Phased Array Feeds

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Abstract. The two open-ended frontiers in radio astronomy instrumentation are collecting area and field of view. Greater collecting area translates directly into greater sensitivity while increased field of view increases observing efficiency and makes feasible new areas of science, such as searches for transient radio sources, rare types of pulsars, and surveys of large portions of our Galaxy and of the universe. Steady progress will be made in more affordable collecting area, but the main limitation will continue to be cost. Greater field of view depends much more on technology breakthroughs that can happen in the next decade with adequate support for research and development in antennas and receiver systems.

There are three basic methods for obtaining greater field of view: aperture arrays of small elements, each of which sees most of the sky and beams are formed by combining their signals in electronics, smaller reflector antennas that have broader beams, and arrays of reflector antenna feeds that form the equivalent of a radio camera. This white paper outlines a technology development program for a specific form of radio camera called a phased array feed. This type of feed retains the efficiency of the best waveguide feed while fully sampling the telescope focal plane and making complete use of the available information at the focal plane.

Phased array feeds must be realized with system temperatures equal to or approaching those of the best single-beam receivers in use today. Otherwise, focal plane area and signal processing power will be squandered on restoring lost sensitivity instead of increasing observing efficiency. Cryogenic technology that can cool the key components of a large array is one area requiring R&D. Other areas include the design of array elements and low-noise amplifiers that are well matched in the presence of strong mutual coupling between array elements; the reduction of size, weight, power consumption and cost of receiver systems to make feasible the use of tens or hundreds of receivers at the focal plane; and greater data transport and signal processing bandwidth required by multi-element arrays. Given the current status of feed research and development, an array feed with preliminary science capability could be available within three to five years and mature operational instruments deployed soon thereafter.

Phased Array Feeds

1 Introduction

The generation of radio astronomy instruments now coming on line will fill much of the observational parameter space—frequency coverage, instantaneous bandwidth, system noise temperature, angular resolution, and time and frequency resolution. The two remaining open-ended parameters where fundamentally new science will be explored are collecting area and field of view. More collecting area will allow us to observe known phenomena much deeper in the universe, and greater fields of view open the possibility of finding new phenomena, such as transient radio sources and rare types of pulsars, by making large-area sky surveys much more efficient. A number of talented groups around the world, notably in Australia, The Netherlands, United States and Canada, are actively working on radio cameras, variously referred to as active, phased, beam-forming, or smart arrays to distinguish them from the more conventional independent-pixel feed-horn arrays which sample less than 1/16th of the available sky area within the array's field-of-view (FoV).

A phased array feed opens the possibility of a multi-beam receiver that can adapt to the optics of any radio telescope by synthesizing multiple, simultaneous beams on the sky for complete coverage of the available field of view, without loss of sensitivity in each beam. As a result, the survey speed figure of merit (SVS) is expected to increase by more than an order of magnitude. The SVS metric is proportional to the number of pixels or beams, $N_{\rm b}$, the solid angle per beam, $\Omega_{\rm b}$, the system bandwidth, B, and effective collecting area divided by system temperature squared, $(A_{\rm eff}/T_{\rm sys})^2$,

$$\mathrm{SVS} \propto N_{\rm b}\,\Omega_{\rm b}\,B\ (A_{\rm eff}/T_{\rm sys})^2 \tag{1}$$

Survey speed will increase linearly with the number of beams, and improvements in system noise temperature will increase SVS quadratically. Since effective aperture is equally important, large aperture radio telescopes such as Arecibo (AO) and the Green Bank Telescope (GBT) are prime candidates for this technology.

A substantial amount of signal processing is required to form each PAF beam. While economic and technology constraints limit the product, $N_{\rm b}B$, ongoing technology developments in digital beam-forming as well as photonic beam-forming in this decade are expected to increase this product by more than one order of magnitude, making PAF technology extremely attractive for astronomical use.

