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HIGH FREQUENCY RECEIVER DEVELOPMENT FOR ASTRONOMY

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ABSTRACT

To address numerous science questions over the next ten years, state-of-the-art high-frequency (i.e., 1-1000 GHz) heterodyne receiver technology will be required. Fortunately, Canada has a long tradition in developing such technology for use in astronomical instrumentation. In this White Paper, we describe several key paths for future research that build on Canada's recent success with the ALMA Band 3 receivers. These include near-term development of Band 1 and upgraded Band 3 receivers for ALMA. In addition, long-term research is needed for competitive technology for SKA, such as low noise amplifiers, wide-band single-pixel feeds, and planar arrays.

1. INTRODUCTION

Astronomical discovery at high radio frequencies (i.e., 1-1000 GHz) has been a long-standing tradition in the Canadian community. This success has been made possible only by strong investment in the technologies needed to acquire data of the highest quality at these frequencies. For example, Canadian astronomers in years past have benefitted well from strong Canadian receiver development for the Algonquin Radio Observatory and the James Clerk Maxwell Telescope (JCMT). Further development of forefront technologies will be critical for tackling new fundamental science probed uniquely in this spectral range. Notably, future success at these frequencies demands the highest possible angular and frequency resolutions that are only available from heterodyne interferometers. Indeed, the Atacama Large Millimetre/submillimetre Array (ALMA) and the Square Kilometer Array (SKA) are being designed by international collaborations to meet this demand. Given its vital history in this spectral regime, it is unsurprising that Canada currently is engaged in each of these projects on many levels, including high-profile receiver and antenna research and development.

The last LRP [1] strongly recommended "the enhancement of the correlator and receiver groups within NRC" and "that Canada should quickly join the ALMA project." This White Paper summarizes current and potential future Canadian developmental efforts in high radio frequency receiver technology. We first describe briefly the science drivers behind such development and then summarize the current work done in Canada for ALMA. Then we describe new lines of technology research for ALMA and SKA that would ensure Canada's continued high-profile engagement in these facilities.

2. SCIENCE DRIVERS

Separate White Papers describing ALMA and SKA have been written by Christine Wilson and Sean Dougherty separately, and these include detailed descriptions of the science drivers behind the construction of each. In brief, ALMA will reveal the formation of galaxies, stars and planets. Cold molecular gas and dust involved in these processes emit strongly at 30-1000 GHz, the frequencies that ALMA will receive. In turn, SKA will reveal the origins of cosmic and galactic structure and the termini of stellar evolution. Cold atomic gas and nonthermal processes associated with these emit strongly at 1-30 GHz, the frequencies that SKA will receive. These observatories are unprecedented in scope and so require high-quality and low-priced antenna and receiver technology to succeed. Canada is presently involved in many research and development projects to realize these goals.

Other White Papers describing ALMA and SKA science drivers include those on star formation (Johnstone), circumstellar disks (Matthews), the submillimetre universe (Scott), planetary science (Kavelaars), structure & kinematics of galaxies (Cote), supernovae (Carlberg), the extragalactic ISM/IGM (Ellison), galaxy formation (Willis), neutron stars & pulsars (Stairs & Thompson), AGNs (McNamara), accretion powered compact objects (Heinke), cosmic magnetic fields (Brown), 21-cm cosmology (Pen), dark matter & dark energy (Siggurdson) and general relativity & gravitational waves (Poisson).

3. THE ALMA BAND 3 PROJECT

The ALMA Band 3 project started at NRC-HIA in Victoria in April 2002 and the first prototype was completed after a 3-year R&D phase. The team designed components and developed testing techniques to validate the numerous specifications imposed by the ALMA project. A 2-year pre-production phase validated the design and automated test equipment before production started in March 2008. The present production phase will end in 2012 when all 73 units are delivered. This phase has involved considerable effort to meet deadlines by automating all test sets and doubling the cartridge test set. Also, the production team worked with Canadian industry to fabricate, procure, and test many Band 3 components [2]. Following production, a maintenance phase of >5 years is planned. In addition to strengthening the team in design and testing expertise, the Band 3 project led to contracts and technology transfer to industry.

