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A CONTINUOUS APERTURE APPROACH TO THE VLA

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The Whitford Committee report, calling for the design of the VLA, specified a large array with low sidelobe levels. Low sidelobe levels are attainable only with difficulty with the designs now envisioned. The design of the array for use at 10" resolution has been predicted on a 5' field of view, outside of which strong, grating-type sidelobes may occur. This area is one fifth to one tenth of the area of the element beam, so that it would appear necessary to employ five to ten rearrangements of the elements to achieve a 10", low sidelobe beam. Thus, the project of synthesizing such a beam might be expected to occupy many hours of valuable observing time and to last more than a year before completion.

In view of this difficulty, I shall consider some continuous, or essentially continuous, aperture designs which do not suffer from this sidelobe problem to anywhere near the degree that the thirty-odd element grating supersynthesizer does.

The desired sensitivity of the array is achieved with a product of effective area and the square root of observing time of about 30,000 m^2 $(min)^{1/2}$ (.001 flux unit RMS noise for a point source, with 10 Mc/s bandwidth and 100° receivers). In order to satisfy this requirement, and still be able to map a sensible portion of the sky, multiple beams are required. For a number of reasons (ease of construction of correlators versus that of beam formers, ability for <u>post facto</u> position calibration, ease of handling quasisinusoidal outputs, etc.), it appears easiest to employ correlators whose output is used to reconstruct the beams in a digital computer, to achieve this multi-beaming. Therefore, I shall consider the array to be subdivided into a few elements, each of which is internally connected at RF or IF and has only one output which is correlated with the outputs of the other elements.

A. The Helix Array

The effective area of a small, 11 cm helix would be at most about .005 m^2. With any reasonable integration time this requires about half a million helices in order to satisfy the sensitivity criterion. Each helix must have a phase rotator (i.e., mechanical parts for rotating the helix, plus a rotary joint), sufficient waveguide to reach to the next helix (coaxial cable is probably too lossy, though the cost of the guide could be traded off against the cost of more preamplifiers which would be required), and a very good directional coupler to couple the helix into the line (a VSWR as low as 1.005 might be required). It seems likely that this complex machinery would make this design considerably more expensive than any of the others considered.

B. The Cylindrical Paraboloid T

The sensitivity requirement may be met without tracking ability if each arm of the T is made about 15 feet wide. Therefore, our picture of this array is a T, with arms a mile long by fifteen feet wide. Many of the costs of this cross are the same as those of the kilodish cross discussed below, so they will not be considered in detail here. The main difference between the two will be in the feed system. The cylindrical paraboloid T must have feeds along the focal line spaced more often than once per wavelength. There would thus be about 50,000 individual feeds, each with its own phasing mechanism. A considerable part of the problem is the construction of directional couplers for the combination of feeds before the preamplifiers. Because of this great number of feeds, it seems to me extremly likely that the cost of the cylindrical paraboloid T will be greater than that of the kilodish cross described below.

C. The Kilodish Cross

If, rather than making the continuous aperture into a physically continuous cylindrical paraboloid, it is divided into round paraboloidal antennas, then the feed problem is greatly simplified, as the feeds then need to be spaced only once every fifteen feet. In order to avoid the problem of "shadowing," it is possible to follow a suggestion of Christianson, and place the short arm of the T north-south, and then remove every second element from this short arm and place it on the far side of the long arm, resulting in an element spacing in the north-south arm twice that in the east-west arm so that there is no shadowing until 30° elevation angle. This configuration is thus a cross with equal arms, but with the element density in the north-south arm as half that in the east-west arm.

Each of the arms would be subdivided into sub-arrays, consisting of sixteen or thirty-two elements each (a power of two was chosen because of the ease of connecting the antennas in pairs). Each sub-array would be phased to produce an instantaneous fan beam. The outputs from each sub-array would then be correlated with that of every other sub-array and the reconstruction of the actual brightness distribution done by computer. If the elements on the east-west arm are connected in groups of thirty-two, and those on the north-south arm in groups of sixteen, there would be about forty element, approximately the same number as in the case of the large dish array, so that the computer requirements are about the same in the two cases.

I shall consider below a fairly detailed design, with some estimate of the cost of a kilodish cross.