Phased array feeds need more development work to achieve system temperatures comparable to the best single-beam and conventional horn arrays. For survey and mapping applications the $T_{\rm sys}$ penalty of a non-cryogenic PAF can be compensated by forming more beams and trading off the required increase in integration time for greater sky coverage per pointing, but this makes sense only when post-beam-forming signal processing requirements are relatively light, such as modest bandwidth spectral line observations. In applications where single-beam or horn array systems are already starved for signal processing power and data storage capacity, such as pulsar and transient searches and high-redshift HI surveys, the trade-off of more beams at higher $T_{\rm sys}$ does not make economic sense.

In view of these considerations, we propose a development path that focuses on critical areas that will enable the construction of PAF science instruments in the next decade, namely, system temperature reduction with a goal of $T_{\rm sys} \leq 20K$, real time beam-forming techniques, and increased processing bandwidth, for a beam-bandwidth product goal of $N_{\rm b}B \sim 10$ GHz.

A first step in this development starts with a non-cryogenic array with modest signal processing bandwidth, and progressing steadily toward a cryogenic science array. This will offer early benefits of PAF technology to spectral line observers with an uncooled array. At this stage, an important aspect of system temperature reduction will be addressed as comprehensive beam noise optimization of the array front-end, including mutual noise coupling effects and LNA integration. Great progress in understanding the technology of close-packed arrays and sensitivity optimization algorithms has been made in the last five years, but, as with any new technology, there are many subtleties to be discovered and understood before the full potential of PAFs can be realized.

We will emphasize a reusable and scalable PAF architecture that will take advantage of the continuously decreasing costs of signal processing, thereby assuring a steadily increase in the $N_{\rm b}B$ product. Photonics, with true time delays, beam-forming at the device level, and low power consumption, will be assessed during the implementation of this plan, as it offers a potential breakthrough in beam-forming technology and an alternative to all-digital beam-forming.

We acknowledge and commend the aggressive approach to 2:1 wideband PAF implementation on the ASKAP telescope in Western Australia. We will take advantage of their knowledge gain, but our experience to date indicates that a more measured program with a long term goal of the absolute best system temperatures with the largest possible $N_{\rm b}\,B$ product is the best complementary approach for research and development in the U.S.

The frequency range for which PAFs will be feasible in the coming decade is roughly 0.5 to 15 GHz. Below 0.5 GHz the arrays are too large for most telescopes, and aperture phased arrays are more appropriate. Above 15 GHz more conventional horn arrays can produce many efficient beams on the sky in the available focal plane area, and the challenges of constructing close-packed arrays become more severe. PAF technology developed at any one frequency should be reasonably scalable to other frequencies in the 0.5-15 GHz range. The maximum array element spacing must be less than about 0.7λ to avoid grating responses in the reflector illumination pattern. The focal spot size is proportional to f/D so the number of array elements required for a given FoV grows as $(f/D)^2$, and the beam-forming computational effort similarly increases. Hence, optics with $f/D \leq 1$ are favored.

2 Enabled Science

Much of the science enabled by the first PAFs in a steady progression of arrays with be spectral line studies that require bandwidths of less than a few tens of MHz. For example, the formation of the Milky Way is now known to have been extended over time, and there is evidence that it must still be accreting fresh gas at the rate of about 1 solar mass per year. A likely source of this material is the high-velocity HI clouds which cover a significant fraction of the sky. A PAF it will allow the study of many more of these objects to greater depth [1–3]. A forty beam PAF on the Arecibo telescope, has the potential to test for the existence of low mass halos in other groups. Such a system could effectively carry out a a detection survey for narrow-lined HI sources of less than $10^6\ M_\odot$ at the 5-10 Mpc distance range of neighboring galaxy groups [4].

Other galaxies also have gas clouds outside of their disks which may be related to their own ongoing evolution. The HI clouds typically have low surface brightness and can be found far from their associated galaxy, requiring that large areas be mapped to detect them [5–7]. Galaxy groups can also contain extended HI clouds. In some cases these are the products of tidal interactions, but others are of an unknown origin. Deep measurements of galaxy groups with the PAF can provide information on the source of this gas through its kinematics, its relation to star formation or satellite galaxies, or its location along galaxy filaments [6, 8, 9].

