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ARGUS: A NEXT-GENERATION OMNIDIRECTIONAL POWERFUL RADIOTELESCOPE†

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Abstract—The time has come to seriously consider a fundamentally different approach for radiotelescopes. Compared to a conventional dish, an Argus timed array provides many advantages, including simultaneous omnidirectional high-gain sky coverage (no scanning), high sensitivity, high resolution, low sidelobes, detection of transient sources, retroactive observations, interference rejection, and high efficiency. An Argus array is less expensive since it takes advantage of mass production; has no large or moving parts; and is unaffected by gravity, sunlight or wind. The construction cost of a dish increases with time (since labor costs dominate), whereas the construction cost of an array decreases with time (since computing costs dominate). Hence an array must become less costly at some time, even if it's other advantages are ignored. We have successfully constructed and operated a prototype eight-element circular Argus array at 162 MHz. Continuing developments in computing power will make large arrays possible, and today modest arrays at lower frequencies are within reach. One fully implemented Argus array can simultaneously carry out all observations now being done by other comparable dish radiotelescopes.

1. INTRODUCTION

The time has come to seriously consider a fundamentally different approach for radiotelescopes. Instead of large steel dish structures, a large number of small omnidirectional antennas can be used in an array to obtain much greater performance at lower cost. Such arrays are commonly called "phased" arrays, but that implies narrow bandwidth, so a more correct term for what is discussed here is a "timed" array.

The name Argus originated from the mythological guard-being that had 100 eyes and could look in all directions at once. This name was used for an omnidirectional, all-seeing antenna by Arthur Clarke in his novel *Imperial Earth* and by Carl Sagan in his novel *Contact*. Basically, an Argus array uses computers to combine the outputs of a large number of array elements to create a large number of beams that simultaneously cover the entire sky. An Argus array is actually a telescope, since it forms an image, whereas typical dish antennas are not telescopes at all, and are more accurately called teleradiometers. Another name which has been applied to Argus arrays is radio camera.

2. ADVANTAGES OF ARGUS OVER A DISH-TYPE ANTENNA

Compared to a conventional dish, an Argus timed array provides many advantages, including simultaneous high-gain omnidirectional sky coverage (no scanning), high sensitivity (arbitrarily long integration time), high resolution, variable beam size and shape, low and moveable sidelobes, wide bandwidth, detection and tracking of transient and moving sources, adaptive and retroactive observations, interference rejection, and high efficiency. While the term "high-gain omnidirectional antenna" may seem self-contradictory, that is true only in the transmitting case or only if passive transmission lines are used to form multiple beams in the receiving case. In fact, information and energy are falling on any radio telescope from all directions all the time, and the vast majority of it is ignored; that is in one sense considered "good." The apparent contradiction arises from use of the principle of conservation of energy, whereas the applicable principle is conservation of information. The larger a dish antenna is, the worse it becomes in terms of using all the energy and information that falls on it. Figure 1 illustrates the extremely low total efficiencies of some well-known dish-type antennas, in comparison to the Argus approach. The sensitivity of an Argus array is the same as that of a dish having the same total collecting area and the same sensitivity receiver.

In terms of cost, an Argus array is inherently less expensive than a dish since it takes advantage of mass production; has no large or moving parts; is unaffected by gravity, sunlight or wind. It has no tight mechanical tolerances and requires no mechanical maintenance. The construction cost of a dish increases with time (since labor costs dominate), whereas the construction cost of an array decreases with time (since computing costs dominate). Hence

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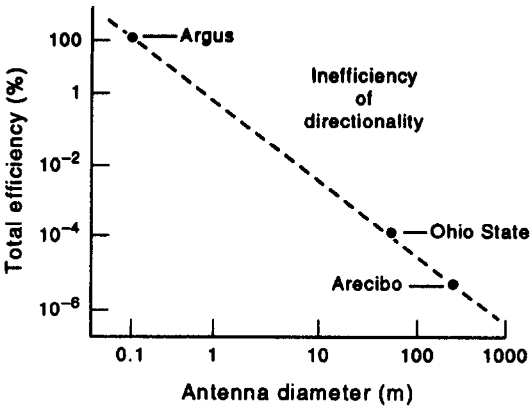

Fig. 1. Efficiencies of various antennas.

an array must become less costly at some time, even if its other advantages are ignored.

