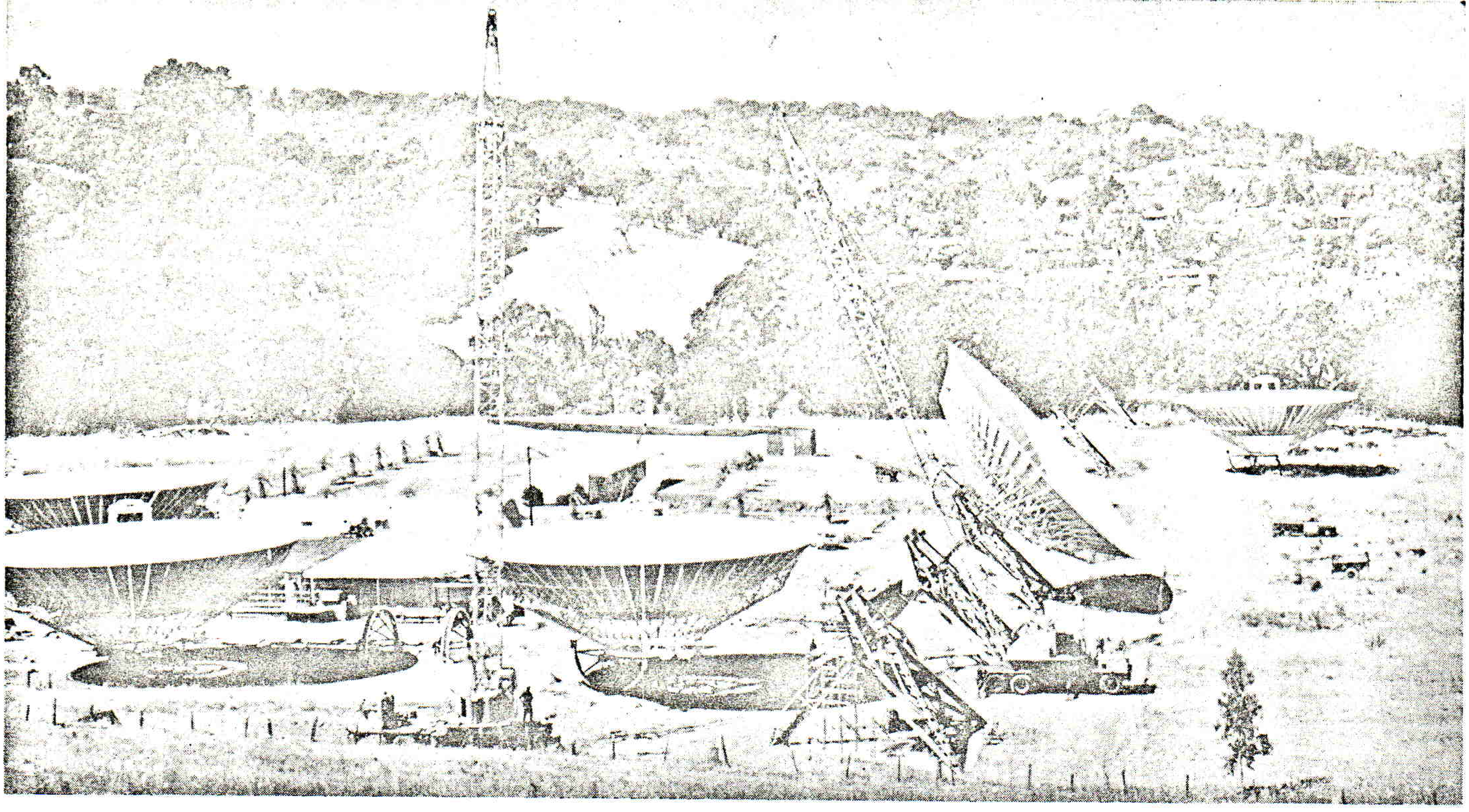


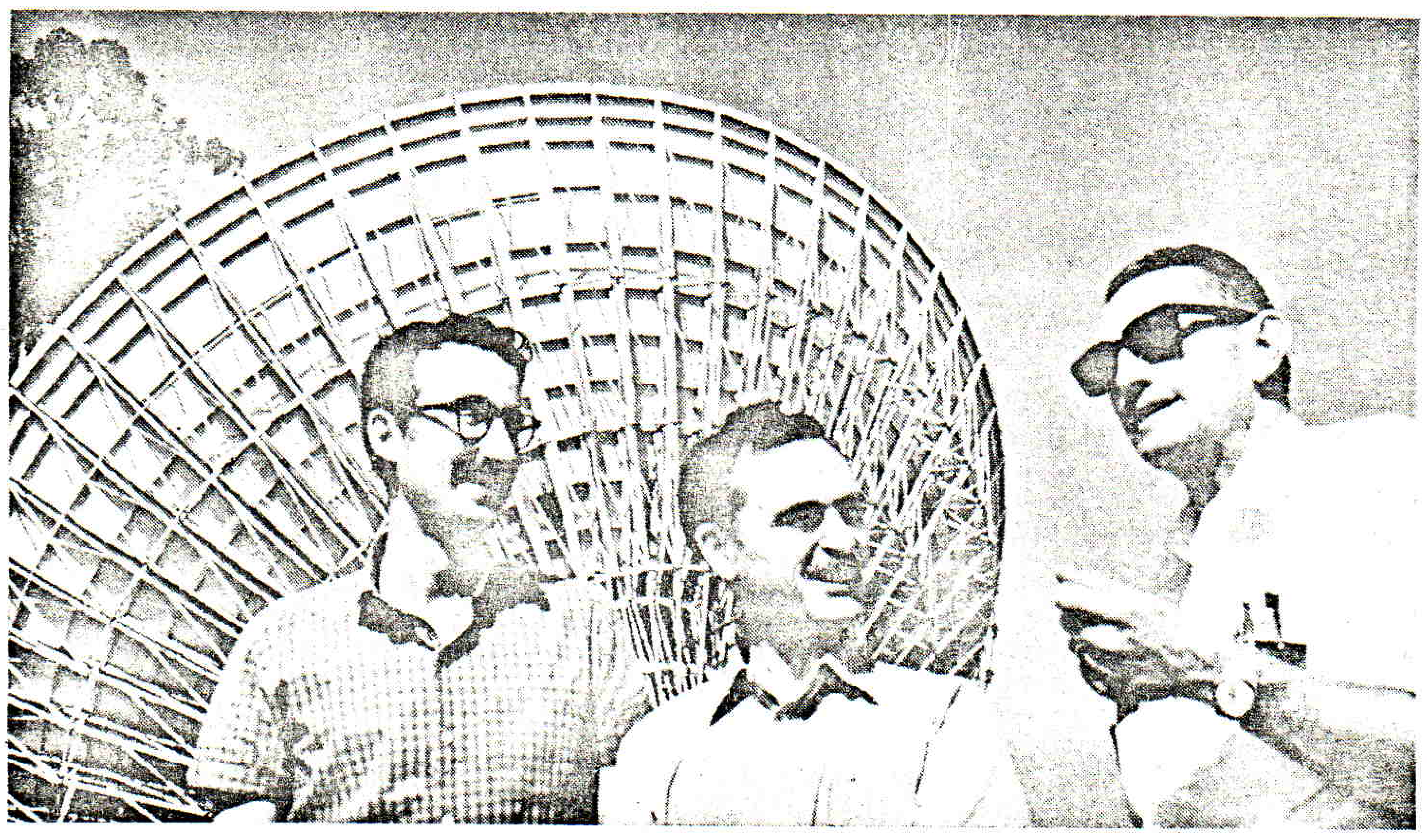
A view from the east showing all five antennas of the Stanford array in various stages of construction. The dish below center is about to be lifted (off a giant sawhorse) by the boom cranes and placed on the No. 1 tripod base (right foreground). The No. 3 dish is already in place and pointing at the north celestial pole. Beyond it are the tripods for Nos. 7 and 10 (see chart opposite). From center to left are 10-foot dishes on two arms of the solar-cross interferometer.

Stanford's High-Resolution Radio Interferometer

R. N. Bracewell, R. S. Colvin, K. M. Price, and A. R. Thompson

Radio Astronomy Institute, Stanford University

SOME YEARS AGO it became apparent that arrays of small radio telescopes have features complementary to those of large single paraboloids.* As far back as 1961 here at Stanford University, we built an array of equatorially mounted 10-foot dishes for work on the sun. It was found that significant results could also be obtained on galactic and extragalactic radio sources, but the modest collecting area of this array (a cross of 32 dishes each 10 feet in diameter) limited us to a handful of the known radio sources.



Participants in the interferometer project included (left to right) authors Price and Bracewell and W. S. Scott, Stanford Linear Accelerator Center.

A few years ago we began planning for a larger instrument, confident that our experience in achieving resolution of less than a minute of arc with the first array could result in 20-second-of-arc resolution with a larger one. By going to a relatively short wavelength of 2.8 centimeters (10,690 megahertz), and by using a *minimum-redundancy* array, we could avoid moving large antennas on rails yet obtain a fast interferometer with resolution up to an order of magnitude better than that of most large paraboloids. We should be able to observe at centimeter wavelengths the sources in the extensive catalogues that have been compiled by existing survey instruments, such as the Cambridge 3C interferometer.