Recent work has shown that there are significant amounts of molecular gas in the diffuse interstellar medium, so much so that half of the high-latitude sky is covered by molecular clouds. Emission from OH at 18cm is an excellent probe of these objects, as this molecule is formed at early times in chemical evolution models—earlier than CO—and is more widely distributed. The OH lines are weak and spatially extended. A PAF would be of immediate use in mapping these clouds to analyze their complex interstellar chemistry and their relationship to dust evolution and the neutral ISM [10–13].

Surveys for pulsars are motivated by the strong interest in finding fast millisecond pulsars and moderately fast rotating objects in compact binary systems. Pulsar searches with the 13-beam horn array at Parkes [14] and the 7-beam horn array at Arecibo [15] have been enormously fruitful. Phased-array feed technology needs to exceed multi-feed systems, such as the Arecibo 7-beam, in their overall capabilities. For pulsars, this means going beyond $N_b B = 2\,\mathrm{GHz}$. Millisecond pulsars, with their high spin stability and narrow pulses, can be used as an array of clocks for detecting nano-Hertz gravitational waves. The very fastest spinning objects also elucidate the accretion processes that cause the fast spin as well as those that limit the spin rate, such as losses to gravitational wave emission. Finding millisecond pulsars with periods less than 1 ms will provide extraordinary constraints on the equation of state of nuclear matter. The most important relativistic binaries are those with orbital periods less than a few hours and where the pulsar's companion is either another neutron star or a black hole. Monitoring of binary pulsars [16] allows precision tests of General Relativity and other theories of gravity while also providing precision masses of neutron stars, also important for constraining the equation of state, and probes of pulsar magnetospheres as the beamed radiation interacts with its companion.

Transient radio sources are the subject of considerable recent work and are a prominent target in the science cases for new telescopes, such as the SKA and precursor telescopes (ATA, ASKAP, MeerKAT). Transients come in a wide range of timescales from milliseconds or less to weeks or more so there is a range of survey parameters to be explored. The most recently discovered pulse transient [17] was recognized by the dispersion in its short pulse, presumably due to the intergalactic ionized medium. Fast transients, those with durations less than one second or so, require similar observational strategies as pulsars with one difference: we do not know the full range of expected luminosities and rates nor do we have a full grasp on the types of sources and their locations (Galactic and extragalactic). We do know that very high flux density events must occur at very low rates; otherwise we would have detected such events. Consequently, it is important to have a system that provides as much instantaneous solid-angle coverage as well as maximizing sensitivity. Some fast transients appear to be from objects similar to pulsars (the RRAT phenomenon [18]) while others are from as yet unidentified sources. The allowable phase space for very bright but very low rate transient events is uncharted, so the bandwidth requirements for fast transients can be relaxed (e.g., to 100 MHz) with as many beams as possible. The sampling requirements are the same as for pulsars. Slower transients, such as those associated with flare stars, as well as hypothetical events from extrasolar planets and exotic objects, such as prompt radio emission from gamma-ray burst sources, can also be sampled with a narrower bandwidth system.

As the ASKAP designers are well aware, PAFs on synthesis arrays present an additional demand on signal processing power severe enough to impact operational electrical power costs. Each PAF beam requires is own correlator. Growth in this application of PAFs will be paced by available funds for the indefinite future. The beam characteristics of PAFs and their effects on dynamic range of synthesis maps remains to be explored. Hence, research on image processing needs to be done in parallel with the development of PAFs, if risks and budgets are to be well managed.

3 State of the Art

Three PAF research groups around the world have extensively tested arrays on radio telescopes: ASKAP at CSIRO in Australia, ASTRON in The Netherlands, and a Brigham Young University/NRAO collaboration in the U.S. [19–21]. The ASKAP and ASTRON arrays are designed for wideband operation (2:1 and 3:1 ratios of upper and lower frequency limits, respectively) while the immediate goal of the BYU/NRAO array is 1.3:1. Initial results have been reported mainly in conference proceedings, and all three arrays are works in progress so performance figures are subject to change. The measured ratios of system temperature to aperture efficiencies are roughly 170, 120, and 90 Kelvin for the ASKAP, ASTRON, and BYU/NRAO arrays, respectively. If an aperture efficiency of 75% is assumed for all cases, these values correspond to $T_{\rm sys} =$ 127, 90, and 68 K, respectively. None of the arrays is cryogenic.

