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THE SQUARE KILOMETRE ARRAY

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1. THE INTERNATIONAL SKA PROJECT

The Square Kilometre Array (SKA) is a global project to design and build a next-generation international radio telescope at metre to centimetre wavelengths. The SKA will be one of the largest scientific projects ever undertaken, designed to answer some of the big questions of our time: what is Dark Energy? Was Einstein right about gravity? What is the nature of dark matter? Can we detect gravitational waves? When and how did the first stars and galaxies form? What was the origin of cosmic magnetism? How do Earth-like planets form? Is there life, intelligent or otherwise, elsewhere in the Universe? The SKA will have a collecting area of up to one million square metres spread over at least 3000 km, providing sensitivity 50 times greater than the Expanded VLA. In addition, the SKA will deliver an instantaneous field of view (FOV), many times that of existing instruments - a capability enabled by exploiting advanced information and telecommunications technologies.

Since its genesis in the early 1990s, the SKA has benefited from a distributed development model, with aspects of the R&D required to build the SKA worked on in different institutes around the world. Canada has been a leader in the development of this international project since the beginning, as one of the six countries that formed the initial consortium in 2000. The international Collaboration Agreement for the SKA now involves over 20 countries.

The European Strategy Forum on Research Initiatives (ESFRI) Roadmap for Research Infrastructures[1], lists the Square Kilometre Array as the next generation radio telescope for Europe, to become operational on the 2014-2020 time frame. As part of its Seventh Framework Programme, the European Commission has funded a Preparatory Phase project for the SKA (PrepSKA). PrepSKA is the umbrella project that has responsibility for integrating the international design efforts. It is coordinated by the UK Science and Technologies Facilities Council, and includes seven major work packages with participation by 20 organizations from the international collaboration, including the NRC and the University of Calgary in Canada. The international PrepSKA agreement was begun in April 2008 and continues to 2012. Participation by non-EU members is self-funded.

About €300M is being spent worldwide on the design phase (2008- 2012) including design study programs in Australia, Canada, Europe, South Africa and the U.S., as well as site development and construction of precursor telescopes at the two proposed sites in Australia and South Africa. The Canadian participation in the system design under PrepSKA is funded through 2012 at the level of about \$8 M from a combination of sources, including NRC, NSERC, CANARIE and the University of Calgary.

The US participation in PrepSKA is funded by the National Science Foundation at \$12M USD, through the NSF Technology Development Program (TDP). This work is coordinated by Cornell University on behalf of the US SKA Consortium. Cooperation between the Canadian program and the US TDP exist on antenna design and on calibration, imaging and data processing techniques.

Australia, with international partners, is designing and constructing a 1%-scale SKA prototype and pathfinder on their proposed SKA site. Australian funding for construction of ASKAP (\$111 M) is secured with a target for completion by late 2012. ASKAP will prototype the SKA reference design technology, including focal plane phased array feed systems. It will demonstrate its scientific capability through a program of survey projects on key SKA science. A Statement of Intent has been signed between Canada and Australia for Cooperative Development of ASKAP. This agreement provides an avenue for collaboration between Canadian and Australia on SKA technologies and for Canadian scientists to participate in the design and execution of the early key science programs. Fourteen Canadian scientists have helped to co-author the ASKAP science case (Johnston et al. 2008), and twenty-three Canadian scientists from ten institutions are participating in the ASKAP survey design projects (Figure 1). Canadian interests span the full range of projects, including pulsars, transients and variable phenomena, polarization and the magnetic universe, atomic hydrogen in our Galaxy and the extragalactic sky, galaxy evolution, and ultra high resolution studies of stars, supernovae and galactic nuclei through VLBI techniques.

A similar scale SKA precursor telescope called MeerKAT is under development at the South African site. MeerKAT will consist of 80 antennas with single-pixel broad-band feed arrays. Canadian teams are developing proposals for early survey science.

The SKA project is directed by a Science and Engineering Committee (SSEC) with 24 representatives from the global SKA Consortium. Canada has two representatives on the SSEC. The SKA Program Development Office is sited at the University of Manchester (UK) and funded partially by the EC through PrepSKA, and partially through an international common fund of contributions from the countries represented on the SSEC. It reports to the SSEC and is charged with coordinating the engineering and science efforts globally as well the further characterization of the candidate sites for the SKA.

An Agency SKA Group has been formed with representatives of funding agencies from the countries involved in the SKA. It is chaired by the UK Science and Technology Facilities Council, and has the goal to "deliver a non-binding Joint Agreement on the implementation of the SKA, with emphasis on Phase 1 and Phase 2, to coincide with the conclusion of the PrepSKA in 2011-12".

The overall project timeline over the next decade con-

[1] Office for Official Publications of the European Communities, 2006, IBN 92-79-02694-1

sists of four stages:
2008 – 2012: System Design and site decision,
2013 – 2014: Detailed design and production engineering,
2015 – 2018: Phase I construction and first science,
2018 – 2022: Phase 2 completion and commissioning.