This should all be possible with five 60-foot paraboloids, equatorially mounted and spaced as explained below along a 675-foot east-west base line (corresponding to 7,336 wavelengths). They would form a minimum-redundancy interferometer which, when pointed at the meridian, would have a very narrow response peak in hour angle, while resolution in declination would be obtained by observing over a wide range of hour angles, a technique known as earth-rotation synthesis. This takes advantage of the rotation of the earth to change the position angle of the

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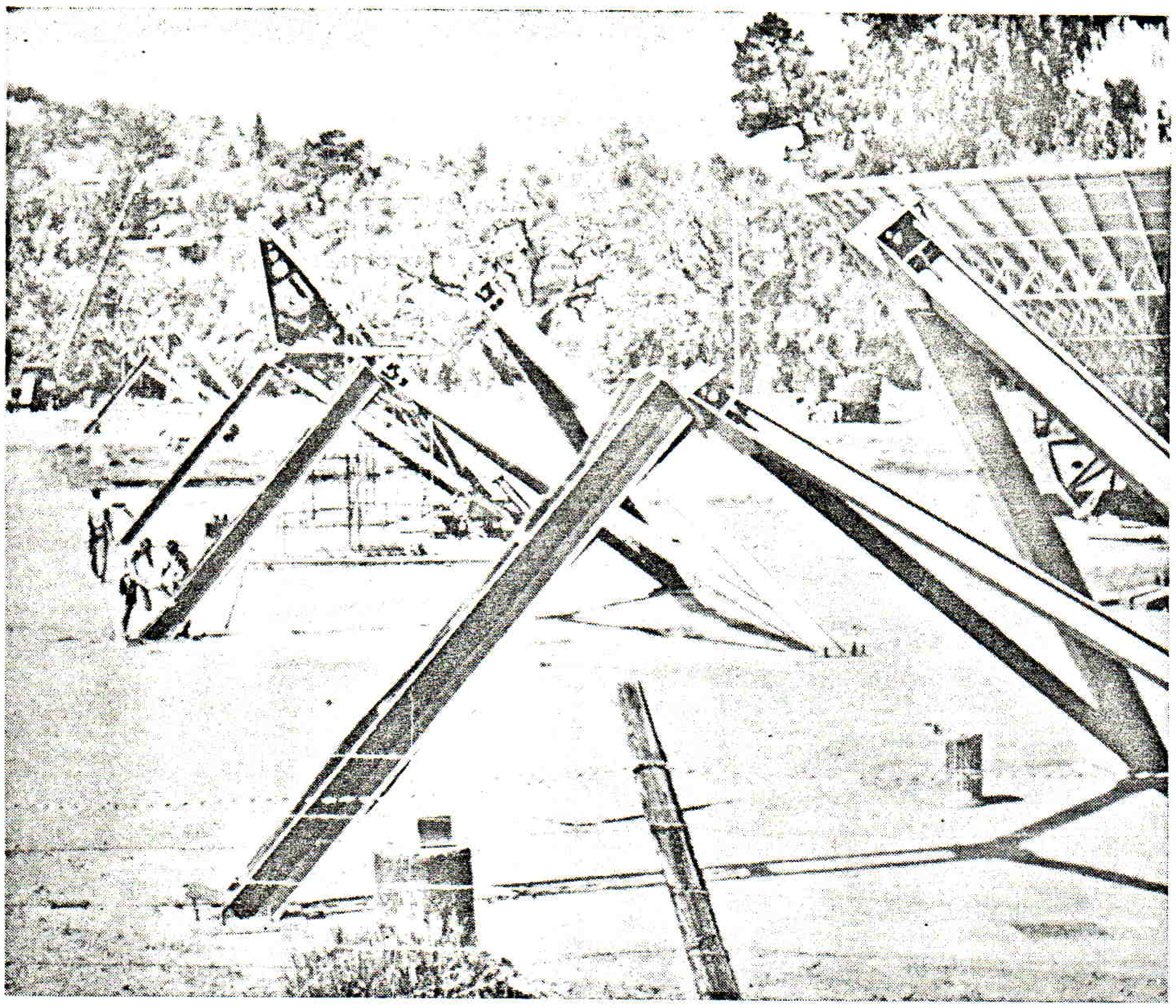
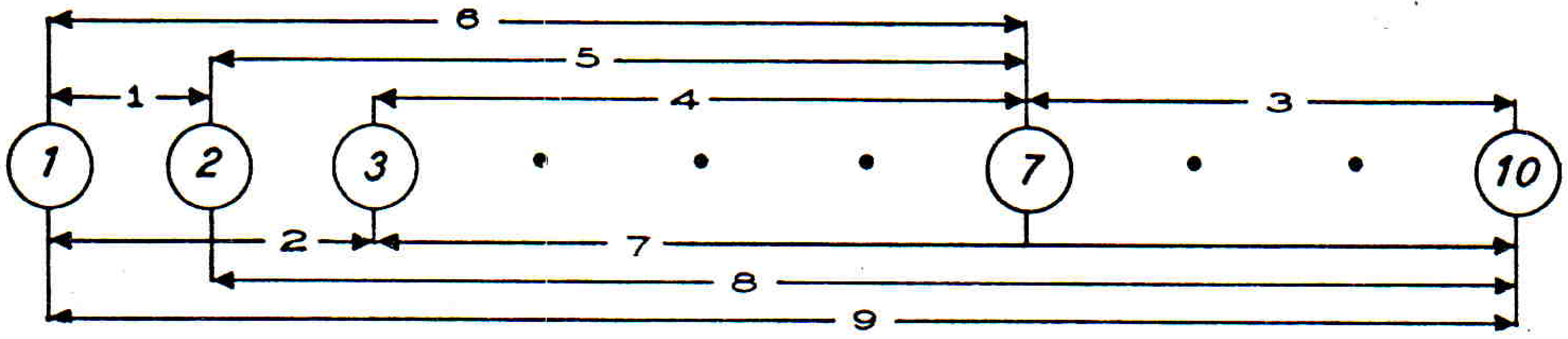
*For example, the Bonn 100-meter and the Illinois 120-foot dishes, described in Sky and Telescope for December, 1970, page 339, and March, 1971, page 132.



