Draft version February 15, 2010
Preprint typeset using LATEX style emulateapj

THE HIA DOMINION RADIO ASTROPHYSICAL OBSERVATORY

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ABSTRACT

HIA-DRAO plays a crucial role in the future of Canadian radio astronomy. HIA-DRAO has a highly skilled multi-disciplinary science and engineering team which has developed a world-leading reputation in science and technology R&D, with successful projects such as the Canadian Galactic Plane project, DRAO Planck Deep Field, JCMT ACSIS and the EVLA WIDAR correlator projects. Keys to this success are strong collaborations with universities, industry, and international organizations; a blend of instrument research and development, strong partnerships in international science projects, and state of the art facilities for the community. The next generation of radio astronomers and engineers is being trained at DRAO and we are an important nucleus for regional economic development, providing a highly-visible return on Canada's investment in astronomy. All together, this has placed HIA-DRAO in a very strong position to engage in both science and technology developments for the leading astronomy facilities of the next decade around the world, primarily the SKA, but also the TMT.

1. LEADERSHIP IN TECHNOLOGY R&D AND RADIO ASTROPHYSICS

1.1. *Technology*

The digital group at DRAO is one of the strongest and most experienced in the world, grown over many years and using the latest technologies and design tools. We have designed and built some of the most technically advanced digital systems in the world, the S2 VLBI correlator, the ACSIS correlator that is central to the current operation of the JCMT, and the WIDAR correlator for the EVLA and eMERLIN. All of the instrumentation projects we have undertaken have used innovative techniques and designs to enhance performance. ACSIS used a design that lowered the power requirements to 30 % of other designs using the same chip set; the patented WIDAR concept enabled highly efficient and flexible ultra-broad band correlation, and has endowed the EVLA with exquisite science capability which goes far beyond what was originally envisaged.

Our expertise with large FPGA systems led to a collaboration with the University of Victoria and Lyrtech Signal Processing in Québec that established the feasibility of using FPGAs for real-time control of the large-scale adaptive optics systems demanded by the TMT. The concept design for a multi-FPGA processor board is being advanced as it has broad applications not only in astronomy but also in other fields, including potential commercial applications.

In response to one of the key aspects of the last LRP, HIA-DRAO has been heavily engaged in technology R&D for the SKA across a broad range of telescope systems: reflectors, wide-field broad-band receiver systems, digital-system architectures and calibration/imaging. We have successfully prototyped 10 m-diameter, high performance, cost-effective composite reflectors, which we are advancing toward an offset 15 m design for the SKA. We have also built and tested the largest and the only dual-polarization broadband prototype phased-array feed system in the world. This work is on-going and along with new digital designs, represents R&D that we aim to advance in the next decade as the SKA transitions to a detailed design phase prior to construction.

1.2. *Science*

A series of impressive, large-scale surveys have been either completed or initiated using the on-site instruments at HIA-DRAO – the Synthesis Telescope and the 26 m telescope. The Canadian Galactic Plane Survey (CGPS) of the outer Milky Way Galaxy, a university-led, international consortium project to study the ecology, structure and dynamics of the Interstellar Medium was recently completed, and has been a highly successful project by all measures. To date more than 140 research papers based on CGPS data products and involving CGPS team members have been published, and the project produced 29 post-graduate degrees and employed 24 post-docs. Its success leveraged Canadian leadership of the International Galactic Plane Survey, which produced a data set of the complete Milky Way Galaxy using the CGPS and observations from the VLA and the ATCA. The expertise developed in the CGPS led to the DRAO Planck Deep Field (DPDF), an ultra-sensitive survey of the ELAIS N1 field, to study Galactic foregrounds particularly in the context of CMB studies, and the polarization properties of the faint extra-galactic source population.

The DRAO 26 m Telescope has been used to map the Northern sky in linear polarization at 1420 MHz. These excellent data surpass previous surveys by an order of magnitude in sensitivity and two orders of magnitude in coverage. This is of significance not only to Galactic science projects but is being actively used for deconvolving the polarized foreground through which the Planck satellite views the Cosmic Microwave Background. This success led to the Global Magneto-Ionic Medium Survey (GMIMS), a high resolution, broad-band rotation measure survey of the whole sky between 300 MHz and 1.8 GHz that is being carried out by an international consortium led from DRAO, and using the DRAO 26 m and facilities in Germany (Effelsberg 100 m), Australia (Parkes 64 m), and China (Kunming 40 m). The preliminary data from the DRAO 26 m have already shown structure in the Galactic magnetic field that could only be detected through Rotation Measure Synthesis applied to wide-band, multi-channel polarization data. This work is blazing the trail for future high-sensitivity and high-resolution surveys proposed for ASKAP and the SKA.