2. SKA SCIENCE

The SKA will advance our capabilities in radio astronomy by orders of magnitude in sensitivity and instantaneous imaging speed. It will address a broad range of science goals that impact virtually every area of modern astrophysics. Over the past several years, there has been extensive activity related to developing a detailed science case for the SKA, culminating in the SKA Science Book (Carilli & Rawlings 2004). Highlighting the SKA Science Case are Key Science Projects (KSPs), which represent unanswered questions in fundamental physics, astrophysics, and astrobiology. Furthermore, each of these projects has been selected using the criterion that it represents science that is either unique to the SKA or in which the SKA will provide essential data for a multi-wavelength analysis (Gaensler 2004). The KSPs are

2.1. *Emerging from the Dark Ages*

The ionizing ultra-violet radiation from the first stars and galaxies produced a fundamental change in the surrounding intergalactic medium, from a nearly completely neutral state to the nearly completely ionized Universe in which we live today. The most direct probe of this Epoch of Re-ionization (EoR), and of the first large-scale structure formation, will be obtained by imaging neutral hydrogen and tracking the transition of the intergalactic medium from a neutral to ionized state. Moreover, as the first galaxies and AGN formed, the SKA will provide an unobscured view of their gas content and dynamics via observations of highly redshifted, low-order molecular transitions (e.g., CO).

2.2. *Galaxy Evolution, Cosmology, and Dark Energy*

Hydrogen is the fundamental baryonic component of the Universe. The SKA will have sufficient sensitivity to the 21-cm hyperfine transition of H I to detect galaxies to redshifts $z > 1$ (Figure 2). One of the key questions for 21$^{\text{st}}$ Century astronomy is the assembly of galaxies; the SKA will probe how galaxies convert their gas to stars over a significant fraction of cosmic time and how the environment affects galactic properties. Simultaneously, baryon acoustic oscillations (BAOs), remnants of early density fluctuations in the Universe, serve as a tracer of the early expansion of the Universe. The SKA will assemble a large sample of galaxies to measure BAOs as a function of redshift to constrain the equation of state of dark energy (Figure 3).

2.3. *The Origin and Evolution of Cosmic Magnetism*

Magnetic fields likely play an important role throughout astrophysics, including in particle acceleration, cosmic ray propagation, and star formation. Unlike gravity, which has been present since the earliest times in the Universe, magnetic fields may have been generated essentially *ab initio* in galaxies and clusters of galaxies. By measuring the Faraday rotation toward large numbers of background sources (Figure 4), the SKA will track the evolution of magnetic fields in galaxies and clusters of galaxies over a large fraction of cosmic time. The SKA observations also will also seek to distinguish galaxy-generated from primordial magnetic fields. The latter provide important clues on the physics of the Universe origins.

2.4. *Strong Field Tests of Gravity*

With magnetic field strengths as large as 10^{14} G, rotation rates approaching 1000 Hz, central densities exceeding 10^{14} g cm^{-3}, and normalized gravitational strengths of order 0.4, neutron stars represent extreme laboratories. Their utility as fundamental laboratories has already been demonstrated through results from observations of a variety of objects. The SKA will find many new millisecond pulsars and engage in high precision timing of them in order to construct a Pulsar Timing Array for the detection of nanohertz gravitational waves (Figure 5), probe the space-time environment around black holes via both ultra- relativistic binaries (e.g., pulsar-black hole binaries) and pulsars orbiting the central supermassive black hole in the centre of the Milky Way, and probe the equation of state of nuclear matter.

2.5. *The Cradle of Life*

The existence of life elsewhere in the Universe has been a topic of speculation for millennia. In the latter half of the 20$^{\text{th}}$ Century, these speculations began to be informed by observational data, including organic molecules in interstellar space, and proto-planetary disks and planets themselves orbiting nearby stars. With its sensitivity and resolution, the SKA will be able to observe the centimeter-wavelength thermal radiation from dust in the inner regions of nearby proto-planetary disks (Figure 6) and monitor changes as planets form; probing a key regime in the planetary formation process. On larger scales in molecular clouds, the SKA will search for complex prebiotic molecules. Finally, detection of transmissions from another civilization would provide immediate and direct evidence of life elsewhere in the Universe, and the SKA will provide sufficient sensitivity to enable, for the first time, searches for unintentional emissions or "leakage."

2.6. *The Unknown*

In addition to the KSPs listed, and recognizing the long history of discovery at radio wavelengths (pulsars, cosmic microwave background, quasars, masers, the first extrasolar planets, etc.), the international science community also recommended that the design and development of the SKA have "Exploration of the Unknown" as a philosophy. Wherever possible, the design of the telescope is being developed in a manner to allow maximum flexibility and evolution of its capabilities to probe new parameter spaces (e.g., time-variable phenomena that current telescopes are not well-equipped to detect). This philosophy is essential as many of the outstanding questions of the 2020–2050 era—when the SKA will be in its most productive years—are likely not even known today.

3. THE CANADIAN SKA PROGRAM

The Canadian SKA Program is a coalition of government laboratories, university science and engineering research groups, and industry. It is directed by a Board of Directors established through a formal Memorandum of Understanding signed in 2005 between ACURA, the NRC-HIA and industries, with formal representation by ACURA, NRC, CASCA and the industry partners.

The Canadian SKA Program is formally designated as an SKA Design Study by the SSEC, and has specific technology deliverables to the PrepSKA program on the 2011/12 time frame. SKA design areas in which has responsibilities include

- wide-band single pixel feed and RF design
- low-noise amplifiers and receiver systems based on CMOS technology
- phase-array feed design
- software and computing
- composite materials antenna design
- digital signal processing systems

The research and development into these technologies is being undertaken as a collaboration between NRC-HIA and university-based groups. Some examples are shown in Figures 7-9. Locations of R&D activity are indicated by blue stars in Figure 1.