The polar axle and hour wheel of each antenna will slip into the gap formed by the double legs on the north (right) side of its tripod. Two men at the left edge of this picture are installing the baseplate for the polar-alignment theodolite on the No. 2 antenna (see diagram on page 4).

beam with respect to the source. Such a versatile instrument would be very useful for galactic, extragalactic, planetary, lunar and solar work, but it would require a computer and also costly phase-stable electronics.

Much of the development has been done "in house," beginning with panel design for a 60-foot reflector in 1965. Since then the Air Force Office of Scientific Research has funded hardware design and construction, while the National Science Foundation has supported development of the microwave front ends, the computer, and the central electronics package. In all, these two agencies have provided somewhat less than two million dollars for the entire installation, which has taken about 4½ years to build.



The ways of connecting the antennas in pairs for minimum redundancy.

MINIMUM REDUNDANCY

An array of antennas can be thought of as having a beam that maps out a distant source of radiation by scanning its different parts. We can also understand what the array is doing by thinking of the source as producing a complicated radiation field in the neighborhood of the observer. By exploring the field with our antennas, we can reconstruct the image of the source.

The first way of thinking corresponds to what happens when a single paraboloid is pointed to different parts of a source long enough to map out its characteristics. The beam-width can be reduced by increasing the diameter of the dish. Similarly, in an interferometer array the beam-width depends on the maximum dimension, but it is convenient to think of the array as composed of pairs of antennas with various spacings.