In terms of flexibility, an Argus array has a number of advantages. It can be easily expanded or changed in shape; its resolution can be chosen independently of its collecting area; and its resolution, beamshape, and sidelobes can be changed at will by software. One example of this is for sidelobe reduction as shown in Fig. 2(a) and (b)[1]. The main beam of an array is only sightly affected by small changes in the array, whereas the sidelobes are strongly affected by such changes. The sidelobes are also half as wide or less than the main beam. If the size of the array is changed periodically and the output averaged, the sidelobes will tend to cancel. The array size can be changed by switching the outer elements on and off (by changing their weighting factors). This results in the sidelobe reduction shown in Fig. 2(b).

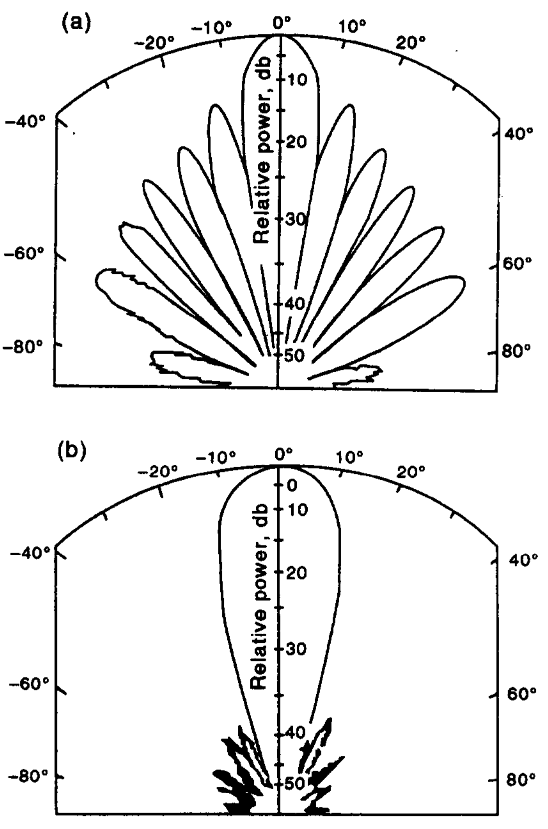

Fig. 2. (a) Classical array sidelobes. (b) Ultralow sidelobes after switching the array size.

Argus can be self-calibrated using test transmitters located within the array. It is fault tolerant since there is no single point of failure, unlike a conventional dish that has a single signal path from feedhorn to detector.

In terms of capability, an Argus array can do many things a dish cannot do, including observe multiple objects simultaneously, track rapidly moving objects, detect transient events in unknown directions, survey the entire sky in a single integration period, receive with very wide bandwidth, observe adaptively in response to current results, and re-observe retroactively objects or events not recognized initially. The retroactive observations can be done by playing back the recorded data from the array elements, and if desired the beam and processing equipment can be re-optimized for the re-observation.

Argus has many advantages over a dish in terms of its ability to deal with radio frequency interference (RFI). The elements can be designed to have nulls at the horizon for rejection of terrestrial signals. The elements are on the ground, in contrast to the elevated feed of a dish, hence the signal strength of terrestrial signals is less. Small shield fences can be used around the elements or array if necessary for further rejection of terrestrial signals. The direction of any RFI signal is immediately known to Argus since one of its beams always points toward the RFI source, and it will be strongest in that beam. That beam will also provide a nearly noise-free version of the RFI which can be used to characterize and identify it and to blank it or cancel it in the rest of the beams. Diagnosis of RFI is immediate with no need to steer the telescope "off-source" to see if it goes away. If it is received in more than one beam, then it is known to be in a sidelobe and hence be RFI. Since each beam can be separately optimized, permanent nulls can be generated by each beam in the direction of known fixed RFI sources. Adaptive nulls can be generated in real time as needed to deal with transient RFI. Moving RFI sources such as aircraft or spacecraft can be immediately identified as such by their movement among the beams, and henceforth tracked, predicted, and removed from the telescope output. Argus can also identify RFI sources by their distance, since it can simultaneously focus itself at all distances. A modest 64-element Argus can resolve distances out to about 3 km, whereas an Arecibo-sized Argus can do so out to 500 km. These distances would allow discrimination against almost all man-made signals.