The cost of the basic antenna, 15' diameter, with backup structure, but no mounting or feed support, is about .... $ 3,200

A rough calculation of the forces involved in survival in 100 MPH wind indicates that the dishes can be supported on a two foot diameter reinforced concrete rod embedded fifteen feet in the ground (assumed strength 1000 lbs/ft^2; it may be necessary to make the rod slightly larger just at ground level)............................ 500

A fairly simple piece of steel webbing is needed to hold the elevation bearing. Again a simple webbing is needed to hold the elevation axle to the dish backup structure. The strengths required in these members is only slightly greater than that in automobile rear ends. Including the main bull gear, the steel parts of the mounting should cost in the neighborhood of 600

The simplest sort of drive system is to have the elevation drive connected to a stepping motor driven by the computer, which keeps track of the number of pulses sent in, and thus requires no position read-out. The torque in a forty MPH wind might be as much as 5,000 ft-lbs; the largest stepping motor manufactured by Slo-Syn has an output of about 20 ft-lbs/sec, so the slewing speed of an antenna driven by this motor is only about 1 1/2° per minute, assuming that the overall efficiency of the gear train is 10%. This may be unacceptable, in which case a servo system, servoing to a stepping motor, or else a position encoder, must be installed. If the main drive motor is an 1800 RPM motor, and the slew speed is 20° per minute, then the beam width is about 100 revolutions of the drive motor. This being the case, I believe an adequate servo system could be constructured of a cam and microswitch, to turn on the drive motor whenever it gets more than about five resolutions out of step with the stepping motor. The entire system, including two reducing worms and the spur gear to mesh with the main bull gear should cost in the neighborhood of 1,500

Estimated cost of feed support legs and a <u>small</u> temperature controlled focus box	1,200
Paramp front end	2,000
Mixer and IF first amplifier, including power supply	1,000
Un-phase-controlled klystron synchronizer a-la-Cal Tech, to provide the local oscillator and paramp pump, including the doubler to provide the pump power	5,000
Cabling, feed, connectors, IF transformer for coupling antenna to sub-array	700
Total cost per antenna	$15,900

or $15.9 M for the lot.

In addition there are some costs which vary as the number of sub-arrays. Firstly, there is the cost of grading. The sub-array should be level over its length of 480 feet. The cost depends greatly on the terrain. But it seems likely that the average excavation involves moving perhaps a thousand yards of earth. A wild guess at the cost of preparing the earth 5,000

Cost of cables running to each element, if the IF's from the antennas are combined as soon as possible	5,000
Booster amplifiers and equalizers for sending the output back to a central location	2,000
Cost of a takeoff on the master LO system. I would envision this takeoff to be phase locked...	10,000
Internal delay system (north-south arm only) with switching network. Ability to rotate phase to steer beam	8,000
Fixed, bias delays for east-west sub-arrays plus shorter internal delays for tracking a source through the element beam	5,000
Delay lines for the sub-array (north-south arm only)	25,000
<u>Total additional cost of the sub-arrays</u>	$ 27,000 E-W
	$ 60,000 N-S

For a total cost of $1.8 M.

There is then a number of costs which occur once per system. These are listed below:

Cable to connect the sub-arrays	1,000,000

Computer to analyze correlator outputs	800,000
Correlators and associated circuitry	200,000
Controls and checkpoint provisions	300,000
Systems design	1,000,000
Initial phasing of 1000 antennas	1,000,000
Buildings and improvements in the site.........	1,000,000
Total cost of a minimum array	$22,500,000

In addition, for the convenience and reliability of operating the array, several improvements beyond the bare minimum are extremely desirable. First of these is a separate AGC on the output of each element. With the associated extra IF amplifiers, this would probably amount to the order of $2000 per element. The second improvement badly needed is an alarm system, which would ring a bell at the telescope whenever one of several signals exceeds its limit. This might cost of the order of $1000 per element, these two together increasing the cost of the array by 3,000,000