The Band 3 receiver (see Figure 1 and [3] and [4]) detects emission at 84-116 GHz and represents state-of-the-art technology for its low noise and high stability. First, the science signal is split into two orthogonal

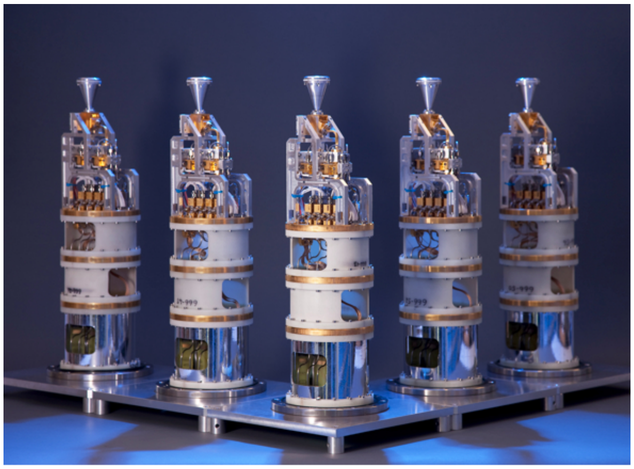

Fig. 1.— A collection of Band 3 receivers at NRC-HIA.

polarizations using an Orthomode Transducer (OMT). For each of the OMTs output, high sensitivity detection is obtained by first using a mixer that contains a Superconductor-Isolator-Superconductor (SIS) diode [5] cooled below 4 K. This mixer converts the high frequency (84-116 GHz) signal collected by the telescope to a much lower frequency signal (6 GHz). This low frequency signal is then amplified (by a factor of 1000) with a low noise amplifier (LNA) using HEMT (High Electron Mobility Transistor) technology [6]. After this cryogenic detection chain, the signal is further amplified at room temperature before it is sent to the backend correlator where all the signals from each antenna are combined. Given the large amount of antennas and the remoteness of the ALMA site where these receivers will be deployed, considerable effort was dedicated to design for high reliability over long lifetimes (e.g., 15 years).

Some smaller projects were generated out of the Band 3 project. First, a technology transfer allowed the Band 3 Low Noise Amplifier (LNA) designed at NRC-HIA to be fabricated under licence at Nanowave Inc., a high-tech company in Toronto. This LNA attracted customers outside the astronomy community; for example, the Commissariat à l'Énergie Atomique in France purchased two units for its research into low noise carbon nanotube transistors. In addition to the LNA, the Band 3 mixers' low noise attracted attention. The 12-m single-dish Arizona Radio Observatory purchased two Band 3 mixers because of their low noise and their unique image rejection. Also, the Combined Array for Research in Millimetre-wave Astronomy (CARMA) purchased Band 3 mixers for one of its polarization channels, increasing the array sensitivity by a factor of two. CARMA is interested in ordering a second set for the other polarization.

4. CURRENT AND FUTURE R&D

The demands on astronomical millimeter instrumentation include needs for higher sensitivity and wide-field imaging. The first demand has led to R&D efforts to increase band width and decrease detector noise. The second demand has led to development of planar receiver technologies (see §4.4 for details).

In the short term (i.e., <5 years from now), the ALMA Development Plan for instrumentation beyond the initial construction phase includes design and fabrication of receivers at Band 1 (31-45 GHz) and upgrading receivers at Band 3 with new low-noise amplifiers. In the medium to long term (i.e., 5-10 years from now), SKA technologies must be developed, including mass-produced noise amplifiers and single pixel feeds (see §4.3 for details) for the high frequency 1-10 GHz band. In the very long term (i.e., 5-15 years from now), development of planar receiver technology for wide field spectroscopic cameras for single-dish or array facilities should occur.

Over the next 10 years, heterodyne detectors will be required for CCAT [8], where large heterodyne arrays at frequencies 85-1500 GHz can be developed. Even higher frequencies may be probed from future space platforms [9] involving Canada, and so new explorations must be made into SIS mixer performance in the Terahertz regime.

NRC-HIA has an excellent track record for instrument design, testing, and delivery thanks to its R&D expertise and robust project management structure. In addition to astronomy, other fields are driving engineering departments at Canadian universities to develop new technologies. For instance, the telecommunication industry has a strong interest in the increased band widths possible at frequencies up to 90 GHz. Also, integrated planar arrays as smart antennas offer increased capacity and superior interference suppression compared to current systems. Through electronic beam steering (as opposed to slower and less reliable mechanical steering), the receiving base station can adjust its beam direction to narrow in on a desired user signal. Although it is understood that astronomy has special requirements that differ from other fields, there is a non-negligible amount of technology overlap. That is why it is fundamental to bring together instrument builders and technology researchers to develop instruments of the future.