3. PREVIOUS WORK IN THIS FIELD

Several telescopes have been built and proposed which image a small portion of the sky over a narrow bandwidth, but none have approached the general case discussed here of the entire sky at a wide bandwidth. Daishido *et al.*[2,3] proposed a 4096-element horn array operating at 10 GHz, imaging a 9-degree field with a bandwidth of 20 MHz. The Clark Lake telescope[4] has 720 conical helix elements, operating over the range 15–125 MHz, imaging a 6 to 1.5-degree field with a bandwidth of 0.15–3 MHz. NRL[5] proposed a 20-element array of 3 m dishes, covering a 2.6-degree field at 2.7 and 8.1 GHz with bandwidths of 64 and 448 NHz. A conference was held in 1989 to discuss a Radio Schmidt telescope[6] with a "strawman" configuration of 100 12 m dishes, mapping a 1.5-degree field at 1500 MHz and other bands. Steinberg and co-workers[7,8] invented the term Radio Camera and has written extensively on the topic. His interest is in imaging aircraft in the vicinity of airports to provide much greater detail than is now provided by radars, such as the shape of the aircraft, whether the landing gear is down, etc. His plan is to use a single nondirectional transmitter and a large number of receiving elements placed essentially randomly wherever possible throughout the airport. An example of his images is in Fig. 3[8]. His camera work is contrasted from that discussed here in that it is "flash" photography rather than "available light" photography.

3.1. The Argus Mark I telescope

We have constructed and operated a prototype 8-element circular Argus array at 162 MHz[9]. Its parameters were chosen to match those of available radio stations so they could be used as known sources. The United States Weather Service operates many FM transmitters throughout the country, which continuously make voice announcements of weather conditions. There are hundreds on the same frequency, all at various and varying signal strengths and directions from any given location, making them ideal test signals for developing Argus beamforming techniques. Figure 4[9] shows the locations of the stations nearest our location in Columbus, Ohio. Our array was one wavelength in diameter, giving a theoretical beamwidth of about 90 degrees between nulls (see Fig. 5[9]). A bandwidth of 7 kHz was sampled for 1.7 ms, and then processed to form 36 simultaneous beams, equally spaced around the horizon. Each beam was averaged over 360 samples and

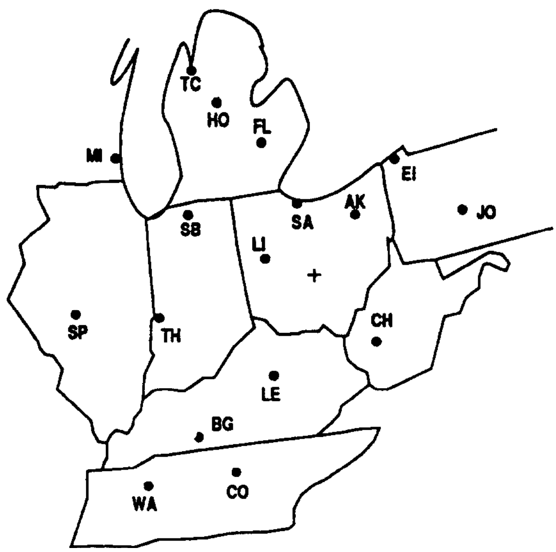

Fig. 4. Weather stations nearest Columbus, Ohio (designated by +).