4. INDUSTRIAL PARTNERSHIPS

The Canadian SKA program Board has recognized from its inception the tremendous opportunities for Canadian industry offered by the SKA. The SKA is an ambitious technology challenge. Many of the enabling technologies, such as those listed in the previous section, have been under investigation for over a decade. Examples of strategic industry sectors include: information and communications technologies, RF wireless telecommunications, advance materials fabrication and manufacture, and micro/nano-electronics. The industrial strategy of the Canadian program has the goals of

- developing capacity in Canada for manufacture and production of the Canadian technology contribution(s) to the SKA,
- securing visibility in the international project for Canadian industry early in the project, and
- maximizing the return on investment and economic benefit of the SKA program to Canada.

The scale of the industries involved in the Canadian program range from large coorporations such as IBM Canada, to small to medium sized enterprises (SMEs) in microelectronics (BreconRidge, Mirandi Communications, Lyrtech Signal Processing) and advanced materials (Profile Composites). A major challenge for Canadian SMEs investing in R&D of innovative technologies with long-term return on investment potential, are cost and risk, when the bottom line is survival into the next quarter. Early phase collaboration in pre-competitive R&D with government labs and university research groups is a critical strategy to mitigate both cost and risk.

The SKA has been called an ICT telescope - a notion well captured by Bruce Elmegreen, a senior research scientist at the IBM Watson Research Center, who notes that "The SKA will be the most sophisticated sensor network in the world attached to a computer and storage system that is one thousand times more powerful and efficient than anything today." The very large number of antennas of the SKA will support up to millions of new-technology, broad-band receiver systems that will amplify and digitize the faint signals received from the cosmos over a very large field of view, and turn them into a vast digital data stream in excess of 700 Tb/sec into the correlator and 10's of TBytes/sec out. The SKA is at the vanguard of scientific programs that will drive the "grand data challenge" (see Nature, Vol 455).

Canadian scientists and engineers have skills and capabilities that are competitive and in some cases world leading in the SKA technology challenge. HIA-DRAO has an international reputation for leadership in development of large-scale, advanced digital signal processors. The new HIA WIDAR correlator being delivered to the EVLA is the largest and most complex correlator ever constructed in radio astronomy. It was constructed with engagement of Canadian industry partners that are also participating in the Canadian SKA program. The broad-band, low-noise amplifier systems that have been prototyped at the Institute for Space Imaging Science (ISIS) at the University of Calgary have been recognized as the best performing in the world. With the CANARIE project for Cyber-SKA Canada, researchers at McGill University, the University of British Columbia (Vancouver and Okanagan) and University of Calgary are leading in the development of the cyber-infrastructure for distributed end-to-end execution of large-scale survey projects producing massive datasets. HIA research into design and fabrication of low-cost, high-performance radio antennas has recently received international recognition and awards. Canadian developments in all these areas have involved industry participation, either through contracts or direct R&D partnerships. Over the next few years, prototype systems building on these innovations will be developed in partnership with industry, in preparation for the detailed design and production engineering phase of the SKA.

The importance of industrial participation in the SKA development is recognized by the international SKA project which has begun a process to implement an industry engagement strategy coordinated by the SKA Program Development Office. Two Canadians, the Business Development Officers at HIA and ISIS, participate in the international SKA industry working group and work to coordinate the industrial strategy of the Canadian SKA program with the international effort.

5. CANADIAN FUNDING TIMELINE

The cost target and timeline for the SKA construction has been developed jointly by the SKA Science and Engineering Committee and the Agency SKA Group. The target cost for construction of the full SKA is €1.5 B. Phase I (2015 – 2018) is targeted at €300M, with the remaining €1.2 B starting in 2018. The current funding model for the SKA is 1/3 European Community, 1/3 United States and 1/3 the rest of the world (ROW). Canada has participated in the design phase at the 10% level, both in terms of our representation on the SSEC and our financial contribution to the Project Development Office. This level of participation is consistent with our relative GDP in the international consortium and our technology and scientific capacity in radio astronomy, and is at the same level as Australia and South Africa. Based on a 10% partnership, Canadian funding requirements for the construction phase of the SKA beyond 2012 are:

2013 – 2014 $3-4 M detailed design and engineering
2015 – 2018 $45 M SKA phase I construction
2018 – 2022 $180 M SKA completion/commissioning

Funds are in $CDN based on current conversion rate against the euro. The detailed design and engineering phase will primarily be contracts to industry for production engineering of Canadian technologies developed during the current R&D and phase.