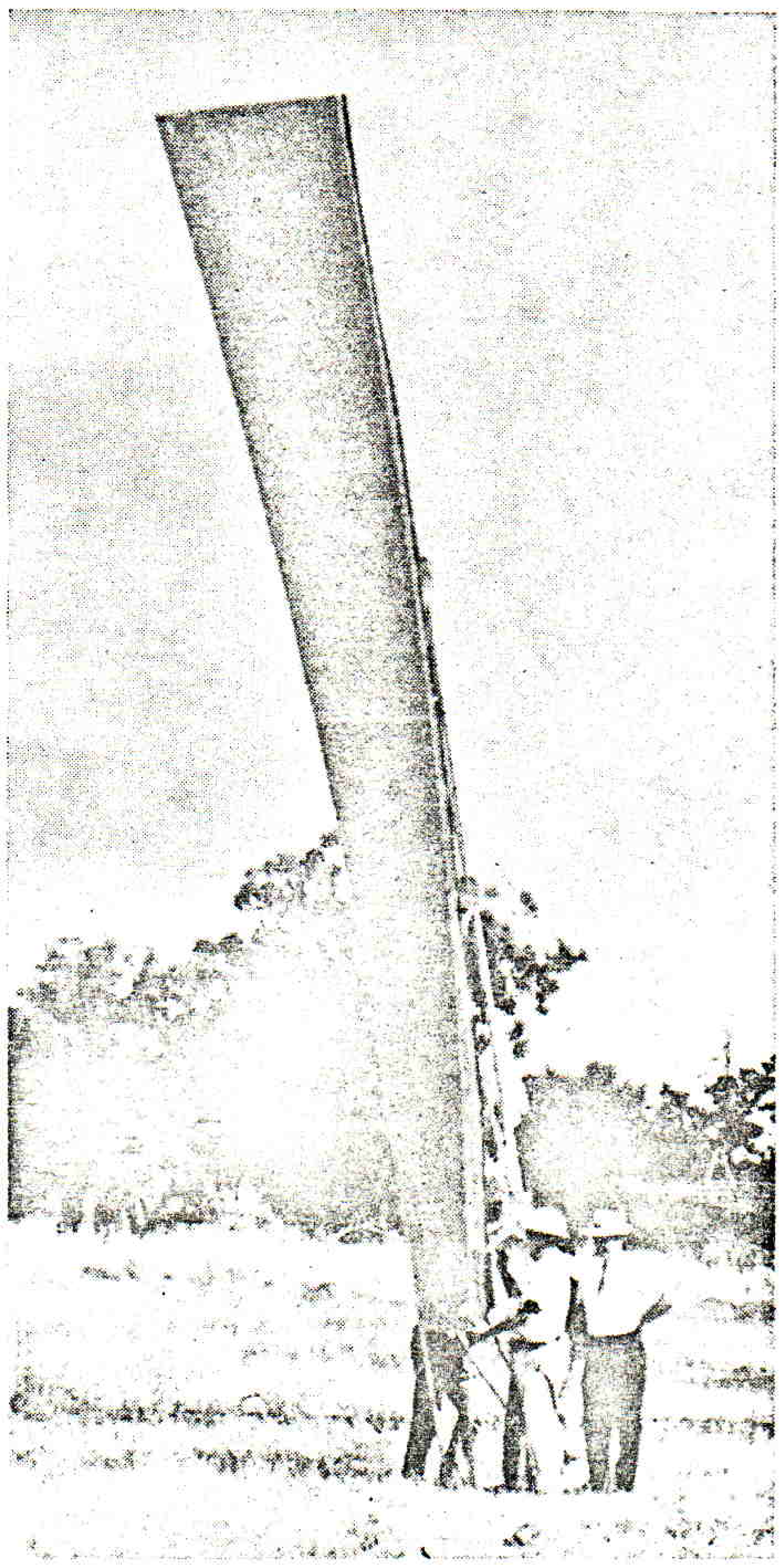
In the usual fixed array, the antennas are equally spaced along a base line, but such an array is highly redundant, since many of the separations are provided in more than one way. For example, the distance between antennas 1 and 3 is the same as between 2 and 4. Yet the maximum separation can be produced in one way only.

When the data are properly processed, we need only one pair of antennas for each separation, and to reduce the redundancy some elements of the uniformly spaced array can be left out. The omission either saves money and maintenance or permits the use of larger antennas to increase the overall instrument sensitivity.

