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ARRAY2K: MULTIPLE DISHES, MULTIPLE MODES

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ABSTRACT

For the past two years, the SETI community has marveled at the development of the ambitious Paul Allen Telescope, a mini-Cyclops consisting of up to a thousand phased satellite TV-type dishes. While saluting the efforts of our California colleagues, The SETI League has been hard at work on its own phased array design, more modest in scope but quite as technologically audacious. When completed, Array2k will employ a unique mix of analog and digital techniques to operate in five distinct modes simultaneously. Optimized as a drift-scan sky survey instrument in the proud tradition of Ohio State's Big Ear, its multi-mode capability will enable Array2k to serve as its own Follow-Up Detection Device, verifying its own findings in real time.

INTRODUCTION

The SETI League, Inc. launched its *Project Argus* all-sky survey in April 1996, with the ambitious goal of real-time all-sky coverage (Shuch, 1997). Our experience in implementing a global network of small radio telescopes (Shuch, 2000) has underscored the importance of developing larger scale telescopes with improved sensitivity. Due to negative economies of scale, we early decided to explore the arraying of a quantity of the very type of antennas used in the current Project Argus network -- that is, extrapolating from our area of greatest expertise.

The technological breakthroughs described here may be applied generally to radio astronomy, and the microwave antenna arrays and systems utilized in such installations. More particularly, the present invention describes a multi-dish antenna array primarily adapted for astrophysical research and the Search for Extra-Terrestrial Intelligence (SETI). We have named our proposed antenna *Array2k*, not for the year past, or the much-feared computer crisis, but rather in recognition of its 2,000 square feet of collecting area, which can be expected to yield performance equivalent to that of a single 50-foot dish, but at perhaps a tenth the cost.

THE NEED FOR MULTIPLE MODES

It has long been recognized by those skilled in the art that multiple antennas can be combined together for increased receiver performance. The advantages are numerous and well known. Various forms of prior art technology exist for combining the antennas.

For example, in astrophysical research and the electromagnetic Search for Extra-Terrestrial Intelligence (SETI), it has been the common practice to combine multiple dish antennas into an array, optimized to produce a specific beam geometry. Beam geometries tend to be highly application-specific. For example, drift-scan SETI receiving stations are best served by an antenna pattern that is somewhat broader in the declination axis than it is in right ascension. This very type of beam pattern was implemented by the late Ohio State University "Big Ear" radio telescope, circa 1964 – 1997, which was one of the great pioneers in SETI. Total power studies of the galactic core favor an opposite antenna pattern (that is, a geometry which is broader in right ascension than it is in declination). Targeted searches of individual stars and quasi-stellar objects require a spot beam, narrow in both planes.

At this time, in order to achieve a given beam pattern distinct, application-specific arrays of antennas are used. Obviously this approach has limitations when funds are limited, and only one array is practicable. Alternatively, antennas may be physically relocated. Obviously this approach is difficult, and sometimes proves impractical. For example, the twenty-seven dish antennas at the 78 million dollar Very Large Array (VLA) in Socorro New Mexico each weigh 230 tons. To change this array between operating configurations, each of its dishes is moved along approximately thirty miles of railroad track.

It has long been accepted that diverse beam geometries tend to be mutually exclusive. An adaptive antenna array, one that can operate in multiple geometric modes simultaneously, would be highly advantageous.

REVIEW OF PRIOR ART

The advantages gained by combining multiple antennas into an array are well known, and fall into two broad categories: (a) improving sensitivity, and (b) improving resolution. The two most common ways of connecting multiple antennas into an array are (a) as a radiometer, and (b) into correlation detectors. (Burke and Graham-Smith, 1997).

In the case of the radiometer connection, a single detector is connected to all of the antennas in the array via a branched feedline, which maximizes sensitivity by producing a single beam. The best known (though never implemented) example of this configuration is Project Cyclops (Oliver et. al., 1973).

In an interferometer (Ryle, 1952) resolution is improved by combining the signals of two antennas, which are separated by a specified distance (called the baseline). With dish antennas, the resulting gain is simply that which would be achieved by a single dish with a surface area equal to the sum of that of the two antennas. However, the angular resolution of such an interferometer is equivalent to that of a single dish with a diameter equal to the baseline. Thus, interferometers provide a modest improvement in sensitivity with a much greater increase in resolution.