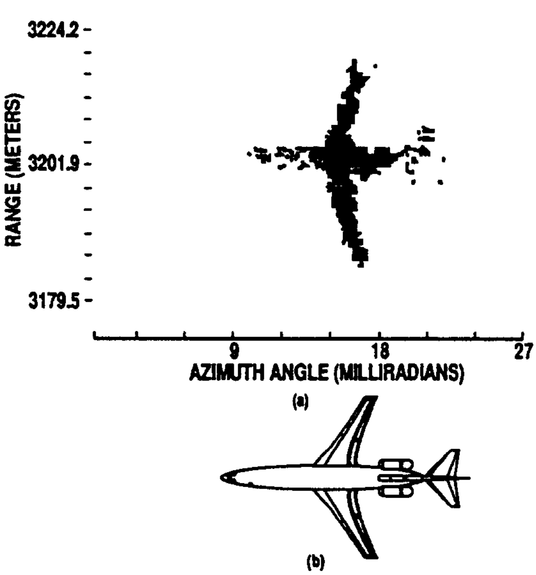

Fig. 3. Steinberg aircraft image.

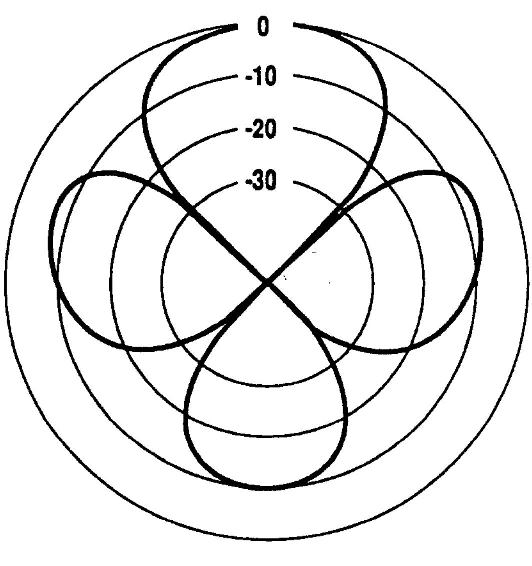

Fig. 5. Theoretical beamshape of the Argus Mark I array. The radial scale is in db.

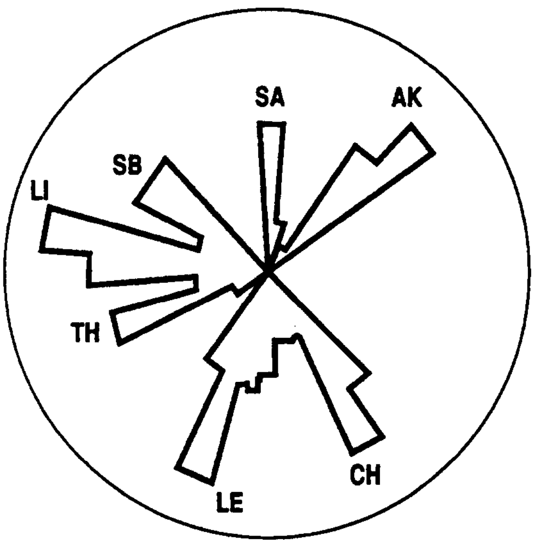

Fig. 6. Sample plot of received signals using the Argus Mark I array. The same scale is used as in Fig. 5.

then its resolution was enhanced with a deconvolution method analogous to CLEAN. Plots of the received signals were made every hour (an example is shown in Fig. 6[9]). Note that many signals on the same frequency are clearly resolved and that the resolution is much greater than would be expected from such a small array. By comparing the plots made over a long period of time, one can observe interesting effects as propagation changes to the various stations, and as thunderstorms move past the Argus location.

3.2. *Argus Mark II antenna element design*

The elements of a general-purpose Argus array should have hemispherical coverage, aimed straight up. They should have nulls at the horizon for rejection of terrestrial interference, have dual circular polarization, be broadband, and mass producible. The best candidates are from the helix family. A multifilar contrawound conical helix can achieve these requirements. Such an antenna element design can be visualized by combining the architecture of the helices shown in Figs 7 [10] and 8.