The ASKAP array is a variation on a connected dipole array in the form of a checkerboard pattern of conducting patches on a printed circuit substrate roughly one quarter wavelength above a ground plane. The low-noise amplifiers (LNAs) are connected with parallel transmission lines to the adjacent corners of conductor patches to form two orthogonally polarized arrays with shared radiating elements. The ASTRON array uses Vivaldi antenna elements in a box pattern to get orthogonal polarizations. The Vivaldi antenna is a traveling wave slot antenna with a flared gap between two coplanar conducting sheets and does not require a ground plane. A Vivaldi array feed (PHAD) is under development by DRAO in Canada [22]. The BYU/NRAO array is composed of thickened dipoles one quarter wavelength above a ground screen, currently only in one polarization.

All three arrays work better at some frequencies than at others in their designed frequency ranges. The performance parameter matrices remain to be fully explored. The fundamental challenge to low-noise performance is to achieve a good impedance match between the array elements and the LNAs. This is severely complicated by mutual coupling between elements in the compact array. A well matched element-LNA unit in isolation is no longer matched when embedded in the array. Element impedances naturally depend on frequency as well. Moreover, the best noise impedance match between element and LNA depends on how the signals are combined in signal processing, so the optimal noise impedance for a given amplifier varies from one formed beam to the next. Hence, the designer is presented with a complex optimization problem involving the array, amplifiers, and signal processing algorithms. Fortunately, the noise added to $T_{\rm sys}$ by this compromise is proportional to the optimum noise temperature ($T_{\rm min}$) of the LNA, so it is subject to improvement with physical cooling. Design tools do exist for computing the electromagnetic, impedance, and added noise effects of mutual coupling and, to some extent, optimizing the array design for best noise performance. The basic antenna element type, impedance modification structure, and connection topology are still left to the designer's experience and intuition to establish a starting point and free parameter set. The two very different wideband array types clearly illustrate different initial assumptions.

For array feeds, tests of individual element-LNA sets in isolation are of limited value. The normal engineering strategy of designing and testing individual components separately with the confidence that they will then work well in unison no longer holds. An array must be tested as a unit, including its beam-former. To this end the array development teams have built setups that allow running "hot-cold" noise measurements with absorber over the entire array for the "hot" value and cold sky as the "cold" environment. Since the array has a broad reception pattern care must be taken to account for all sources of thermal noise in the surroundings, including elevation dependence of atmospheric noise and time dependence of the galactic background. Example

Table 1: System noise budgets.

	19 Element Dipole Array Measured (July, 2008)	19 × 2 Element Array Design Target	Cryogenic Array Design Target
LNA $T_{\rm min}$	33 K	33 K	4 K
Mutual coupling	16 K	2 K	1 K
Spillover	7 K	5 K	5 K
Sky	5 K	5 K	5 K
Loss	5 K	5 K	5 K
$T_{\rm sys}$	66 K	50 K	20 K

noise budgets are shown in Table 1, where the first column is measured values for the prototype BYU/NRAO array. The second column assumes an optimized impedance match between array elements and their LNAs, and the third column illustrates the effects of cryogenic cooling of the lossy parts of the array with LNAs designed for low temperatures.

The beam-forming calibration and mathematics is now reasonably well understood [23]. The basic goal is to optimize the aperture efficiency to system temperature ratio for points in the FoV where beam are to be placed by adjusting the complex weights with which the array element signal are combined to form each beam. This starts with the measurement of the output of the array in the hot-cold measurement described above. The array outputs are cross-correlation matrices, $\mathbf{R}_{\rm hot}$ and $\mathbf{R}_{\rm cold}$ of the array element signals with and without absorber. These are exactly analogous to total power values in a conventional receiver noise calibration. These matrices are then combined to produce an isotropic array response matrix,

$$\mathbf{R}_{\rm iso} = \frac{T_{\rm iso}}{T_{\rm hot} - T_{\rm cold}}(\mathbf{R}_{\rm hot} - \mathbf{R}_{\rm cold}) \tag{2}$$