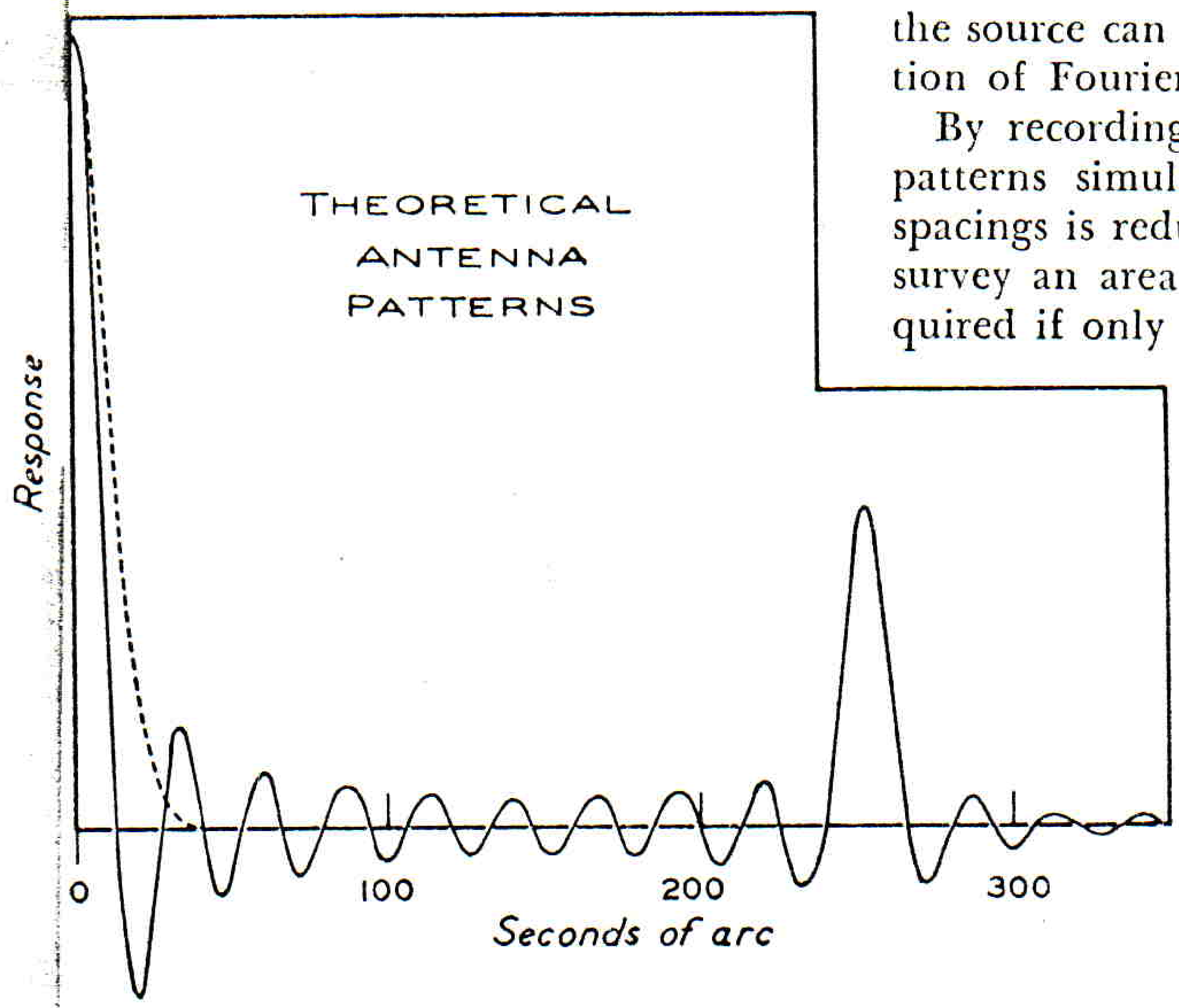
To visualize our array, first consider 10 paraboloids equally spaced 75 feet apart on an east-west line, and then remove the 4th, 5th, 6th, 8th, and 9th. The chart at left below shows how the remaining five paraboloids can be paired to produce every separation from one unit of 75 feet up to nine units. All the information that can be extracted from an electromagnetic field by the full 10-antenna array can be found by this five-element array. Only for the single-unit separation is there redundancy (1-2 and 2-3), which cannot be avoided with this number of antennas.

However, if this array is connected up by simply adding the five signals received, it will have a poor reception pattern, with strong side lobes. Therefore, we operate the 10 different antenna pairs as separate two-element interferometers and record their outputs simultaneously but separately. The signals received at each antenna are first divided four ways and combined in 10 voltage multipliers in such a way as to produce 10 two-element interferometer responses. These are sinusoidal and analogous to the sinusoidal optical interference fringes produced by a two-pinhole Young's interferometer.

Because of the earth's rotation, the output from every multiplier rises and falls with a period of about two to 20 seconds or more, depending on the separation of



Some four years ago, C. C. Lee, R. N. Bracewell, and a sheet-metal expert completed this first dish panel. Set horizontally, it was tested by loading with sandbags until it broke.