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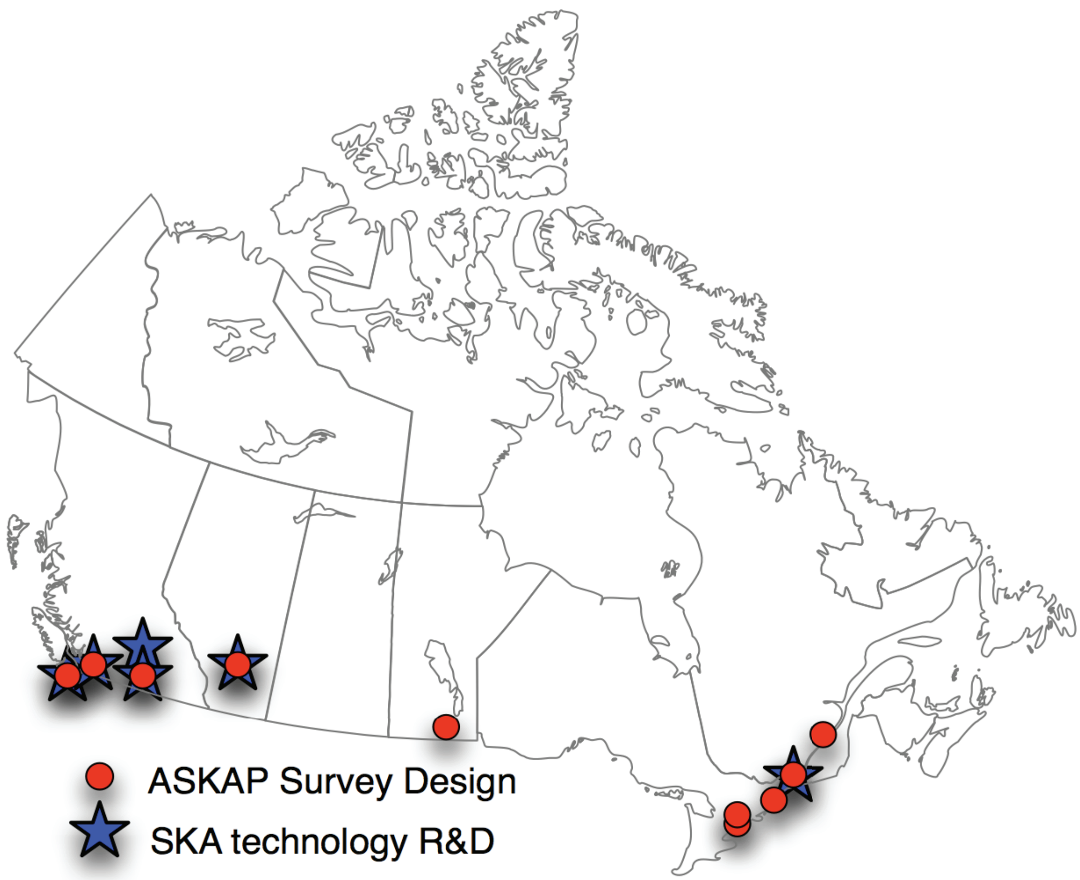

Figure 1. Distribution of Canadian SKA R&D and science planning activity. Twenty-three Canadian researchers at ten universities are formal co-investigators on the survey design projects for the Australia SKA Pathfinder, which will begin early test observations in 2011. (This figure does not include several graduate students and postdocs working with Canadian faculty.) Stairs at UBC is principle investigator for the COAST project (Compact Objects with ASKAP: Surveys and Timing), and Taylor (Calgary) and Landecker (HIA-DRAO) are co-principle investigators on POSSUM – the polarization survey to explore cosmic magnetism. The stars show SKA R&D centres contributing to PrepSKA work packages at University of Victoria, University of British Columbia – Vancouver, University of British Columbia – Okanagan, HIA (DRAO and Victoria), University of Calgary and McGill University.

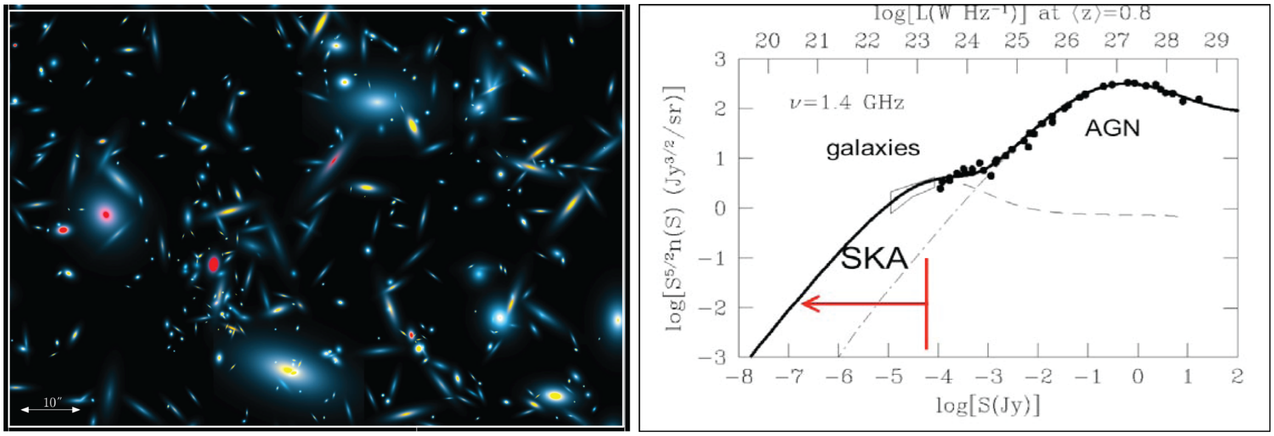

Figure 2. Left: From the EU SKA Design Study (SKADS) sky simulations (e.g. Wilman et al. 2008) a simulation of the H I sky to z = 1 as observed by the SKA showing the large number of galaxies that it will detect. The H I component of galaxies is shown in blue, and the CO component is shown in yellow (as traced in the 1-0 line) and red (6-5 line). SKA observations of the H I component, when combined with ALMA observations of the molecular component, will be used to trace galaxy evolution, and the SKA H I observations will also use these galaxies as test particles for cosmological observations. (Figure courtesy of D. Obreshkow.) **Right:** Source counts vs. flux density S weighted by $S^{5/2}$ at 1.4 GHz. The upper axis shows equivalent luminosity at z=0.8. SKA surveys will probe to sub-μJy levels, as shown, in large-scale surveys. Figure adapted from Condon (2007).