3.3. *Argus Mark II antenna array design*

The Argus array geometry should have approximately circular symmetry (for uniform beams), not have uniform spacings (to avoid grating lobes), and be spatially and frequency (element size) tapered from the center outward (to achieve frequency independence). Placing the elements logarithmically spaced along the arms of a multiarm logarithmic spiral (Fig. 9) achieves these requirements. To calibrate the array, small remote-controlled omnidirectional transmitters are placed inside and near the array. In the example shown, they are located at the center of the array and at the ends of each spiral arm.

3.4. *Argus computing architecture*

The performance of an Argus array (as measured by its number of elements, number of beams, and bandwidth) is limited primarily by its computing power. Hence this is the most critical portion of the design. Fortunately, available computing power is rapidly increasing and its price is falling. Thus the Argus capability can only improve with time.

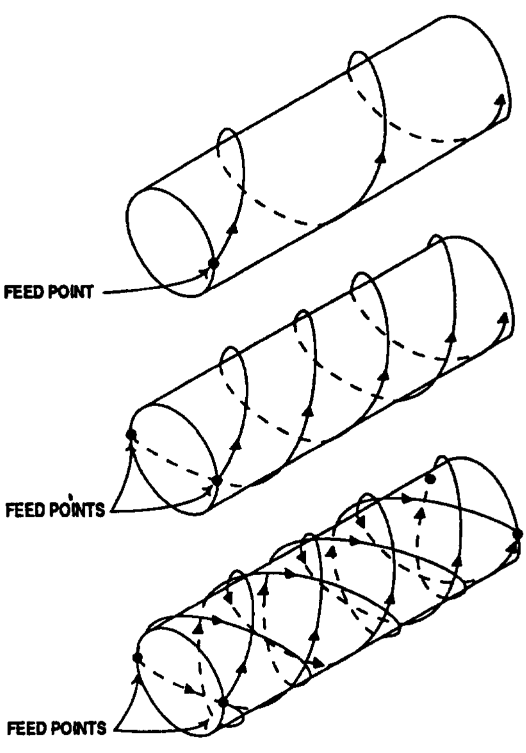

Fig. 7. Multifilar contrawound cylindrical helix.

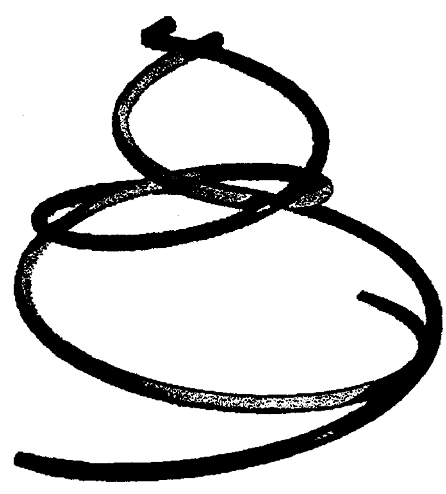

Fig. 8. Contrawound conical helix.

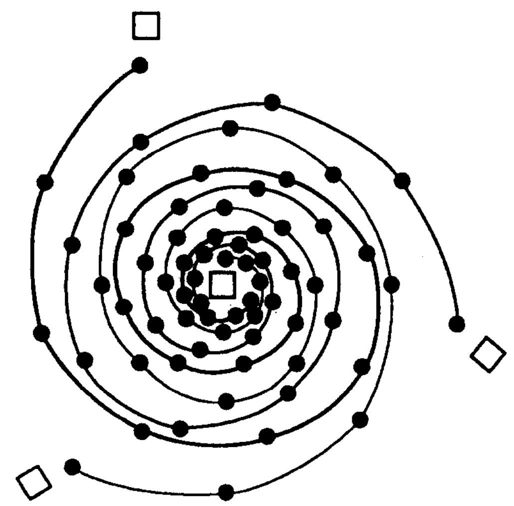

Fig. 9. Element locations along the arms of the multiarm logarithmic spiral. The open squares are calibration transmitters.