A multiple-antenna interferometer array may be constructed using a technique known as aperture synthesis. Each possible pairing of antennas in the array is accomplished by applying the outputs of the antennas to a multitude of correlator circuits. The correlator outputs may be combined to produce multiple beams, making it possible to image distant astrophysical objects with high levels of detail.

Well-known multiple-antenna interferometers include the Very Large Array (Napier et. al., 1983) and the Giant Meter-Wave Radio Telescope (Swarup et. al., 1991). Both of these arrays arrange their antennas (27 in the case of the VLA; 30 at the GMRT) in a "Y" configuration with extremely wide baselines, and use digital correlators to combine the signals from the multiple dishes.

The Mills Cross arrangement (Mills, 1963) consists of two line-type antennas, one oriented North-South and the other East-West. The former antenna produces a beam pattern which is narrow in declination and broad in right ascension. The latter produces a beam pattern which is broad in declination and narrow in right ascension. When signals from the two antennas are combined, a beam is produced which is narrow in both axes. Bracewell and Swarup (1961) produced an array of 32 small parabolic dish antennas, oriented in a Mills Cross, to produce a pencil-beam interferometer with micro-steradian resolution.

All of the antenna arrays described above achieve stated design goals of high sensitivity or high angular resolution. In each case, one and only one of these design objectives can be achieved, and invariably at the expense of the other.

The present invention resembles the Bracewell and Swarup array in physical configuration. Unique circuitry is added to allow it to operate both as a total-power radiometer, and as a correlated interferometer, simultaneously. The multiple operating modes envisioned will allow the array to achieve both high sensitivity and high angular resolution, allowing it to fulfill a variety of research objectives.

ARRAY2K DESIGN OBJECTIVES:

Array2k is an array of small, dish antennas all interconnected to accomplish specific beam patterning. As initially envisioned, the array comprises 16 individual parabolic dish antennas, each four meters in diameter. Four sub-arrays, each with four individual antennas, are established in a cross-like formation, with one sub-array each running north, south, west and east of the array's phase center.

We propose a means for electronically changing a complex multiple-antenna array into different configurations for producing different beam patterns. In other words, radio signals derived from the sub-arrays can be analog-processed and combined into control signals that are useful for generating steering parameters. Control signals are synthesized through a combination of analog signal quadrature techniques, combined with digital conversion and software correlation. As different individual antennas forming each sub-array monitor at least portions of overlapping sky viewed by others, quadrature processing of signals derived from each individual antennas can be processed not only to yield the composite observed target sought by the radio telescope, but can be correlated to generate the required steering parameters to observe the desired beam patterns.

The basic objectives of this design are:

1. to provide an adaptive antenna array system which can operate in multiple geometric modes simultaneously.
2. to provide an adaptive antenna array of the character described that can achieve a beam pattern that is broader in the declination axis than in right ascension, and at the whim of the user, be quickly changed to a beam pattern that is broader in right ascension than in declination.
3. to utilize sensed antenna data and parameters to develop steering signals for the array.
4. to aid drift-scan SETI receiving stations by deriving antenna patterns that are somewhat broader in the declination axis than in right ascension.
5. to provide an electronic means of creating a beam geometry broader in right ascension than it is in declination.
6. to be able to electronically convert a radio telescope and switch it between beam patters.
7. to provide an array that can be switched to a spot beam, that is narrow in both planes, to aid

in the study of individual stars, quasi-stellar objects, and other deep space targets.

8. to simplify the changing from one beam pattern to another.
9. to minimize the necessity of physically moving antennas.
10. to provide a highly versatile multiple antenna array system suitable for use by universities and layman, public and private experimenters, professionals and amateurs alike.

The following descriptive sections show how we intend to meet the above objectives.

ARRAY2K PHYSICAL CONFIGURATION:

Figure 1 shows an artist's rendering of an embodiment of the Array2k concept. In this example, the sixteen antennas depicted consist of parabolic reflectors four meters in diameter. The antennas are physically arranged in rows that emanate outwardly from a specified, central location (known as the array phase center). A laboratory building sheltering computers and other components of the array will occupy the phase center. Four sub-arrays are oriented along baselines radiating outwardly from the array center, in the directions of true North, South, East and West. Each sub-array shown comprises four individual antennas, equally spaced at two dish diameters. These groups of four identical antennas each are known as the East, West, North and South sub-arrays. Of course, a larger number of dishes could be used in a similar configuration.