The NRC-HIA instrumentation team is working in radio R&D with leading engineering departments at two universities, the École Polytechnique de Montréal and the University of Victoria (UVic). The former is a leader in planar technology and future applications for radio astronomy focal plane arrays have been explored through the work of a PhD student. The latter has done considerable research into wide-band antennas, mixers and LNA integration to planar waveguides, again through graduate students. An NSERC Strategic Grant, with the PI at UVic and co-PIs at NRC-HIA and École Polytechique de Montréal, was obtained for research into a "Highly Integrated Broadband Antenna Array Receiver for Wireless Millimetre-Wave Networks." In the process of astronomical technology development, key technologies are developed at universities and implemented at NRC-HIA, followed by on-sky tests within visitor instruments before incorporation within facility instruments.

Described below are four high frequency radio R&D programs that need prioritization in LRP 2010 to meet the future needs of the Canadian astronomical community.

4.1. *ALMA Band 1*

The ALMA Band 1 (31-45 GHz) receiver project is currently unassigned to any group, but some development is being carried out at a few institutes. In anticipation for a Development Plan call for proposals from ALMA, a program for research into the key technologies required to build a Band 1 prototype started at NRC-HIA in 2007, consisting of the development of prototypes of a low noise amplifier (LNA) and an orthomode transducer (OMT; a polarization splitter) for Band 1. The prototype LNA has been built and shows promising performances [11]. The OMT has been designed and prototypes tested at HIA [12]. Systems design (RF, quasi-optics and mechanical) has also started to produce a prototype that will help evaluate overall performance. In addition, a Master's student at UVic is currently developing a Band 1 mixer. Further Band 1 collaboration has begun between NRC-HIA, the University of Chile and Academia Sinica Institute of Astronomy and Astrophysics (ASIAA) in Taiwan. For example, a Chilean team member visited HIA for one month to work on Band 1 optical design [13] and a design review is planned in Chile in fall 2010.

4.2. *Low Noise Amplifiers*

Cryogenic Low Noise Amplifiers (LNA) are at the heart of most spectroscopic receivers that will be needed for future telescopes. Leveraging the expertise developed on cryogenic LNAs at 4-8 GHz during the Band 3 project [6], NRC-HIA is expanding to other frequency bands.

The high frequency band of SKA (1-10 GHz) will require low noise cryogenic amplifiers. Due to the large number of detectors, the LNA technology must use Monolithic Microwave Integrated Circuits (MMICs). This technology is used for large volume production because it allows the fabrication of all the components of the amplifier on a single chip in lieu of the discreet component assembly used for the Band 3 (and Band 1) receivers. Given the nature of the SKA feed system, a differential LNA would need to be developed that requires MMIC technology. With the National Taiwan University and ASIAA in Taiwan, collaborations have begun to develop new types of transistors that could prove to be cheaper than the conventionally used InP HEMTs (Indium Phosphide High Electron Mobility Transistors). These new transistors, metamorphic HEMTs [10], use the more common gallium arsenide substrate on which one can grow an InxGa1-xAs active layer. Such a component would be a good candidate for SKA because of its estimated low cost and high performance.

For the ALMA Band 1 receiver, a very wide band cryogenic LNA design is required. Two prototypes have already been built at NRC-HIA and further development with low noise InP HEMTs is ongoing.

4.3. *Wide Band Feeds*

The SKA project [14] has recently identified several key technologies that need to be developed before the construction phase. For its high frequency band, namely 1-10 GHz, the square kilometer surface area will be achieved by thousands of parabolic dishes, each with a wideband Single Pixel Feed (SPF) situated at its focal point. To attain this ultra wide band width, frequency independent designs are employed, but none have been singled out yet for the SKA. Example candidates include the Allen Telescope Array (ATA) feed [15], the Quasi-Self-Complementary (QSC) feed [16], and the Eleven feed [17]. None of these feeds are truly planar, however, making them difficult to fabricate in large numbers. New planar feed designs for SKA have been developed by NRC-HIA and UVic. One design, using log-periodic structures in a plane, has great potential for a low-cost solution due to ease in fabrication [18]. Figure 2 shows the design prototype in the NRC-HIA anechoic test chamber in Penticton where it underwent radio frequency tests. A second prototype, with mechanical and RF improvements, will be fabricated for the next phase of the project.

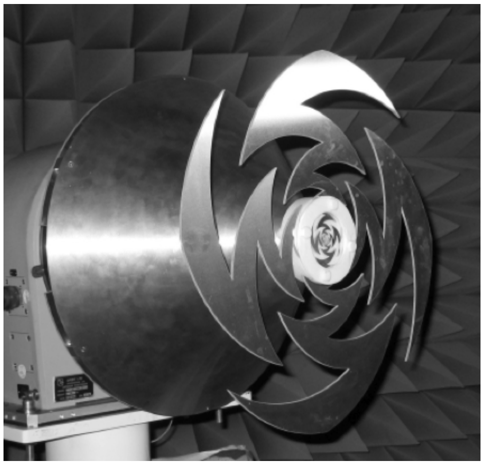

FIG. 2.— Prototype Single Pixel Feed for SKA.