An appropriate computing architecture for Argus is shown in Fig. 10. A small computer is used at each of the n elements, which does all computations that can be done on the data coming from that element. A different set of m small computers is used to perform the calculations for each of the m beams. In general, m is much greater than n, since the array is sparse.

All the element and beam computers communicate via a token ring network. Such a network may be viewed as a circular railroad track. As the train passes each element, the element computer places its load of data into the boxcar reserved for it, and there are n boxcars. So by the time the train reaches the beam computers, it is fully loaded. Each of the m beam computers reads the data from all of the boxcars as they pass it. As soon as the train has passed a beam computer, that computer starts its dedicated task of calculating its beam, using a pipelined approach. Note that all of the beam computers will not (and need not) complete their calculations at the same time, and there could be a number of beam calculations proceeding through their pipelines at the same time. The only requirement is that their pipelines be able to keep accepting new data as fast as the trains arrive. There may in fact be many trains circling the track at the same time. All of the element and beam computers are dedicated, programmed, and optimized to do just one set of fixed calculations, so they can be made very fast. The element weightings used for beamforming are kept in lookup tables that are separate for each beam and can be rapidly changed as desired.

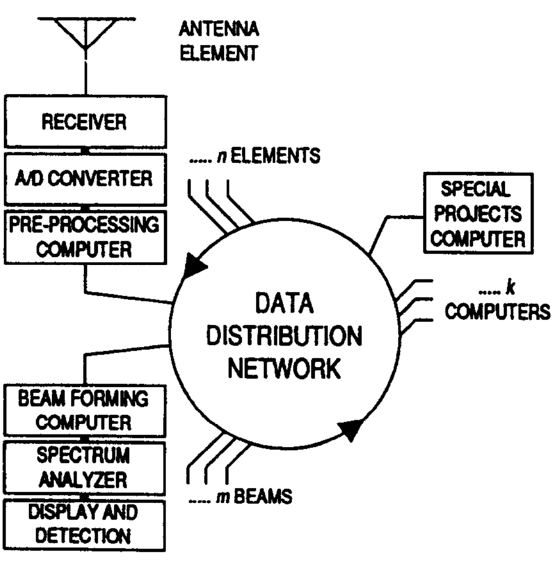

Fig. 10. Proposed Argus computing architecture.

In addition to the element and beam computers, there is another much smaller group of small computers attached to the network, each dedicated to some special project. Examples of such projects include monitoring a pulsar, tracking a spacecraft, lunar occultation, identifying RFI, calibrating the system, etc. Each special project computer is free to use whatever data is wishes and make whatever calculations it wishes, with no interference with the main computers or with each other. Hence there is no limit to the number of special projects that can occur simultaneously. One particularly important special project is to record all the element data in a compressed form for later analysis. This makes it possible to re-observe an event that occurred long ago, but was not recognized at the time. The special projects computers can also be attached to the worldwide Internet, making it possible for anyone anywhere to control them and to obtain data from them.

The computational power required for an Argus array of equivalent size to a large dish is greater than can be reasonably achieved today in the microwave region. But future developments in computing will make this possible, and today modest arrays at lower frequencies are possible. Argus is limited only by the available computing power.

3.5. *Argus output data*

One output of Argus is a real-time image of the whole radio sky. A circular CRT display, centered on the zenith (or transformed to the celestial pole if desired) indicates the directions of all signals being received. Signal strength is mapped into display intensity, and signal frequency is mapped into color (low frequencies toward the red, etc.). Signal polarization type and degree can be displayed with ellipses of varying axial ratio, orientation and diameter. The integration time can be arbitrarily long, so eventually the telescope would reach its classical resolution-limited condition. But for large signal-to-noise ratios, super-resolution techniques can be applied to achieve greater resolution. This would result in strong sources having small bright dots, whereas weaker ones would be more diffuse.

Such a display would show bright dots around the outer edge, representing terrestrial signals, and a line of dots along the synchronous satellite orbit (assuming their frequencies were included in the Argus coverage). Other spacecraft and all aircraft would appear as lines across the display of all colors. Aircraft can be detected by a number of modes, including their transponders, voice transmissions, reflection of distant terrestrial transmitters, and thermal radiation. Continuum radio sources would appear randomly scattered throughout the display, being generally white in color because of their broadband emissions.