The array would be greatly increased in usefulness if it could be made polarization sensitive. Probably the cheapest way to do this is to spend the design money necessary to construct a good rotary joint so that the horn may be rotated without rotating the receiver. The requirements on a horn rotator are not as great with interferometer-type receivers as with single dish receivers, as the polarized beam can be produced by crossing the horns, almost independent of the joint characteristics. Even this system, with its positioning motor and control wiring would probably run about $2,000 per element. In addition, one might wish to use a more sophisticated feed to eliminate or reduce the cross polarized sidelobes of the antennas. Thus the total cost might be 2,500,000

Contingency @ 20%	6,000,000
<u>Total cost of the array</u>	$34,000,000

Expanding the array for more resolution is very expensive. The arms may be extended indefinitely at a cost of about $8 million per mile, which is prohibitive for resolution as small as 1". A 1" by 2° fan beam, however, can be constructed by simply adding 5 large (about 100') dishes to one end of the E-W arm, at appropriate distances.

To summarize, the kilodish cross has the following advantages:

1. Very low sidelobe levels. The grating sidelobes are spaced 1.2° and, although only moderately discriminated against by the element beam, they are virtually eliminated by the delay pattern.

2. Very high information rate. This cross could look at 50 sources per day as contrasted with the five per day of the tracking array.

To offset these, it has the following disadvantages:

1. It cannot be expanded to give a narrower pencil beam except at great monetary cost.
2. It is slightly more difficult than the tracking array to compact to give an array with higher willing factor for use on low brightness objects.
3. Maintenance costs will be much higher than for a 30-40 element system. Not only is each of 1000 elements nearly as complicated as each of the 40 but the interconnection equipment must be rephased on occasion to preserve a clean sub-array beam.
5. Because of the greater number of elements, they cannot be monitored as precisely.
6. Changing the front ends of the receivers would be an enormous job, so that changing the frequency of the array, or taking advantage of advances in the state of the art would be enormously expensive.
7. Since it is impractical to build such small antennas as Cassegrains, the system noise temperature would necessarily be perhaps 20° higher than for the large dish array.

The various realms of astronomical research are examined below to see whether the kilodish cross or the tracking array is more effective for their problems.

A. The Cosmological Problem

The matters of interest are almost entirely statistical. Therefore, sidelobes, so long as they are a minute of arc or so out and are well known, are no bother. They can be allowed for in a statistical sense in the diagrams of the log N-log S plot and in the histograms of size for various flux values. These investigations may be carried out without even performing a full synthesis with the tracking array, but merely accumulating sufficient observing time to reach the desired flux level. On the other hand, a 1" fan or pencil beam might be very advantageous.

B. Small Extragalactic Sources

For these, the five minute sidelobeless field of view which we have set for ourselves is sufficient. The probability of a confusing source appearing within the outline of a 1' source, with fifteen or twenty side lobes of grating intensity within the element beam, is $\sim$10% at .02 flux units.

C. Large Extragalactic Sources

The problem of confusion might be very high, in the case of a large source of low surface brightness, such as, for instance searching for fine structure in Fornax A or in the halo of Virgo A.

D. Normal galaxies require very high sensitivity, a very small beam, and very low grating lobes. The requirements are just barely met by the kilodish cross, but the tracking array with several moves would satisfy them nicely.

E. Galactic sources are probably all sufficiently big and bright to be seen in the 10" beam of the kilodish cross; however many of them would also be resolved in a 30" beam that the large dish array would be capable of producing free from sidelobes. In the case of the galactic sources, because of their close proximity, the prime consideration is freedom from sidelobes.

F. Hydrogen line work would also require freedom from sidelobes and also a larger filling factor. The kilodish cross would probably be slightly too insensitive unless some of its outlying elements were moved nearer the center. It would also be very expensive to install 21 cm front ends in the kilodish cross. OH work would probably stress resolution again, and sidelobes become of much less interest, with the possible exception of the galactic center region.

Of these considerations, A, B, and F favor the tracking array because of its flexibility in changing frequency and configuration, especially its ability to extend itself to obtain higher resolution. D, C, and E favor the kilodish cross, as for these experiments a low sidelobe level is of great importance. The choice between these two basic concepts of the VLA is essentially that of weighting the relative importance of these experimental themes. It is my feeling that the most important experiments which can be performed with this instrument are the extragalactic and cosmological ones, and on this evaluation I feel that the tracking array is superior to the kilodish cross.

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