The new feed designs must be integrated to a low noise amplifier. In addition, they must be cooled for optimum noise performance, and studies of an optimal cryogenic implementation are planned. Furthermore, plans are forming to test a SPF receiver on one of the Composite Antennas for Radio Telescopes (CART) with the phased-array feed demonstrator backend (PHAD) in at NRC-HIA in Penticton. Since the design can be scaled to other frequencies, it is possible to test the design on a different telescope such as the Effelsberg 100-m Radio Telescope of the Max Planck Institute in Germany.

4.4. *Planar Receiver Technology*

Waveguide technology is currently used for high frequency (60-1000 GHz) low noise detectors because it allows for signal transmission of a very large band width with low losses. If the absolute lowest noise is required, as in the case of astronomical instruments, waveguides can be cooled to reduce loss further.

Single pixel spectroscopic detectors, such as those developed for ALMA, offer state-of-the-art noise performance but are very bulky and only a limited number can be put together across the focal plane. Heterodyne imaging spectrometers have been recently placed on telescopes with a number of pixels varying from 4 at 810 GHz for the airborne CASIMIR receiver on SOFIA [19] to 64 at 320-380 GHz (SuperCam) for the Heinrich Hertz Submillimetre Telescope [20]. Also, the Atacama Pathfinder EXperiment (APEX) telescope has two 7 pixel arrays covering the bands 285-375 GHz and 385-520 GHz [21] and the JCMT has the HARP array with 16 pixels covering the band 325-375 GHz [22]. The level of integration and number of pixels for these arrays have been limited by waveguide dimensions.

If heterodyne arrays will ever reach the size of the bolometer arrays of 1000s of pixels, e.g., SCUBA-2, a technology change is necessary. One way to increase pixel

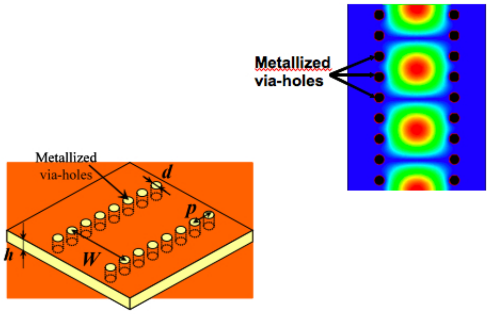

FIG. 3.— Substrate Integrated Waveguide layout (left) and electrical field distribution (right).

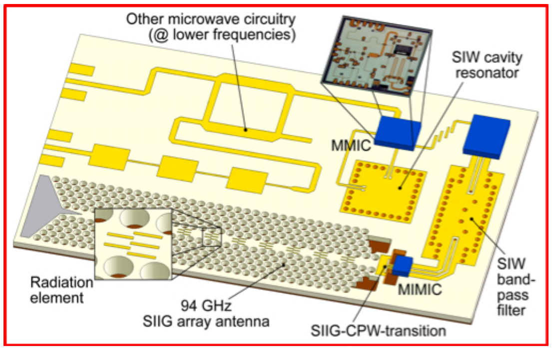

FIG. 4.— Combining planar and synthesized non-planar structures.

surface densities is to replace the (non-planar) waveguide technology with a planar technology. Planar technology allows component integration such as transmission lines, transistors, filters, and antennas on a single substrate. Figure 3 shows an example of a particular low-loss candidate for planar arrays, Substrate Integrated Waveguides (SIWs), that consist of two plates of conductor separated by a dielectric with metallized via holes. As shown in Figure 4, SIWs can be integrated well into a planar circuit, and a recent partnership between NRC-HIA, UVic and École Polytechnique produced a 4x4 planar array of antennas at 24 GHz using SIWs [23]. Indeed, a planar version of the Band 3 waveguide coupler was designed as part of the engineering PhD thesis of a student at the École Polytechnique [24, 25, 26]. Future work involves developing a new process for fabricating SIWs with quartz or alumina substrates and characterizating them at cryogenic temperatures.

5. SUMMARY

Canada has a long tradition in developing high-frequency radio technology for astronomical instrumentation. Building on our recent success with the Band 3 receivers for ALMA, we described several key paths for future research. These include development of Band 1 and upgraded Band 3 receivers for ALMA. In addition, research has begun into competitive technology for SKA, including low noise amplifiers, wide-band single-pixel feeds, and planar arrays.

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