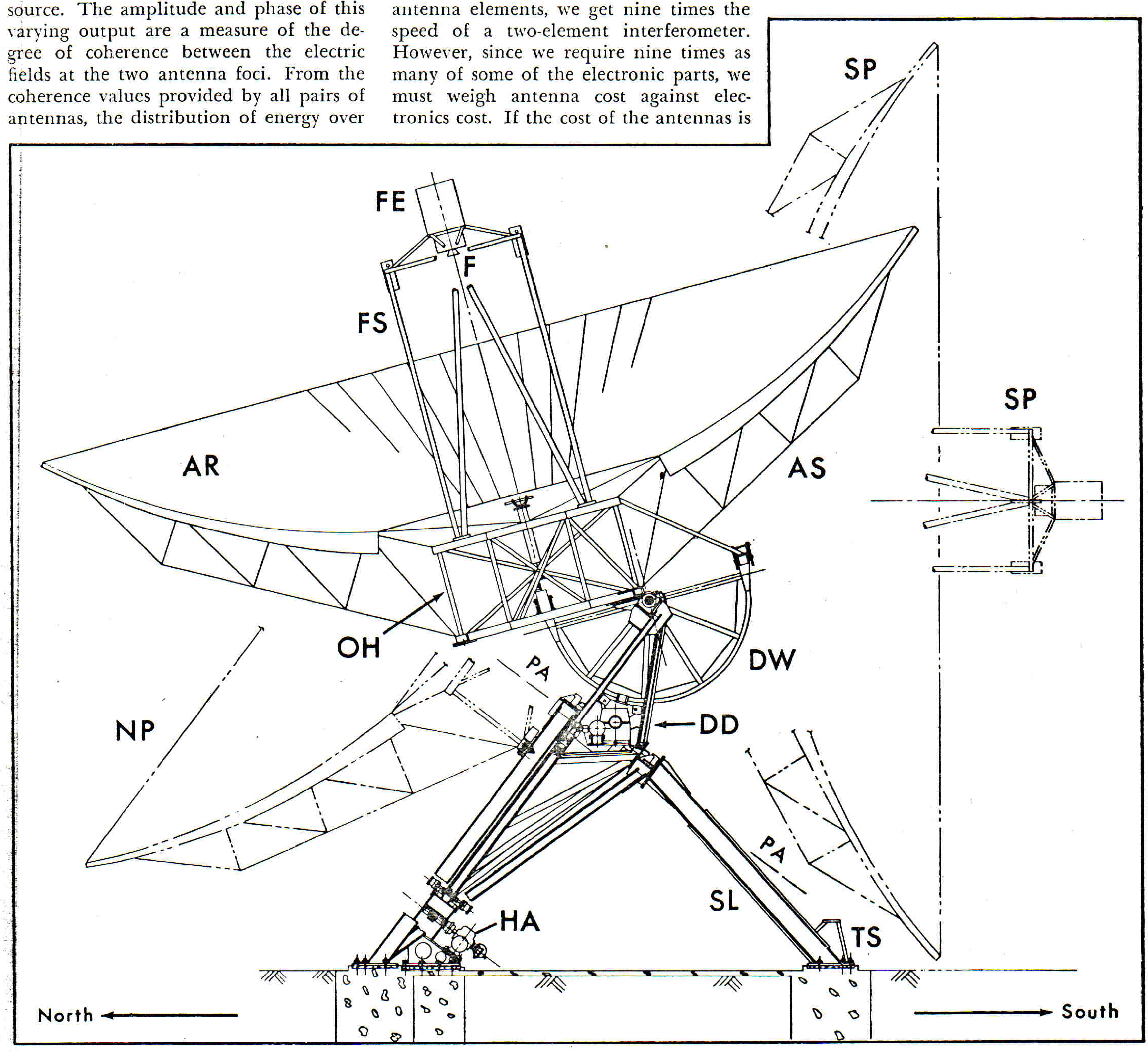


In the array's antenna pattern, the "grating response" peak is some 253 seconds of arc from the main beam. The oscillatory side lobes can be eliminated by combining the fringes from the nine channels with suitable weighting coefficients, resulting in the dashed curve.

the antennas and on the position of the source. The amplitude and phase of this varying output are a measure of the degree of coherence between the electric fields at the two antenna foci. From the coherence values provided by all pairs of antennas, the distribution of energy over the source can be computed — an application of Fourier transforms.

By recording nine independent fringe patterns simultaneously (one of the 10 spacings is redundant), the time taken to survey an area is only one-ninth that required if only one pair of antennas were used. With 2½ times the number of antenna elements, we get nine times the speed of a two-element interferometer. However, since we require nine times as many of some of the electronic parts, we must weigh antenna cost against electronics cost. If the cost of the antennas is significantly greater than that of the electronics, the advantage is clear, especially for antennas more costly than ours.

The pattern of the array is shown in the graph, and we see that there is a main beam 17 seconds of arc wide. In addition, a response is seen 4.2 minutes of arc away, which results from the fact that the array is made up of discrete antennas, the collecting surface not being continuous as in a single large paraboloid. This feature corresponds to the 1st-order fringe of an optical diffraction grating and for this reason is known as a grating response. The beam-width of the single antennas, approximately seven minutes of arc, sets a limit to the field of view, but in practice we are generally limited to 4.2 minutes, because otherwise main beam and grating lobe responses overlap and interpretation of the observing record is complicated.



A scale drawing of a 60-foot reflector with the following principal parts labeled: *AR*, aluminum reflector; *AS*, aluminum structure; *DD*, declination drive; *DW*, declination wheel (steel); *F*, focus; *FE*, front-end box; *FS*, feed support (steel); *HA*, hour-angle drive; *NP*, north-pole-pointing (stow) position; *OH*, octagonal hub (steel); *PA*, polar axis; *SP*, service position; *SL*, south leg; *TS*, theodolite stand (for polar alignment). Stanford Radio Astronomy Institute diagram.