The five planned operating modes are depicted in Figure 2. Through use of a combination of analog and digital signal combining techniques, Array2k will simultaneously produce:

- Beam pattern A, which is broad in both azimuth and elevation, providing maximum sky coverage with minimum resolution.
- Beam pattern B, which is narrow in azimuth and broad in elevation, optimized for meridian transit ('drift-scan') sky surveys.
- Beam pattern C, which is broad in azimuth and narrow in elevation, maximizing sky coverage in the equatorial plane while providing high resolution in the elevation axis.
- Beam pattern D, a narrow spot-beam formed by the intersection of patterns B and C, for higher resolution follow-up
- scrutiny of candidate signals detected in the earlier modes.
- Beam pattern E, a narrow spot-beam, which is steerable electronically and instantaneously anywhere within the beamwidth of the individual antennas comprising the array. This mode is most useful for sky-mapping studies.

FEED ASSEMBLY:

Figure 3 shows the prime-focus feed assembly mounted to a single-dish prototype of the antennas envisioned for the array. Note that each feed assembly consists of a cylindrical waveguide feedhorn (with choke ring) operational over the array's 1.3 to 1.7 GHz intended bandwidth. The feedhorns are fitted with two orthoginally polarized monopole probes, for dual linear polarization, mounted to the center pin of type N coaxial connectors. Gain and phase matched low noise amplifiers (LNAs) are attached to the two probe connectors via identical short lengths of low-loss coaxial cable. Again using identical low-loss cables, the outputs of each pair of preamplifiers are connected to a microstrip quadrature detector and dual in-phase power splitter assembly, to produce two RHCP signals (referred to here as Phased and Combined), and two LHCP signals, similarly labeled. The phased outputs will be used downstream for digital correlation, and the combined signals will drive analog combiner circuitry, as described in the following Sections.

It is important to note that the success of this array depends upon precise phase and gain matching of all 32 LNAs in the system, not only across the operating frequency spectrum, but also over temperature and with changes in applied operating potential. The use in all LNAs of monolithic microwave integrated circuits (MMICs) from the same production wafer, and microstrip circuit boards etched from the same physical substrate stock, is contemplated. For consistency, it is expected that any spare LNAs likely to be needed over the life of the array will have to be manufactured in the same production run as those initially placed into service.

ANALOG SIGNAL COMBINERS:

As seen in Figure 4, for each of the four sub-arrays, the RHCP an LHCP combined signal outputs from Figure 3 are combined in an x-way analog power combiner (where x equals four for the sixteen-dish array described here, but for larger n-dish arrays will be n/4). The combined signals representing each of the four sub-arrays are then split into two identical signal components, A and B in Figure 4.

The first of these components from each sub-array (A in Figure 4) is applied to the network of quadrature couplers shown at the top of Figure 5, to produce the broad-beamwidth combined response shown as Pattern A in Figure 2.

The other of the two identical power-split components from each sub-array (B in Figure 4) is then applied to the network of in-phase power combiners shown at the bottom of Figure 5, thus producing for each circularity the beam responses shown as Patterns B, C, and D in Figure 2.

Note that the above process is repeated for both orthogonal circular polarizations, producing thus far a total of eight beam responses from the array: four RHCP and four LHCP. Collectively, the circuitry described thus far supports multiple search strategies.

DIGITAL CORRELATORS:

The circuitry shown in Figures 2 through 6 utilizes analog techniques to provide four of the five operating modes proposed for Array2k. The fifth mode, a real-time fully steerable spot beam, requires that we employ digital correlation techniques. The required correlator circuitry is the least fully developed aspect of the present project. A very preliminary blueprint of the planned correlator is shown as Figure 6.

Signal samples from each antenna, and in each circular polarization, were generated as shown in Figure 3, and were previously designated "Phased Signals." Each of the 16 RCHP Phased signals and 16 LHCP Phased signals is first applied to its own individual Analog-to-Digital Converter (ADC). Each ADC digitizes the analog signals delivered thereto, and preserves amplitude and phase information, thus producing simultaneous RHCP and LHCP digital signal representations.

Each of a pair of 16-input digital signal correlators is driven by the RHCP and LHCP digital signal representations supplied by the ADCs. Each correlator is controlled by and provides its data output to a beam steering and data analysis computer, and thence a to mass data storage means, as depicted in Figure 6. The software that controls the electrical phases of all digitized signals in the entire array produces a spot beam E (Fig. 2) electrically steerable anywhere within the overall beamwidth A of the original sixteen antennas.