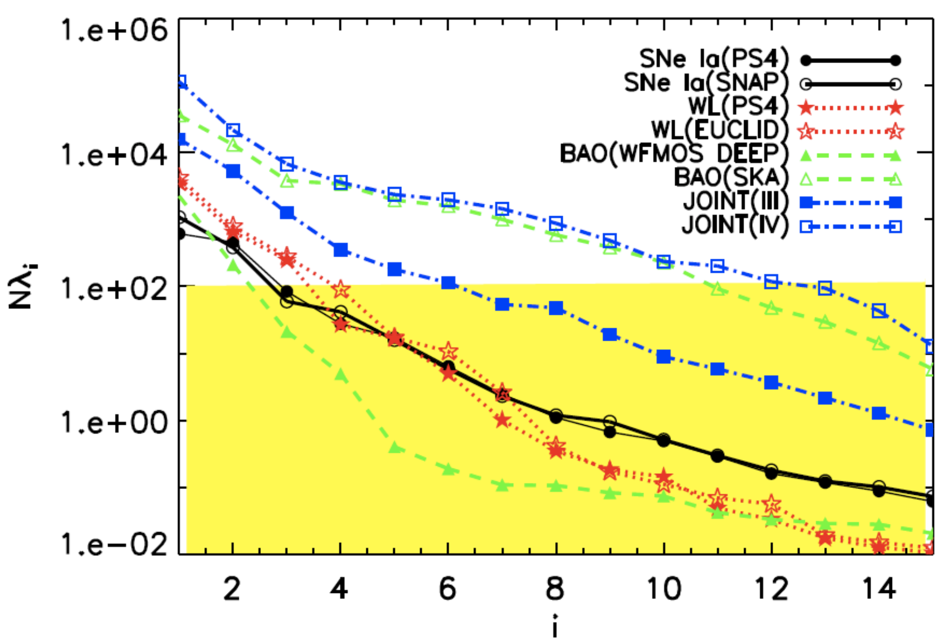

Figure 3. A Fisher-matrix analysis of various methods of probing dark energy, including Type Ia SNe, weak lensing (WL), and baryon acoustic oscillations (BAO) from Tang et al. (2008). The analysis is conducted for both individual observations and joint observations. The SKA BAO observations (dashed green line, open triangles) provides far more precision for a far larger number of modes, and the SKA BAO data would dominate a joint analysis (dot-dash blue line, open squares).