These successes have established HIA-DRAO as the leading centre in the science of radio polarization and in Interstellar Medium studies. These surveys produced the highest quality wide-field radio astronomy images, in all Stokes parameters, available today, largely as a result of new calibration, imaging and deconvolution techniques developed at HIA-DRAO and now in use around the world. They also required development of new instruments. Much of the technology expertise currently at HIA-DRAO grew out of the development of the Synthesis Telescope. GMIMS has led staff at HIA-DRAO to develop novel low-frequency RF systems of relevance to the SKA that have been successfully demonstrated on the Parkes 64m. These low-frequency data are fed to a high-resolution spectro-polarimeter that is a ready demonstration of the rapid development and wide-ranging capabilities of modern off-the-shelf FPGA-based digital equipment, especially for small-scale systems. The RF and polarimeter systems designed at HIA-DRAO are being installed currently on the Effelsberg 100m Telescope.

HIA-DRAO is also involved in other nationally important science programs. In conjunction with the CSA and NRCan, we are part of the Canadian Space Weather system through our solar monitoring program that provides daily 10.7 cm radio flux measurements of the Sun. This is the longest running radio astronomical observing program anywhere in the world, with 64 years of continuous data. These are critical data, distributed by NRCan and used widely by industry, space agencies, and defence for monitoring the state of the Sun, and ensuring the long-term health of the now-extensive satellite network.

1.3. *Other*

HIA-DRAO staff are active in national and international spectrum management discussions. This is an important aspect of protecting astronomy from wavelengths of a few microns in the near-IR to decametres in the radio from the increasing pressure of commercially-driven electromagnetic spectrum allocations. HIA-DRAO staff advise Industry Canada on the impact of non-passive radio and microwave services on the passive astronomical use of the spectrum, and on national policy taken to the UN-led international Telecommunications Union world radio conferences where allocation issues are resolved.

Over the past five years HIA-DRAO has been the home of the Okanagan Research & Innovation Centre (ORIC) that aims to help regional start-up companies with technology development that can take advantage of the HIA-DRAO engineering expertise and infrastructure. ORIC's success is widely acclaimed in the communities of the Okanagan and the tangible benefit that it brings to the local economies provides a highly visible return on Canada's investment in astronomy.

2. HIA-DRAO IN THE EXCITING NEW ERA OF RADIO ASTRONOMY

HIA-DRAO stands to be a major player in the next decade of exciting growth in radio astronomy, both through engagement in science projects and technology development for the latest facilities around the world, as well as developing the necessary HQP in Canada through collaborations with the university community and industry that will take advantage of the technology and science expertise, the observing facilities, the site, and the excellent RF environment at HIA-DRAO.

The coming decade is a very exciting era for centimeter-decameter wavelength astronomy with new radio astronomy facilities and upgrades. These new facilities cover three orders of magnitude of wavelength from a few metres (PAPER, MWA, LOFAR), through centimetre (ATA, ATCA, EVLA), to several millimetres (EVLA), covering an enormous scientific discovery space. The development of these telescopes is driven almost exclusively by the key questions that dominate astronomical research at the start of the 21^{st} century - the Origin of Galaxies and Probing the Dark Ages, Galaxy Evolution, and Dark Energy, Tests of Fundamental Physics, the Origin of Life, the Magnetic Universe, and the Transient Sky.

New science capabilities enabled by today's technologies will drive an explosive advance of radio astrophysics over the next few years. Such rapid development of the science coupled with new and enabling technologies provide the essential foundations for the largest radio astronomy facility of all, the SKA, which will complete its initial phase within the decade. Already SKA precursor telescopes are being constructed, both in Australia (ASKAP) and South Africa (MeerKAT), that will prove a number of these enabling technologies in operating facilities, essential to the scientific successes ultimately of the SKA.