FINANCIAL CONSIDERATIONS:

Economic tradeoff analysis (see Figure 8) suggests that total array costs are minimized when investments in steel and silicon are roughly equal. In the case of Array2k, this sets for us the optimum size, as well of the number, of the individual antennas to achieve a given level of performance. Array2k promises a roughly one order-of-magnitude improvement in performance over existing individual Project Argus stations, at a cost increment only slightly greater that one order of magnitude. We initially contemplated an array of sixteen parabolic reflector antennas, each four meters in diameter. When the costs of the electronics and the mechanical systems for such an array were set roughly equal, the budget in Table 1 resulted. Thus, our stated goal has been to raise the required $160,000 to turn this system into reality.

As will be seen in the following section, unanticipated events have recently transformed the design of the planned array, obsolescing this planned budget while (ironically) not appreciably altering our total funding needs.

PROJECT STATUS:

To date, Array2k is very much vaporware, as the project is yet to be funded. A single-dish prototype (see Figure 7) has been on the air for two years in North Central Pennsylvania, implementing the circuitry shown in Figure 3, and validating our hardware choices for the parabolic dish, feed assembly, mounting method, and rotors.

A suitable piece of land has been donated to the project. Located on a remote ostrich farm in northern New Jersey, the planned site represents the best in compatible land use planning, as the area is far from industry and its accompanying electromagnetic interference, and ostriches are not known to emit electromagnetic radiation of their own. In addition, the ostrich farm provides an eloquent metaphor for the mentality of those policy makers who have terminated the funding of past SETI projects.

We contemplate implementing beam patterns A through D first, and then applying the various "combined signal" outputs from the feed assemblies (Figure 3) to the correlator system as it evolves, to produce pattern E. We choose to tackle the analog combining modes first because the required microwave circuitry is a mature technology, whereas the digital techniques and computer power required in this last phase are still evolutionary. It is hoped that by the time Modes A through D are active some months to years downstream, more capable and affordable digital solutions will present themselves.

In the summer of 2001, while completing our paper design of a sixteen-dish array, The SETI League received an unanticipated contribution of 47 small (1.8 meter diameter) high-quality parabolic reflectors and az-el mounts. Initially, we thought these antennas too small to be of much use in Array2k, if it were to achieve its stated performance objectives and remain within our preliminary budget. Two factors have convinced us to redesign the array around this most generous gift.

The antennas in hand (see Figure 9) are offset-fed parabolic sections, rather than full paraboloids. This means their feed assemblies will not block their apertures, and higher efficiencies can be achieved than with the conventional prime-focus parabolas initially envisioned (Figure 7).

One feature of the offset-fed dish is that, for a given true focal length to diameter ratio, the actual feed beamwidth is reduced by a factor of roughly two. This means we can further improve the illumination efficiency of our array, through feed apodizing that would not have been practical in the blocked-aperture case. Here we can draw from the experience of our colleagues.

At the left of Figure 10 is an elegant corrugated waveguide feedhorn developed by engineers at CSIRO in Australia for use in the SETI Institute's *Project Phoenix* targeted search. The one depicted, installed on a 100 foot dish at the Georgia Tech Woodbury Research Facility, covers 1 to 7 GHz with dual polarizations. For our Array2k effort, The SETI League has recently begun developing much narrower-band corrugated feedhorns. At right in Figure 10 is an L-band feed constructed out of surplus materials, at a cost many orders of magnitude below the feeds made by our Australian colleagues.

Preliminary measurement shows that, by combining the advantages of an offset feed with those of a higher gain, narrower beamwidth feedhorn, our illumination efficiency can be raised from around 50% to roughly 70%, which helps to close the performance gap between the dishes envisioned and those donated.

Given their non-blocked apertures, the quality of the offset feedhorns being developed, and the quantity of antennas now available, it is possible to approach with the greater number of smaller dishes the performance planned for a lesser number of larger ones. This would, in fact, seem to negate the careful economic tradeoff analysis shown in Figure 8 and implemented in Table 1. However, when the dishes and mounts have been provided free of charge, it becomes feasible to spend considerably more on the required electronics, while not exceeding the initial project budget. Thus, little has changed but the number of individual elements; we expect the array to perform rather as promised, and remain within the cost levels budgeted (but yet to be raised).

CONCLUSION:

It always comes down to money, doesn't it? The large quantity of dishes just donated has significantly decreased our anticipated costs in one area, while significantly raising them in another. Fortunately, the two fiscal impacts are pretty much a wash. The SETI League still stands ready to place its Array2k system on the air (at least in its first four operating modes) within a year of the project being funded. All we need now is a discretionary $160,000 -- pocket change to professional scientific endeavors, to be sure, but all the money in the world to a group of dedicated amateurs seeking to do breakthrough science with cutting-edge facilities of their own design.