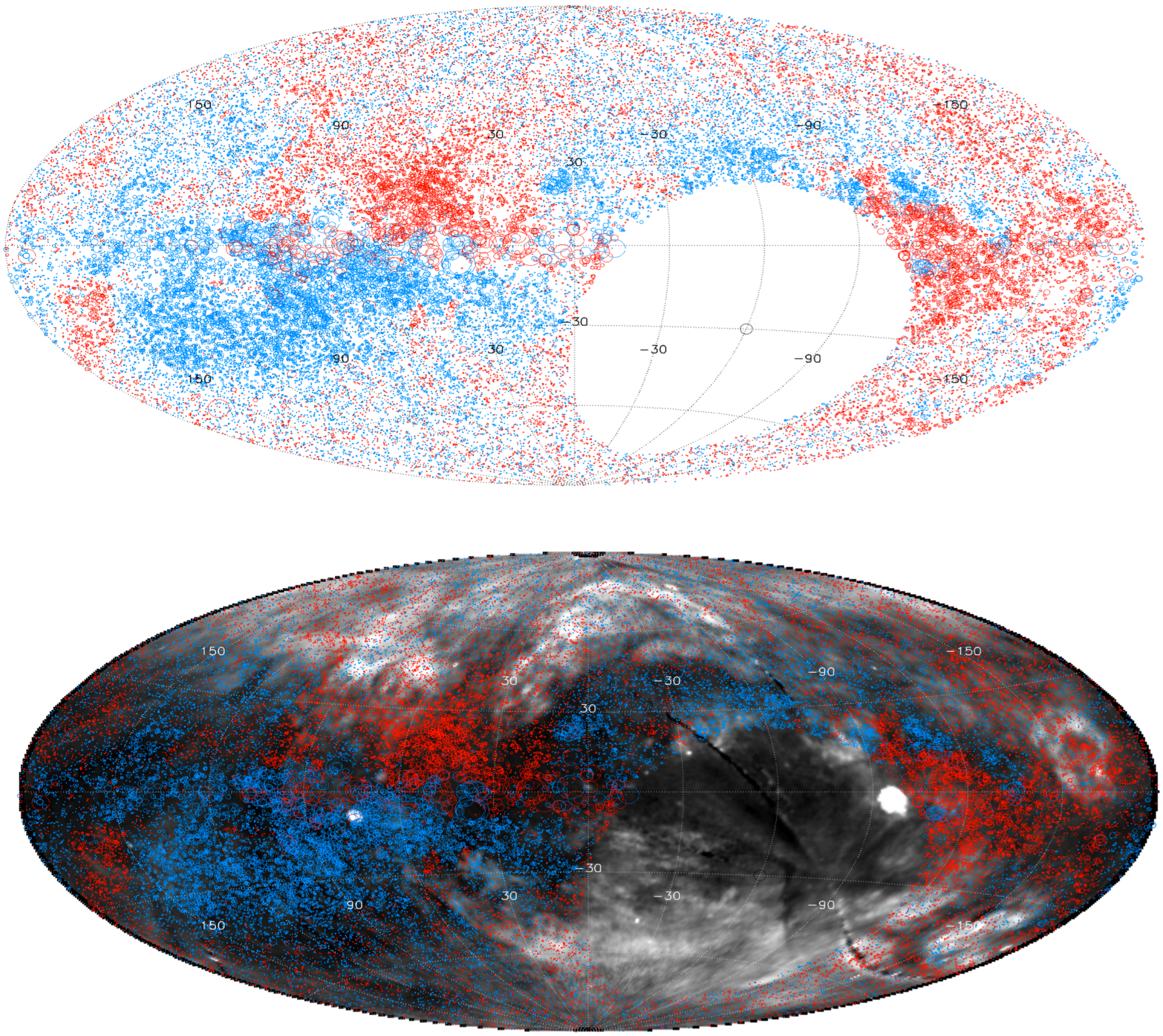

Figure 4. The Rotation Measure Sky. The top panel shows almost 40,000 Rotation Measures (RMs) toward extragalactic sources derived from the Northern VLA Sky Survey using two frequency bands (Taylor et al. 2009). RM values provide a measure of the integrated effects of thermal electron density and magnetic fields along the line of sight. The bottom panel shows the RM data superposed on a ROSAT all-sky image in low-energy x-rays. The RM amplitude show an anti-correlated with x-ray brightness, which is itself anti-correlated with the absorbing path of neutral in the Milky Way. The RM data thus allow us to measure the strength and structure of Galactic fields. The SKA will provide a RM grid of millions of radio sources down to arcminute scales on the sky, not only allowing definitive studies of the magnetic field in the Galaxy, but tracing the evolution of magnetism over cosmic history to the first galaxies and its relation to the large-scale structure of the universe.

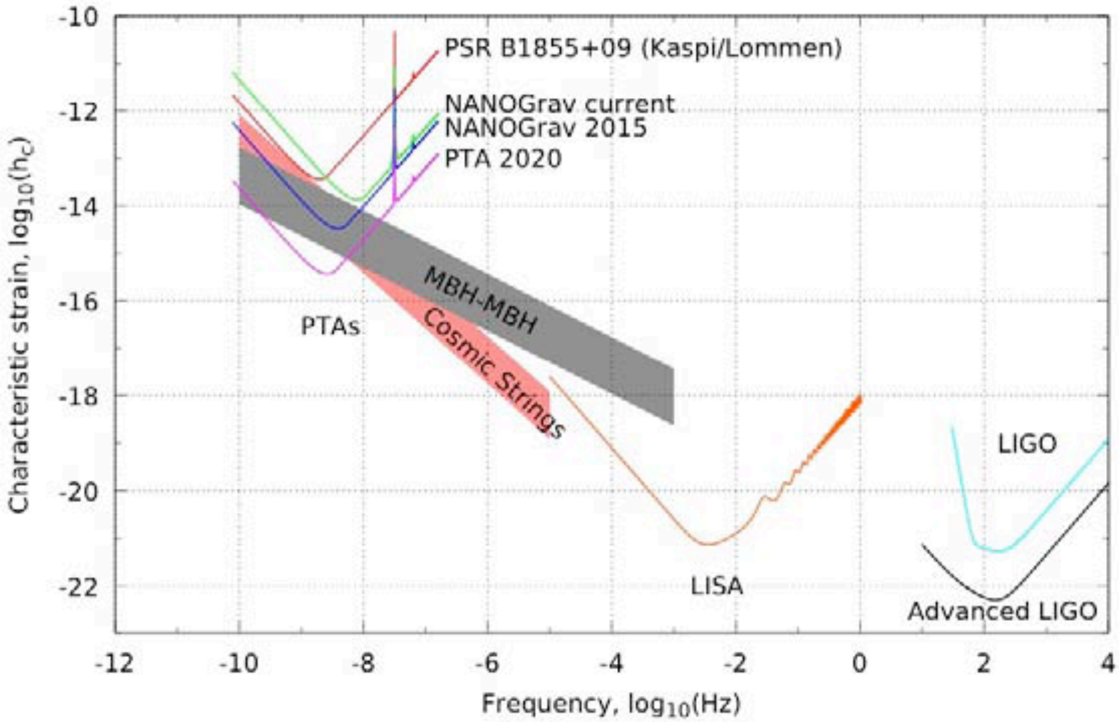

Figure 5. With precise timing of arrival times of signals from an array of pulsars on the sky, the SKA will be our most sensitive gravity wave detector below microHz frequencies. This plot shows the gravitational wave spectrum with expected signal levels from various phenomena and limits set by existing and future pulsar timing arrays (PTAs). This SKA is tagged as "PTA 2020". Sensitivities for LIGO, Advanced LIGO, and LISA are also shown. The SKA will, for example, be able to detect the predicted space-time distortions from massive black holes (MHBs) in galaxy merger events. Figure taken from the SKA submission to the US Astro2010 Panel by the US SKA Consortium (Cordes et al. 2010).