where $T_{\rm hot}$ and $T_{\rm cold}$ are the effective absorber and sky noise temperatures and $T_{\rm iso}$ is an arbitrary reference temperature. This can be used to compute a beam equivalent noise temperature that is equivalent to noise temperatures calculated for single feeds. On the telescope the array system temperature for a given formed beam is then

$$T_{\rm sys} = T_{\rm iso}\frac{\mathbf{w}^H\mathbf{R}_{\rm n}\mathbf{w}}{\mathbf{w}^H\mathbf{R}_{\rm iso}\mathbf{w}} \tag{3}$$

where $\mathbf{w}$ is the complex beam weight vector for the formed beam and $\mathbf{R}_{\rm n}$ is the noise matrix measured with the telescope point at blanks sky. The aperture efficiency equation is then the matrix equivalent of the scalar version familiar to radio astronomers,

$$\eta_{\rm ap} = \frac{k_b T_{\rm iso} B}{A_{\rm ap} S^{\rm sig}}\frac{\mathbf{w}^H\mathbf{R}_{\rm sig}\mathbf{w}}{\mathbf{w}^H\mathbf{R}_{\rm iso}\mathbf{w}} \tag{4}$$

where k_b is Boltzman's constant, B is the noise equivalent bandwidth, $A_{\rm ap}$ is the physical aperture areas, and $S^{\rm sig}$ is the flux density of the source used to make the measurement. The calibration task is then to adjust the beam weight vector $\mathbf{w}$ to optimize $\eta_{\rm ap}/T_{\rm sys}$.

An example of PAF implementation, calibration, and beam-forming results is shown in Figure 1. The left panel of this figure shows the BYU/NRAO 19-element dipole array mounted on the

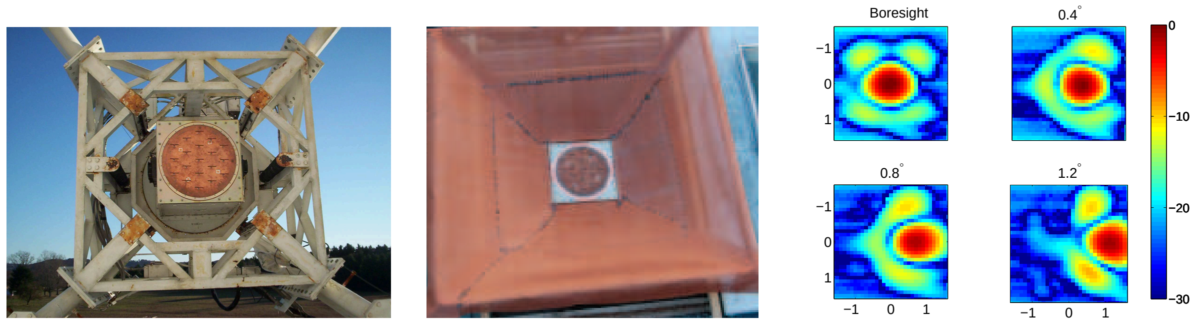


Figure 1: Left: 19 element single polarized PAF and front end box mounted on Green Bank 20-Meter Telescope (October, 2007). Center: Ground shield and PAF in sky noise measurement facility (July, 2008). Right: Measured beam receiving patterns (dB relative to peak).