2.1. *Technology*

HIA-DRAO has a leading role to play in development of new instruments and technology for new facilities. Over the past decade, we have completed the design of the WIDAR correlator system for the EVLA, including custom-designed ASIC correlation chips and a very agile FPGA-based filter system that gives unprecedented spectrometer capability – a minimum of 16k channels across a maximum of 8 GHz of bandwidth in each polarization, at a dump rate as fast as 1 millisecond. This system has been realized in two very large, complex, high-component density circuit boards, built under contract by Brecon-Ridge, Kanata. The installation of this $20M system at the EVLA is now nearing completion. Early tests reveal the amazing capability of this system, and point to a radio astrophysics revolution that is about to start, most especially in centimetre-wave spectroscopy. It is anticipated that the Canadian astronomy community will play a strong role in developing this exciting research capability. Canada's investment in this cutting-edge instrument was made possible by the North American Partnership in Radio Astronomy (NAPRA) agreement between NRC and NRAO, which stands to become an increasingly important tool for collaborative R&D between HIA-DRAO and NRAO, in particular when NRAO can engage more fully in SKA R&D.

Among the many countries involved in the SKA, Canada is a leading source of SKA R&D, and HIA-DRAO is a focus of that R&D in Canada. In particular, we are a very prominent participant in the UK-led, EC-funded, PrepSKA program, through which R&D to develop cost-effective, high-performance telescope systems required to build the SKA is being advanced around the world. At HIA-DRAO we are advancing our unique and very successful work on composite reflectors, designing a prototype for an SKA dish verification system in collaboration with other institutes, particularly in the US. A unique aspect of our work is design for mass production of 3000+ reflectors, that is being pursued with an industry partner. Wide-field, phased-array receiver systems are a critical technology for attaining the survey speeds desired for many SKA key science programs. An astronomy-capable system, central to testing world-leading room temperature low-noise amplifiers under development at University of Calgary, is being designed along with an advanced beam former that builds on our extensive FPGA expertise, and will implement 3D beam-forming algorithms being developed at University of Calgary and University of Victoria. Our successful experience with the latest chip technologies and tools has led to HIA-DRAO leadership in developing concepts for digital systems for the SKA. Initial steps have been taken at exploring digital architectures for correlating data from the 3000+ antennas of the SKA, each telescope with of order 10 beams from the beam former arrays. This represents a staggering data challenge that will drive novel design concepts using the latest technologies.

HIA-DRAO is in a strong position to take full advantage of new opportunities in the rapidly evolving and broad use of powerful FPGAs as compute engines. Such systems can be orders of magnitude more powerful than general purpose computers for certain applications and, coupled with modern programming tools, permit solution of a new class of problems. We are investigating new ways of developing such systems, by involving companies such as Lyrtech Signal Processing early in the design phase in order that our systems can be used directly and across a wide range of research and commercial applications.

Development of world-class instruments and facilities requires a collective approach combining university research with industrial capability, and for large-scale "world" observatories, on an international scale. A critical role is managing and integrating each of these contributions into working system. HIA-DRAO has a strong record of fulfilling this role. The keys to that success are a highly skilled multi-disciplinary science and engineering team, working with universities, industry, and international partners, coupled with the ability to engage in long-term commitments. The role of HIA-DRAO in developing Phased-Array feeds exemplifies this approach, where we are integrating world-leading room-temperature LNAs developed at University of Calgary, with RF and digital beamformer systems developed by NRC and built by industry, into an astronomically capable system.

Additional benefits of our role are the training of HQP in applied science and technology, as well as the fostering of high-technology start-ups and businesses in the local community through organizations such as ORIC. These activities are very important to students, crucial to the region, and a highly visible added value to the community.

It is imperative to retain the leading engineering team. Without a strong team, university and industry efforts will not achieve maximum effectiveness, and Canada stands to not capitalize fully on the SKA opportunity or other future opportunities, such as the TMT. It is equally important to retain the world-calibre science staff at HIA-DRAO who bridge the astronomy-technology divide, and work in conjunction with the engineering teams to maintain the impressive track record of instrument development at HIA-DRAO.