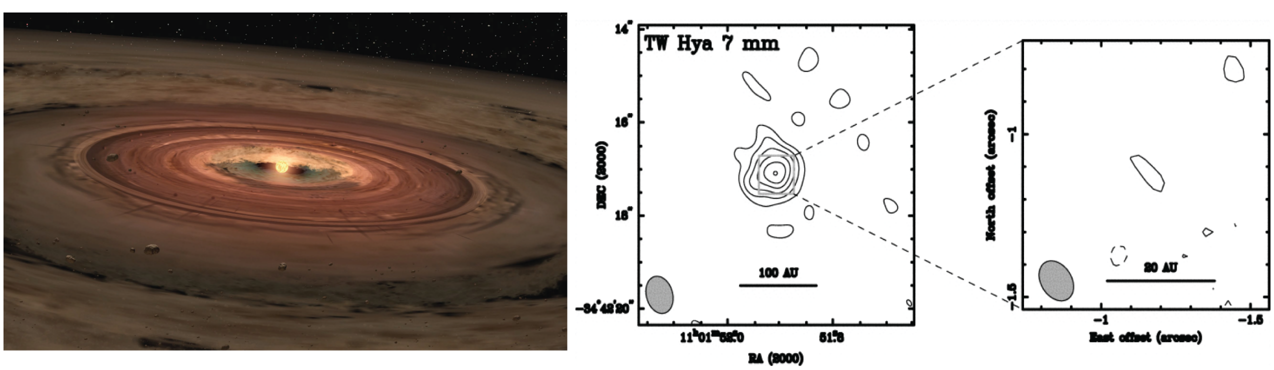

Figure 6. Left: Artist's impression of the inner regions of a protoplanetary disk in process of planet formation. Taken from NASA courtesy of nasaimages.org. Right: VLA image of a proto-planetary disk around TW Hya at a wavelength of 0.7 cm (Wilner et al. 2000). The SKA that it will provide even higher resolution images at longer wavelengths. At these wavelengths, more of the emission originates from "pebbles," so that the SKA will be able to probe later stages in planetary formation.

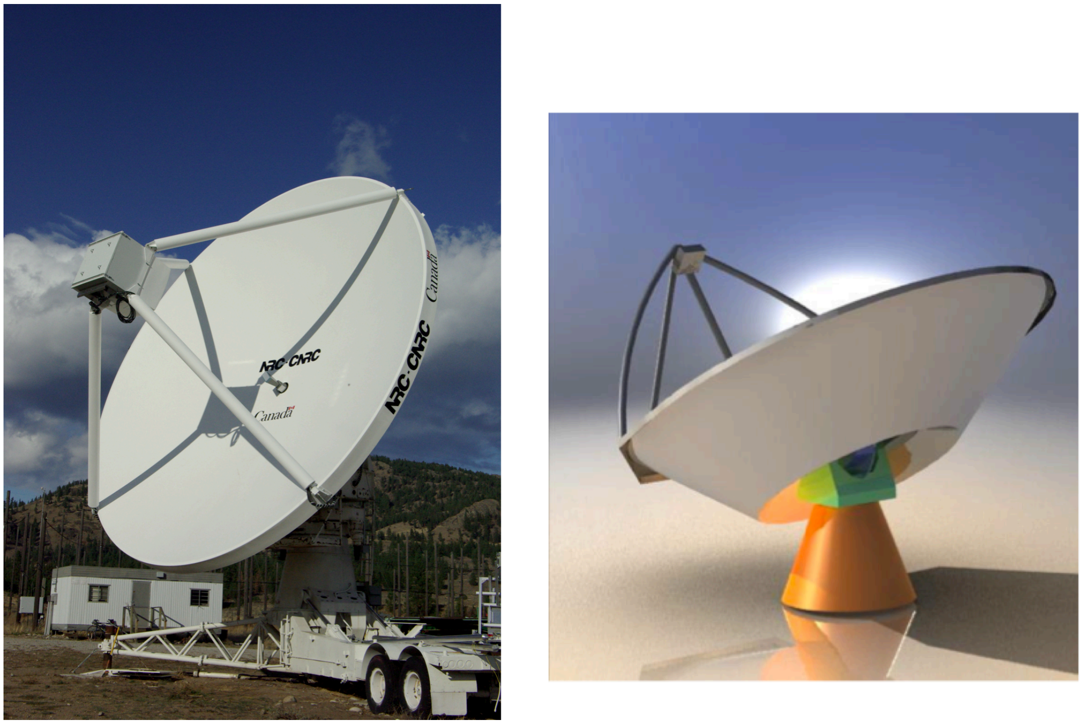

Figure 7. Left: The 10-m Mark 2 prototype composite antenna reflector system at the HIA Dominion Radio Astrophysical Observatory. The reflector has a 0.5mm surface accuracy. The Phased Array Feed Demonstrator (PHAD – Figure 8) is mounted at the prime focus. **Right:** A rendition of the latest composite offset reflector designs being developed at NRC-HIA.