Once an essentially noise-free image of the sky is obtained, a differential mode of operation can come into operation. In this mode, the telescope output displays only the differences between the "normal" sky and the current sky. This drastically reduces the amount of data to be displayed, and allows for immediate discovery of anything which has changed, appeared, or disappeared. Such discoveries could automatically be announced immediately by one of the special projects computers to everyone around the world who chose to receive such announcements, via an Internet newsgroup or mailing list.

4. PLANS FOR THE ARGUS MARK II TELESCOPE

Many technical problems remain to be solved before a large general-purpose Argus array can be constructed. The most limiting factor is the computational power required for the beamforming operations. We are now looking into optimized algorithms and architectures for this. Until a larger and more general prototype than the Mark I is built and operational experience gained, none of the design aspects can be finalized to the point where mass production can be used to create a truly useful instrument. One of the important early choices is the frequency range. The effective aperture of a hemispherical-coverage element is lambda squared over two pi. The cost of Argus is approximately proportional to its number of elements. Hence to obtain a large collecting area at minimum cost for an initial development array it is desirable to make lambda large (i.e. use relatively low radio frequencies). But if one goes too low the elements become large and difficult to construct, and at still lower frequencies (about 30 MHz) ionospheric effects begin to occur. There are a number of advantages for choosing the approximate range 50–500 MHz. Low-noise RF amplifiers are readily available, making it easily possible to achieve resolution limiting, and to apply super-resolution techniques for greater resolution. Continuum radio sources and pulsars are generally stronger in this band than at higher frequencies and hence more easily observable. Little SETI work has been done or planned here. Lunar and solar occultations can be studied. Interstellar scintillation can be mapped in detail by observing the variations of all the continuum sources, and moving images made of the interstellar medium. Solar system events such as Jovian emission and solar bursts studied. See National Radio Astronomy Observatory[11] for more discussion of this.

A second system design choice is system bandwidth, but that choice is straightforward. The system cost is directly proportional to bandwidth. The RF portions of the system can be designed for large bandwidth and will be, even though the computing portion of the system may not be able to process a bandwidth that great. Then the system bandwidth is chosen to be whatever the current computing system can handle, and is expanded with time.

The computing power required for an Argus beamforming system is approximately

$$2B(2K + 1)NL \text{ multiplications per second[12]}$$

where B is the system bandwidth in Hertz, K is the size of the interpolation filters, N is the number of elements, and L is the number of simultaneous beams formed.

For a large-scale system, with a resolution of 10′ of arc, 90-degree field of view, and a bandwidth of 1 MHz, about 500×10^{12} multiplications per second would be required. Of course, no single computer presently in existence can even approach 500 million million multiplications per second. This does not mean that such a system is impossible, but it does mean that conventional single processor serial computing is unsuitable for implementing it. Instead, specially designed computing hardware will be necessary for a large-scale radio camera.

Currently available technology could be used to implement a specialized beamforming processor capable of computing at this rate. Dedicated integrated circuits exist that can multiply at much higher rates than most general-purpose computers. Depending on the required precision, the multiplication circuitry for this system would cost between $162 million and $474 million today. Thus, such a system is technically feasible.

However, this cost is probably unacceptably high for a present-day radio camera. Actual implementation of a radio camera telescope on this scale will therefore have to wait for the cost of computing circuitry to fall. This leads to consideration of a more modest example, which would provide for development of designs and algorithms for larger systems, in anticipation of declining trends in computer costs.