Perhaps this paper will help to bring the required funding, and hence Array2k, closer to reality.

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Table 1
Array2k initial budget (per antenna element)

Electronics		$\simeq$	**Mechanical**	
Preamps	**$ 600**		**Dishes**	**$1800**
Couplers	**$1400**		**Mounts**	**$ 500**
Cabling	**$ 500**		**Feedhorns**	**$ 500**
Receivers	**$1500**		**Rotors**	**$1000**
Computers	**$1000**		**Installation**	**$1200**
Total	**$5000**	$\simeq$	**Total**	**$5000**

Figure 1
Array2k Artist's Rendering (© 2000 by Aurore Simonnet)

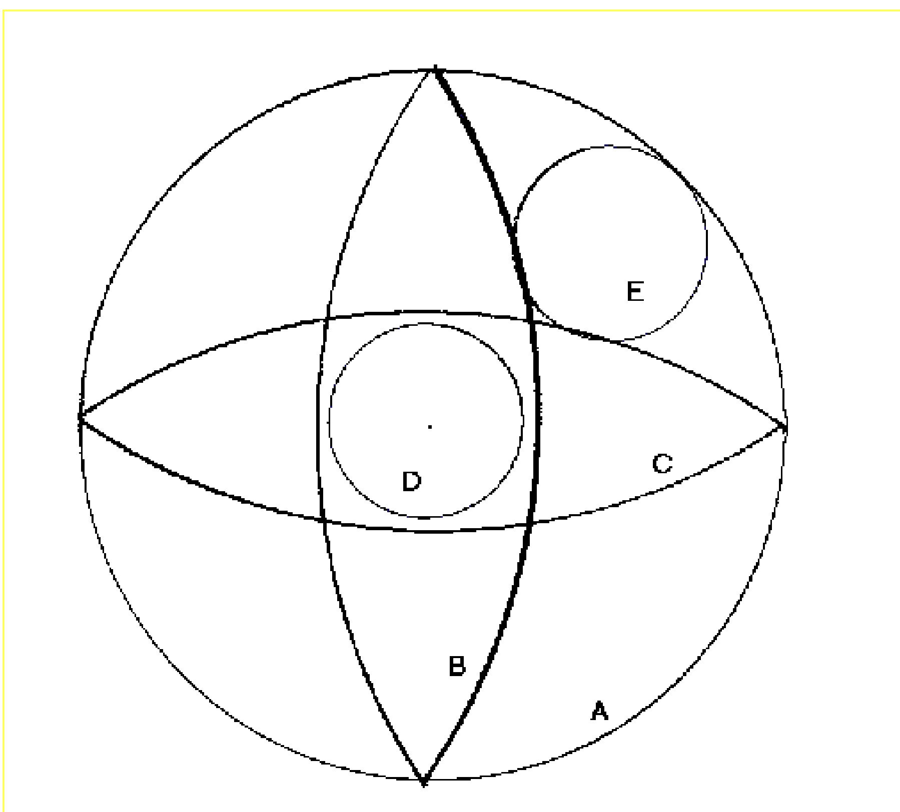

Figure 2
Beam Pattern, plotted in Elevation vs. Azimuth, of the Adaptive Microwave Array in its five operating modes.