2.2. *Science*

The legacy of the CGPS, DPDF, and GMIMS survey projects using the DRAO telescope facilities, the reputation gained in wide-field radio polarimetry, and the management of large, collaborative science projects will be very important in the era of new facilities. Surveys are the increasingly common science operation model proposed for almost all the new facilities such as the EVLA, the SKA precursors, and the SKA itself. Already, our expertise is being actively utilized in current large-survey projects (e.g. GALFACTS with Arecibo) and in planing of large surveys both with the EVLA and ASKAP, as many HIA-DRAO personnel are members of these projects.

In addition to the promise of the new facilities described above, the HIA-DRAO telescopes have a significant continued role to play over the next decade. The full-polarization wide-field imaging capabilities of the Synthesis Telescope and the 26 m Telescope remain unique in the world because of the techniques developed at HIA-DRAO for correction of instrumental polarization effects. It will be some time, maybe the latter half of the decade, possibly later, before other facilities attain the full polarization sensitivities across large fields of view at arcminute resolution that are routine at HIA-DRAO. Proposal pressure to use both the Synthesis and 26 m telescopes in order to take full advantage of these unique capabilities has been maintained since the completion of the CGPS. The maximum number of fields observed with the Synthesis Telescope per year (50) is being requested by the community, with a steady increase in the demands for large area surveys and deep polarization and HI line imaging.

This is very encouraging, not only for the continued advance of survey science in Canada, but also in developing the next generation of HQP required to take best advantage of the next generation of radio astronomy facilities. We aim to train HQP through partnerships with the university community to develop HIA-DRAO as a national training facility for future radio astronomers and engineers. A number of externally-funded programs are being pursued currently with the university community (particularly with UBC-O and University of Calgary) to enable Canadian undergraduate and graduate students to work at HIA-DRAO in planning and carrying out leading edge science and technology projects. Training of engineering students is envisaged through relatively small-scale, low-cost instrument development in areas such as broader bandwidth, receiver sensitivity and programmable digital systems that enhance sensitivity and improve flexibility. Such a program to train HQP is consistent with Canada's Science and Technology Strategy and is essential to build the human capital that Canada must have to remain at the cutting edge of radio astronomy and instrument development.

In addition to the existing facilities, HIA-DRAO has an increasing role to play in hosting dedicated experiments and facilities developed and built by the university community. This takes advantage of the current infrastructure and expertise built up over many decades. The high-quality radio frequency environment of the DRAO site makes it the premier location in Canada for low frequency radio observations. An excellent example of this role is the Canadian Hydrogen Intensity Mapping Experiment (CHIME) proposed by a collaboration of UBC, University of Toronto, and McGill University researchers, to study the nature of dark energy by measuring the distribution of neutral hydrogen in the early Universe. CHIME aims to take advantage of the unique radio-quiet location and the infra-structure of HIA-DRAO to undertake very wide-field observations of the red-shifted HI in the range $0.8 \leq z \leq 2.5$ to study Baryonic Acoustic Oscillations.

Other facilities are already installed at HIA-DRAO: NRCan have low-frequency radiometers for studying the Ionosphere, demonstrating the potential for passive RF use of the excellent HIA-DRAO RF environment.

3. CLOSING REMARKS

Without doubt, radio astronomy is moving rapidly into a very exciting era, with many new instruments providing new and very exciting capabilities and scientific discovery across decametre to centimetre wavelengths. Planning and R&D for the SKA is well advanced, and precursor telescope systems are being built in both Australia and South Africa.

HIA-DRAO is in an excellent position to play an important role in this era as a result of our strong science and engineering teams that have earned a reputation in large area, wide-field, full polarization survey science and leading-edge instrument design and construction across a broad range of telescope subsystems - from novel reflector designs through to innovative data processing algorithms. We are strongly engaged in SKA-related R&D, and survey science planning for the SKA precursor facilities, in conjunction with both the university community and industry.

We aim to foster the next generation of radio astronomers and engineers through collaborative programs with the universities that use, and enhance, the current facilities at HIA-DRAO. Another aspect of enhanced collaborations with the universities is our ambition to make more extensive use of the infrastructure, expertise and the excellent RF environment at HIA-DRAO for dedicated, university-developed experiments sited at DRAO.

Essential to such a portfolio of activities is maintaining our resources and expertise, across both science and engineering. This will ensure our ability to take full advantage of future opportunities in radio astronomy, as well astronomy in general, for the Canadian astronomy community.