A prototype Argus with 64 elements, a resolution of 1 degree, and a bandwidth of 1 kHz will require approximately 140 million multiplications per second. This is well within the capabilities of current computer systems, indicating that a functional prototype could be implemented without custom designed hardware to perform the imaging. Although such a prototype would have limited resolution, it would be

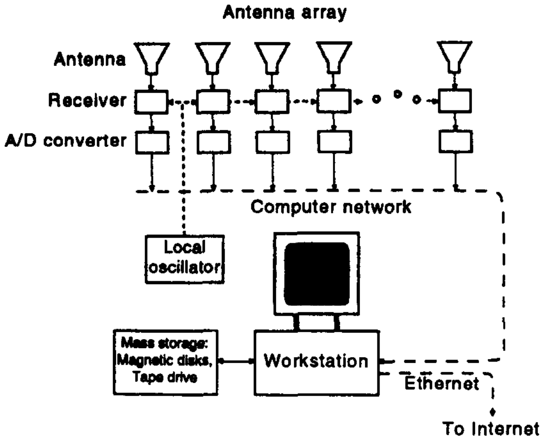

Fig. 11. Possible configuration of a prototype radio camera system.

a versatile experimental instrument. It would allow evaluation of many different geometries and many different implementations of the beamforming algorithms. It would allow various calibration schemes to be tested. Experimentation would not be limited by the computer power within the system, because the data collected could easily be transferred to different computers. The experience in radio camera technology which would be gained from this system would be invaluable when construction of larger scale radio cameras becomes economically feasible.

One possible design for a prototype radio camera is shown in Fig. 11 [12]. Each antenna element has its own receiver and analog-to-digital (A/D) converter. In order to preserve phase information across the array, the receivers share common local oscillator (LO) signals. The digital data is collected by a computer workstation, which includes a high resolution monitor for displaying the images, and sufficient mass storage to hold data for many images. The workstation can also be connected via a computer network to the Internet. Note that, although the instantaneous bandwidth of the beamformer is relatively small, use of a tunable LO means that the system could be used for observations over a wide frequency range. Thus, observations made at any one time are limited by the 1 kHz bandwidth of the beamformer, but the receivers may be retuned quickly to any 1 kHz interval within the total bandwidth of the antennas and analog portions of the receivers.

A general-purpose computer has been proposed for the prototype, instead of a computer specialized to the beamforming computations, in order to minimize the expense and maximize the system's flexibility as an experimental instrument. Although a specialized and custom-designed processor could certainly perform the beamforming more efficiently, it would be more expensive and add considerable complexity and risk to the prototype design. It would also lack the flexibility necessary to experiment with novel algorithms for imaging. The general-purpose computer will be slower, but will be economical and it will provide a laboratory for testing beamforming technology. The lessons learned from this prototype will provide the experience necessary to implement a large scale working system, complete with specialized processors implementing algorithms proven on the prototype.

The network connection to the prototype will have other advantages. By connecting the computer to the Internet, researchers all over the world may have access to the data and images collected. Anybody who wishes can use the prototype, either to perform their own experiments in beamforming or for examining the images. It will also be possible to experiment with beamforming algorithms on novel computer architectures, using data collected with the prototype. Because the radio camera array has no moving parts, there will be no competition among users to point the telescope in any particular direction and all observation programs can share the facility.

Simulations performed at the Ohio State University have shown that 64 elements will be sufficient to allow low sidelobe levels for the prototype system.

5. THE BIG PICTURE

It is commonly believed that humankind is basically aware of everything that goes on around us in the universe. This may seem logical, given all the telescopes in operation around the earth. But the fact is that all telescopes combined see only a tiny fraction of the universe and frequency spectrum at any one time, and as larger telescopes are built, they see even less. In our quest for ever greater detail about the trees, we are ignoring the forest. There are undoubtedly transient events occurring all the time of which we are unaware; previous examples include pulsars and supernovae. We have no global view of our electromagnetic environment, encompassing both natural and manmade signals. We have an obligation to open our eyes widely and be aware of our surroundings so we can learn more about the universe and understand the big picture. Argus will make this possible.

One fully implemented Argus array can simultaneously carry out all the observations now being done by other comparable radiotelescopes, not only for astronomy but for all scientific and commercial monitoring of the electromagnetic environment. The universality and versatility of the Argus approach, together with its riding the crest of mass-production computing, make it inevitable at some time in our future.

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