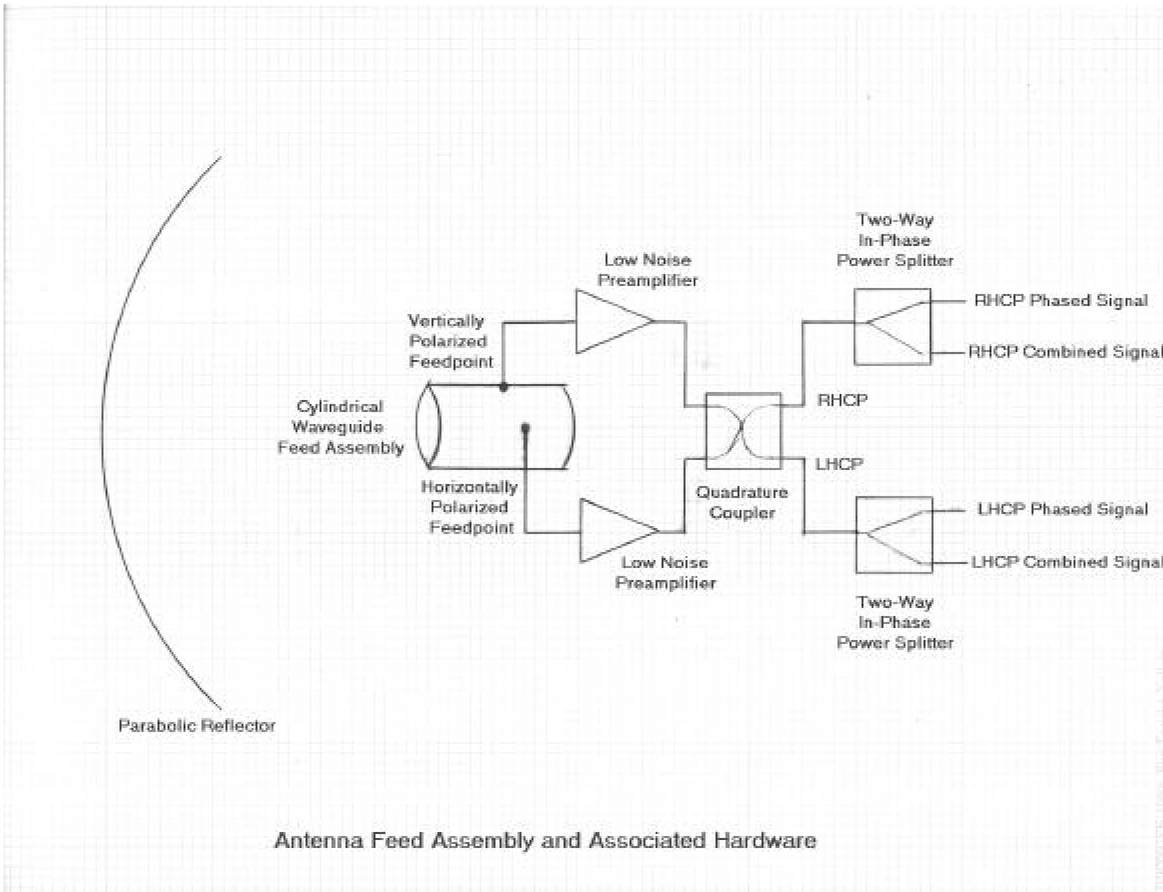

Figure 3
Array2k Feed Assembly (one used on each of the sixteen dishes)

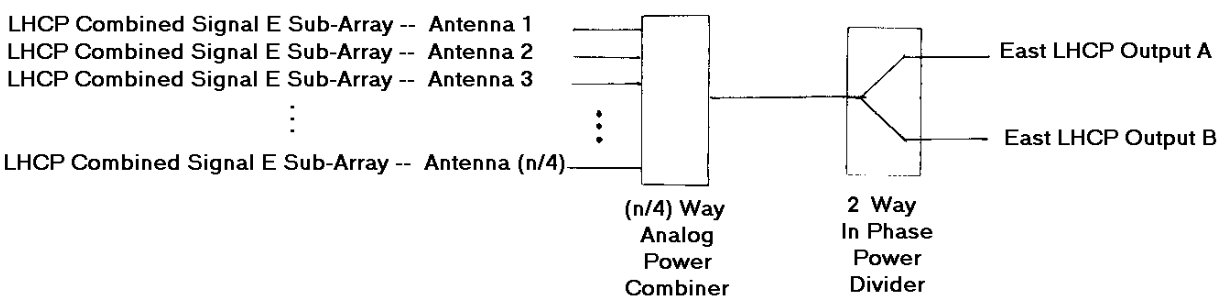

Figure 4
In-Phase Analog Power Combiner Assembly (LHCP East sub-array combiner is shown).
Similar assemblies will be used for both orthogonal circular polarizations on all four sub-arrays.

