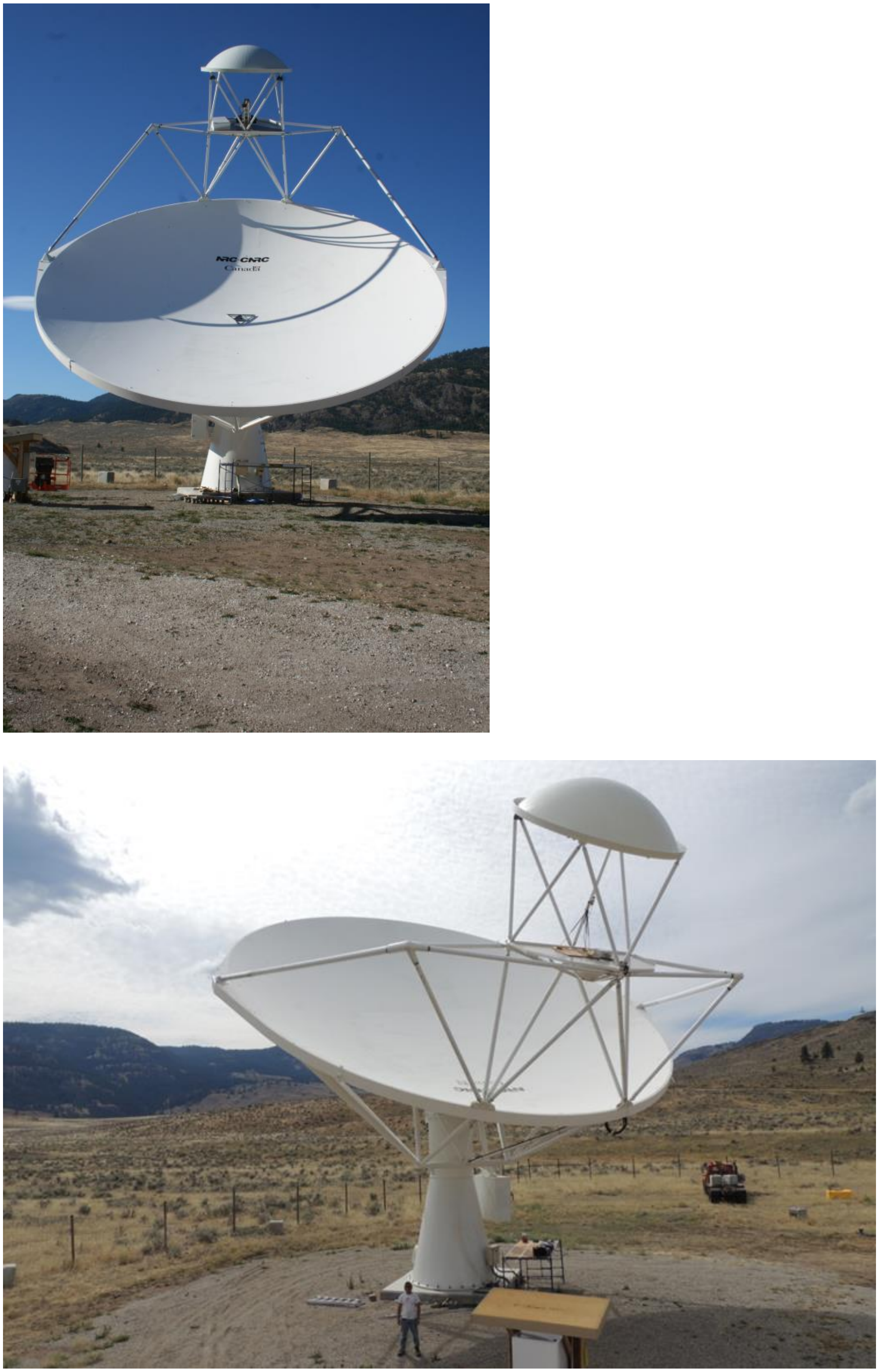

Figure 1. Two views of the Dish Verification Antenna #1 (DVA1) at NRC-DRAO, a novel 15-m diameter, rim-supported composite reflector. This high performance, low cost design is being advanced by Canada to the SKA DISH consortium as part of the SKA Pre-Construction design work.