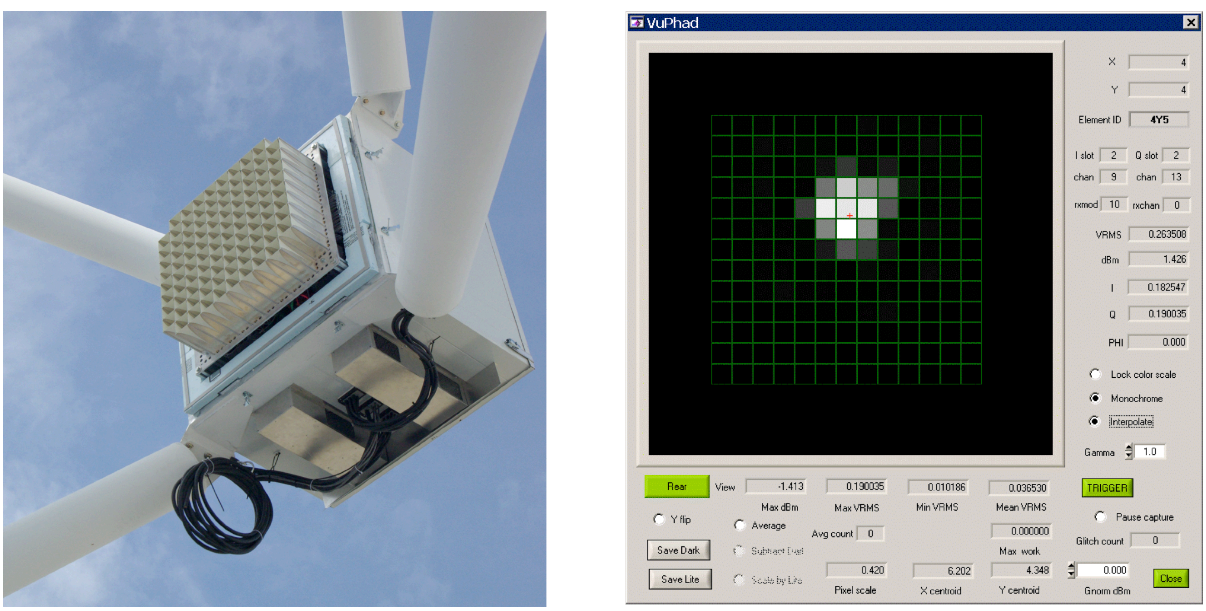

Figure 8. Left: The Phased Array Feed Demonstrator. The array consists of 212 Vivaldi antenna elements, with 180 active elements designed to operate at 1-2 GHz. A set of 84 outputs (42 polarization pairs) is transmitted off feed to digitization and off-line processing and beam forming. The result of a test observation of a geostationary satellite is shown at right.

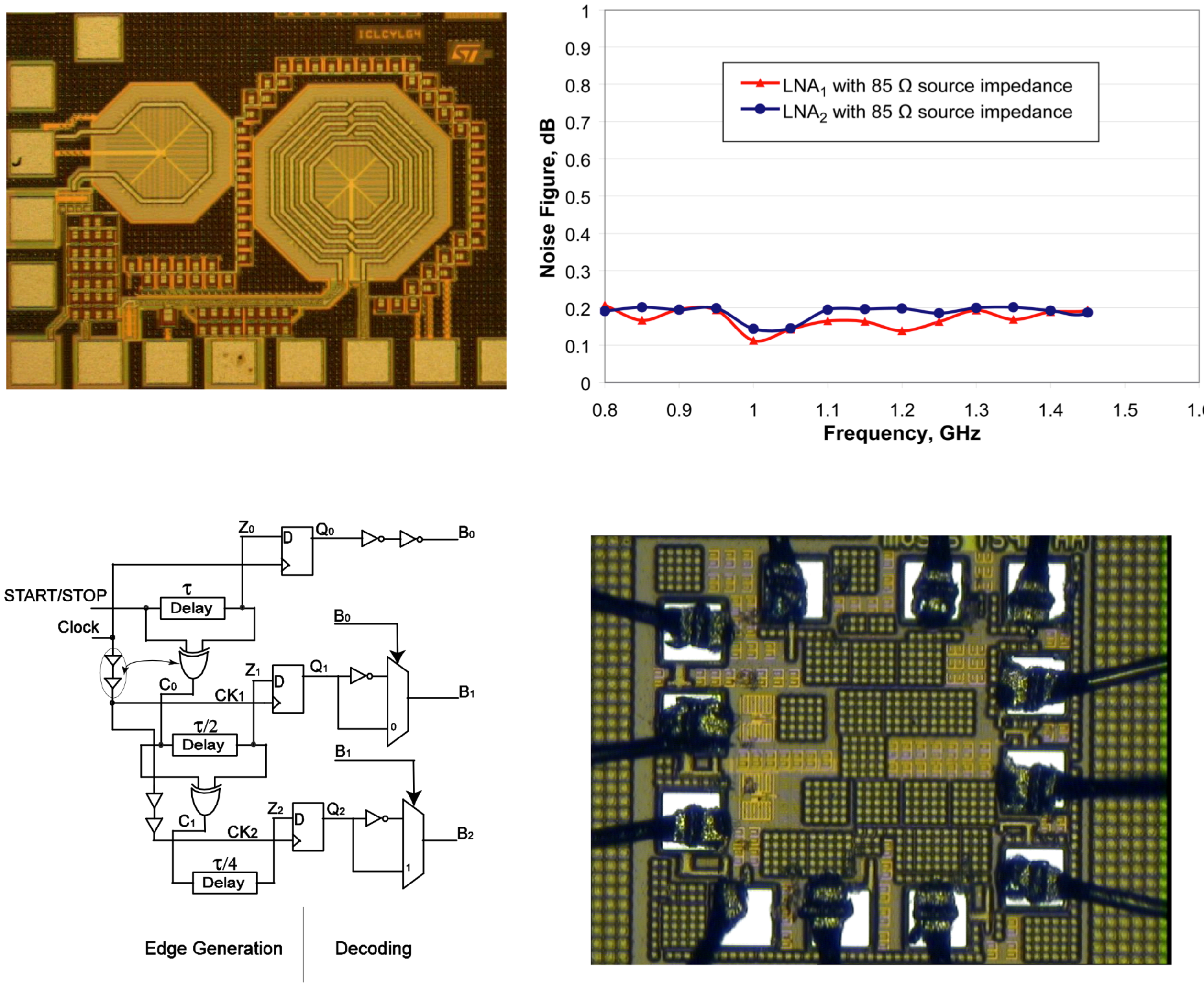

Figure 9. Receiver system signal chain elements under development at the University of Calgary Institute for Space Imaging Science. **Top left:** CMOS based low-noise amplifier micro-device. This amplifier achieved 0.2db noise figure (14K) across a 1 GHz band (top right) while operating at ambient temperature. Bottom: A schematic (left) and prototype analog to digital converter that achieves several GB/s rates at power levels of a few mW. Devices with these specs will be critical for deployment of focal plane phased array feeds systems on the SKA scale.