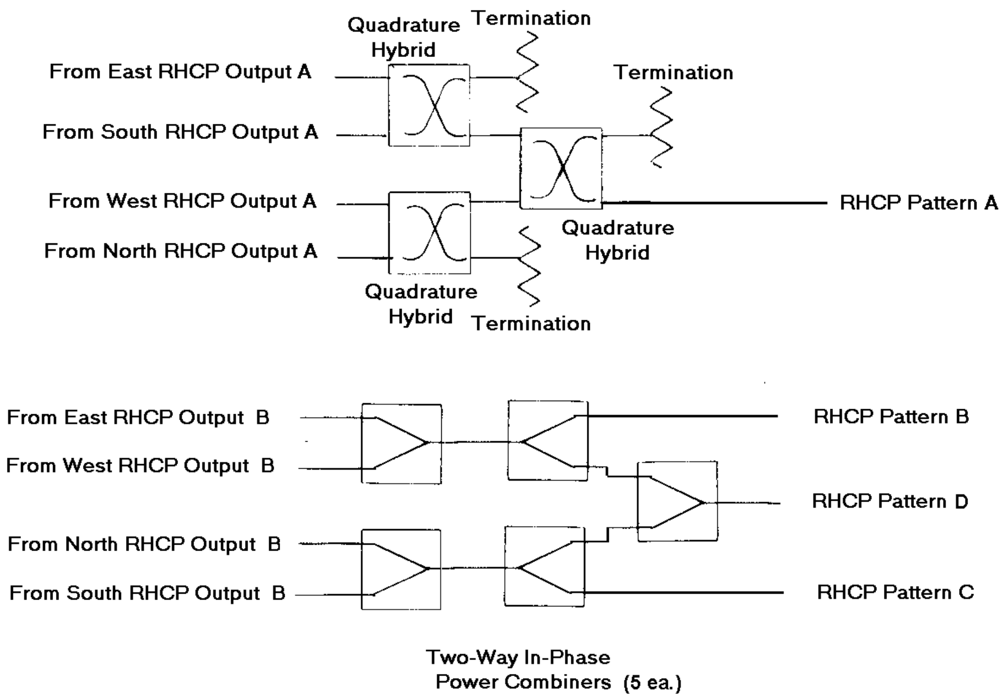

Figure 5
Sub-Array Combiners
(RHCP shown. A similar assembly is used on each of the LHCP sub-array outputs.)