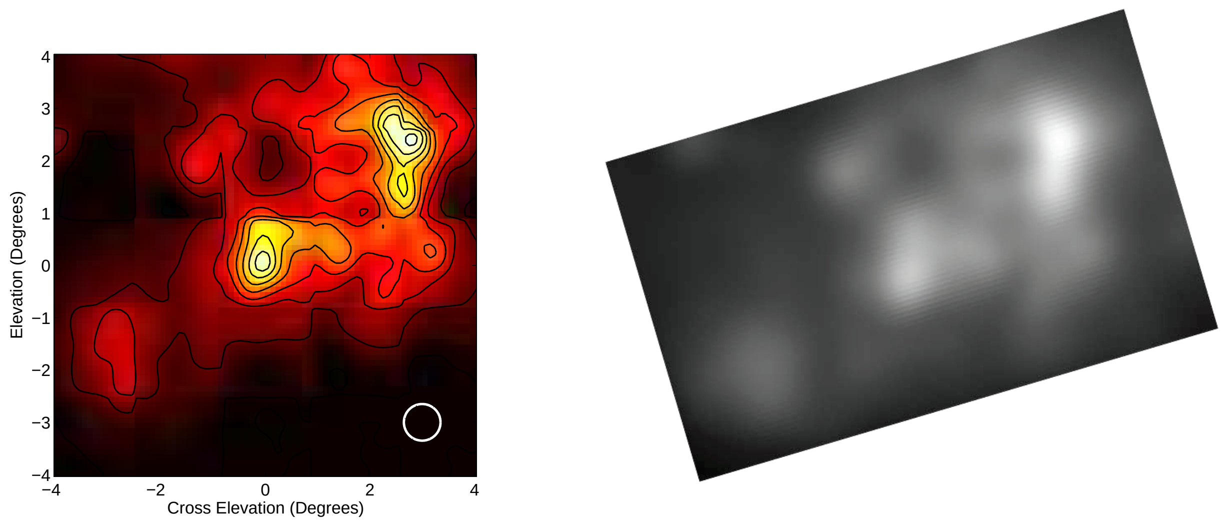
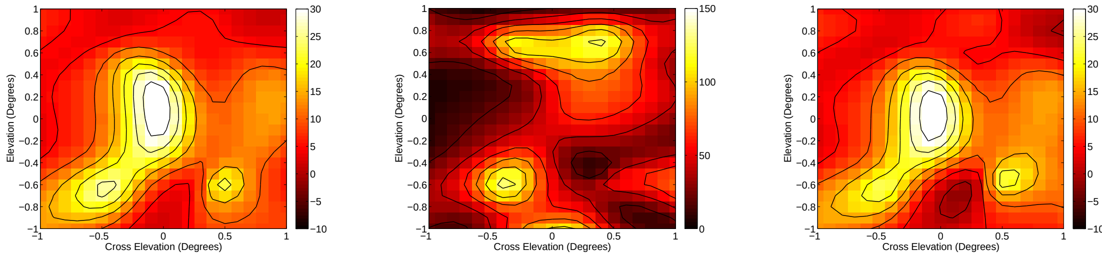


Figure 2: Left: Cygnus X region at 1600 MHz. 5×5 mosaic of images using the 19-element prototype PAF on the Green Bank 20-Meter Telescope. The circle indicates the half-power beamwidth. Right: Canadian Galactic Plane Survey image [24] convolved to the 20-Meter effective beamwidth.

Green Bank 20-meter telescope. Before the array was installed on the telescope it was directed toward the sky and surrounded by a copper shield to minimize noise radiation from the ground as shown in the middle panel. The sky-directed configuration was used to calibrate the isotropic noise response of the array as described by (2). The third panel in Figure 1 shows array beam patterns formed by optimizing $\eta_{\rm ap}/T_{\rm sys}$ by adjusting the coefficients $\mathbf{w}$ in Equations (3) and (4).

To demonstrate the feasibility of "radio camera" imaging, the 19 element prototype dipole array was used to create a mosaic of the Cygnus X region at 1600 MHz, shown in Figure 2. The mosaic was assembled from 25, 1.6×1.6 degree image tiles on a 5×5 grid. Each tile represents a single reflector pointing. An image of the PAF field of view for each pointing is obtained by forming multiple beams electronically. For a single-pixel feed with a raster spacing of one half the half-power beamwidth, approximately 600 pointings would be required to form a similar image, so the observation speedup with the PAF assuming identical sensitivities is a factor of 24. This demonstrates the fundamental advantage offered by PAFs for rapid sky imaging.

Another major goal of the 19-element prototype array was to study the feasibility of adaptive



(a) No RFI (b) With RFI (c) RFI canceled

Figure 3: W3OH image with and without RFI. The color scale is equivalent antenna temperature (K).

RFI mitigation using the beam-forming degrees of freedom offered by a dense array at the reflector focal plane. With the array on the 20m dish, an FM-modulated RFI source overlapping the W3OH spectral line at 1665 MHz was radiated in the far sidelobes of the telescope. The RFI was removed using the subspace projection algorithm [25]. Images of the source with and without RFI mitigation are shown in Figure 3. Some distortion due to residual RFI is apparent in Figure 3(c) after adaptive processing, but the source which was completely obscured by interference is now clearly visible. Other recent results demonstrating feasibility of PAF-based interference mitigation in astronomical applications include [26–33].

4 Research and Development Plan

A phased array feed must be designed as a system at two levels. At the first level, the array elements, LNAs, and cryogenics must be designed as a unit because some antenna element types may be difficult to cool or have too much loss even at low temperatures. Similarly, the thermal isolation from the surroundings must not interfere with the electromagnetic properties of the array. This is a more difficult challenge than with a horn feed because the entire hemisphere above the ground plane, rather than just the horn aperture, must be free of obstruction.

At the second design level the array must be matched with the post-amplifiers, digitizers, data transmission system, and signal processing distributed throughout the telescope system. As wider bandwidth arrays are implemented data throughput will be a major issue so general purpose data transmission systems with bandwidth to spare may no longer be an option. Relative phase stability between array elements will be critical, and this argues for moving the digitizer element as close to the array as possible. There is a very strong case for putting the digitizers in the receiver box behind the array so that signals come away from the focal point in a bundle of thin optical fibers rather than a thick bundle of coaxial cables with the potential for crosstalk and phase and amplitude instabilities. Hence, part of the array development program will be to design and prototype integrate receiver modules that fit in the shadow of each array element and incorporate all electronics from the LNA output to the digital fiber transmitter.

The digital beam-forming electronics will be too large and will certainly generate too much RFI to conveniently locate near the array in even the largest telescopes. The digital signal from each array element needs to be transferred to the telescope base or, more likely, to a central processing location. The current technology for this task is implemented in the ALMA and EVLA signal transmission system, but further development work can reduce the size, weight, and power consumption per unit bandwidth as described in another white paper on "Next Generation Receiver Development" by Morgan and Fisher. This R&D needs to be closely aligned with the requirements of PAFs.

The current front-runner for PAF beam-former signal processing is the CASPER FPGA development system. The design and creation of firmware modules unique to the beam-forming task will be a substantial effort, but many of the modules already in the CASPER library will be directly applicable to PAFs. Because signal processing will be such an integral and crucial part of PAF systems, it is important to implement new beam-formers on the most up-to-date hardware on a continuing basis. This should be built into the R&D plan from the start.

The progression of PAF development steps in the U.S. will proceed roughly as follows with many steps overlapping. The rate of progress will depend on the funding profile, but time must be built into the process to take advantage of adequate prototyping and testing at each stage. Haste toward implementation too far in advance of R&D will result in increased risk and associated cost and schedule overruns. A healthy PAF R&D funding level (not including science array construction) would be in the range of $1-2M/yr divided between university groups and national centers for research engineer and student salaries and benefits, technician and machine shop support, test equipment, and materials and supplies.

In conclusion, we list here the major tasks to be executed in the coming decade in order to realize science-ready phased array feeds:

- Develop a dual polarized cryogenic antenna element/LNA/Dewar configuration with at least 30% bandwidth and less than 4 K total noise contribution at 1.4 GHz when embedded in an array. Verify array performance with relatively narrowband signal processing that can also serve first spectroscopy science use.

- Develop a receiver module with RF input and digital output on fiber that will fit in the shadow of a 1.4 GHz crossed dipole.

- Establish cost model for complete array system with technology proven at this point.

- Develop FPGA-based beam-former with $N_b B \geq 500$ MHz and at least 37 dual-polarized array element inputs incorporating proven beam-forming and RFI canceling algorithms.

- Build 37-element arrays for Arecibo, GBT and possibly other telescopes.

- Evaluate results and performance of ASKAP and ASTRON wideband arrays and feasibility of cryogenic implementation. If not feasible, use wideband design techniques to extend bandwidth of cryogenic array.

- Update cost model for use in proposing next generation of arrays to be proposed and built.

- Extend cryogenic PAF technology to 5 GHz and above, including smaller RF-to-fiber receiver modules.

- Design and build next generation beam-former with at least 61 dual-polarized inputs, 1 GHz bandwidth, and the latest beam-forming and RFI canceling algorithms.

- Continue extending cryogenic array technology to higher frequencies.

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