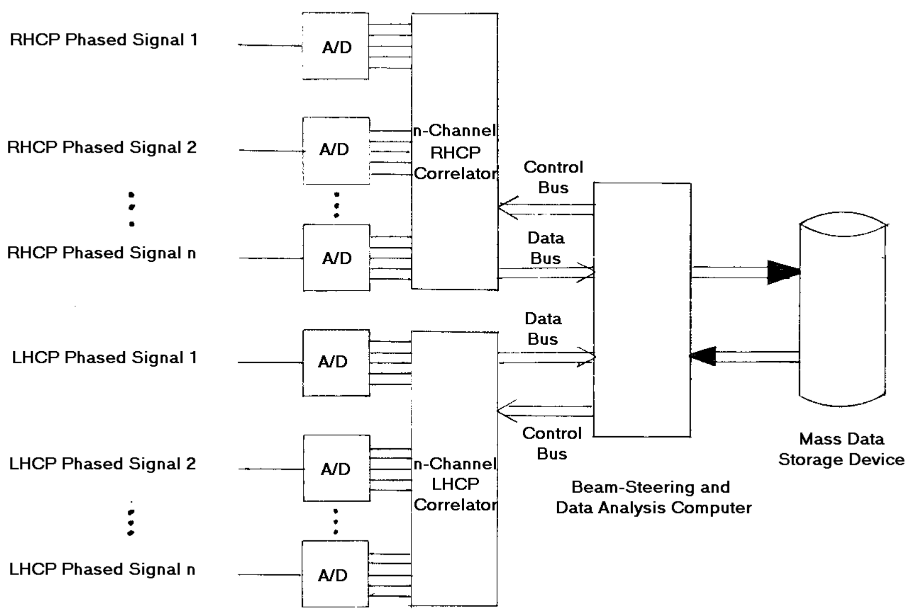

Figure 6
Digital Correlator Assembly for Aperture Synthesis

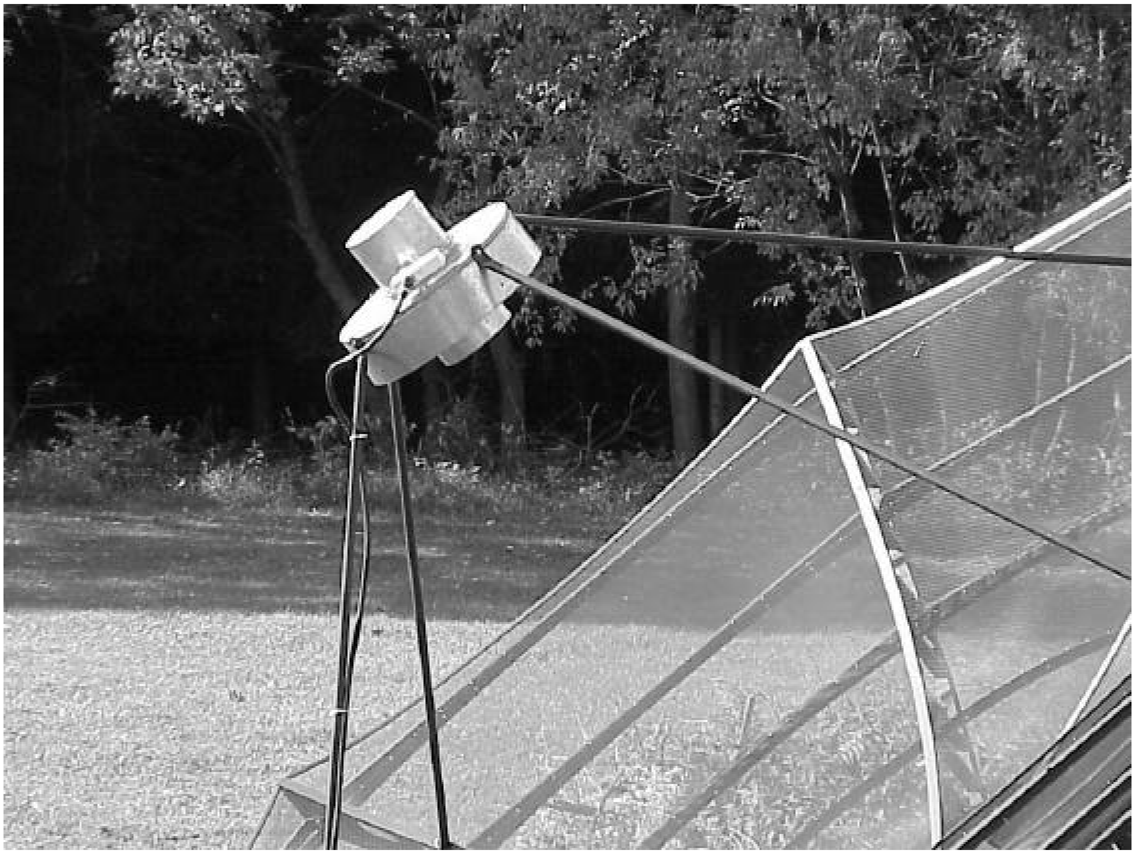

Figure 7
Single-dish prototype for the Array2k antennas, mounts, rotors, and feed assembly

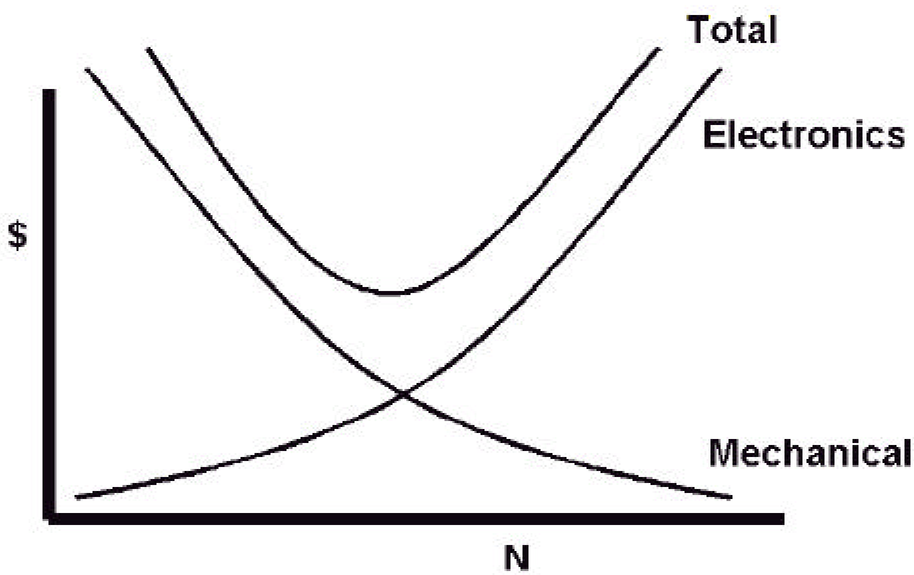

Figure 8
Economic tradeoff analysis for an N-dish array

Figure 9
The author poses with one of 47 donated 1.8 meter dishes

Figure 10
Corrugated waveguide feedhorns, as implemented by CSIRO (left) and The SETI League (right)