EQUIVALENCE TO ANALOGUE IMAGES

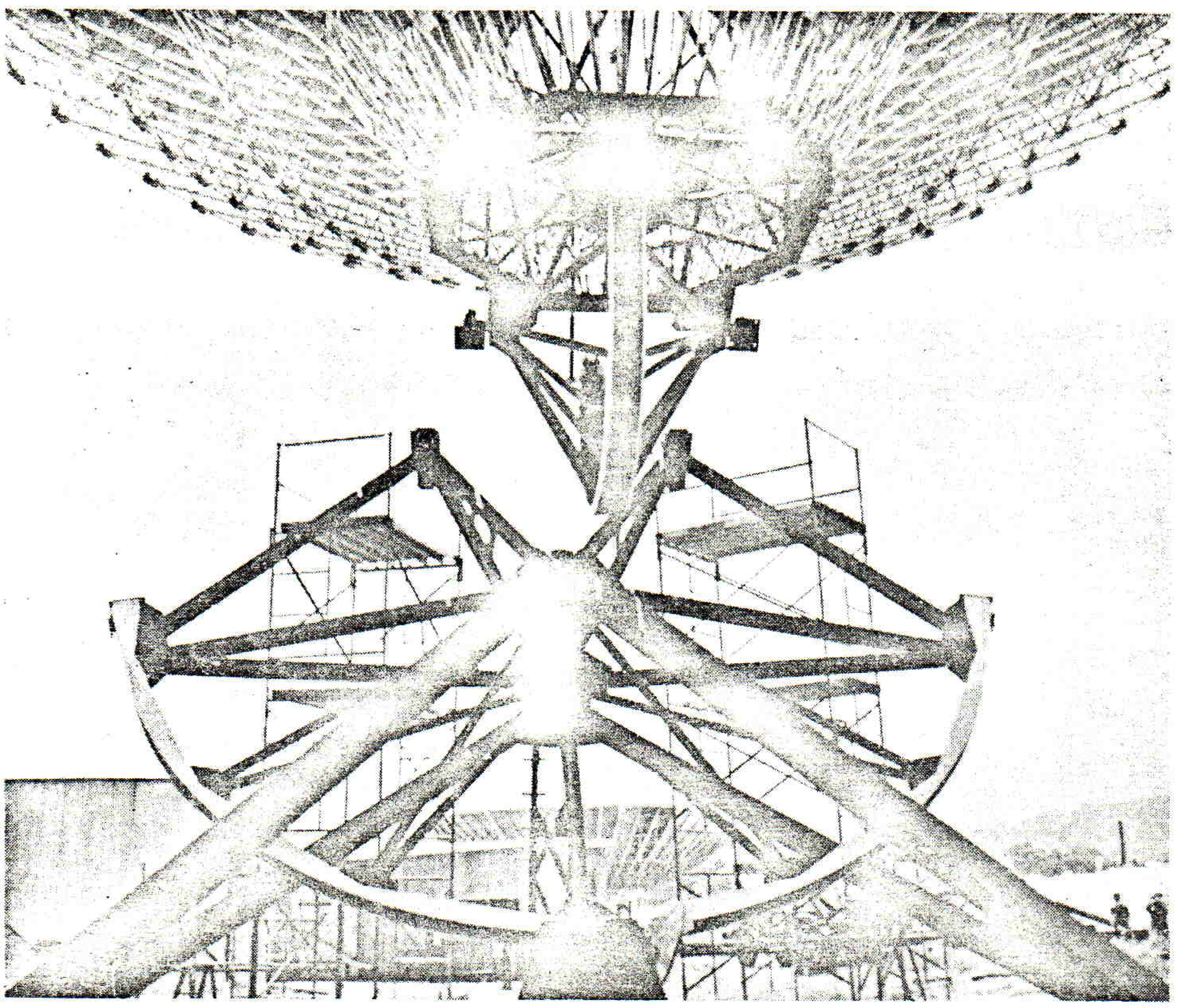
As with an optical telescope, a conventional paraboloid radio telescope forms an image of the source in the focal plane, but only part of this image can be picked up by a feed horn placed on-axis at the focus. If we wish to collect the information elsewhere in the focal plane, we must point the dish to each part of the source sequentially.

Hypothetically, if we had a 675-foot dish (diameter equal to our base line), we could place other horns in the focal plane and observe a number of parts of the source simultaneously, at least in principle. But in practice, difficulties would arise from the proximity of the horns to each other and from aberrations in the image-forming properties of paraboloids.

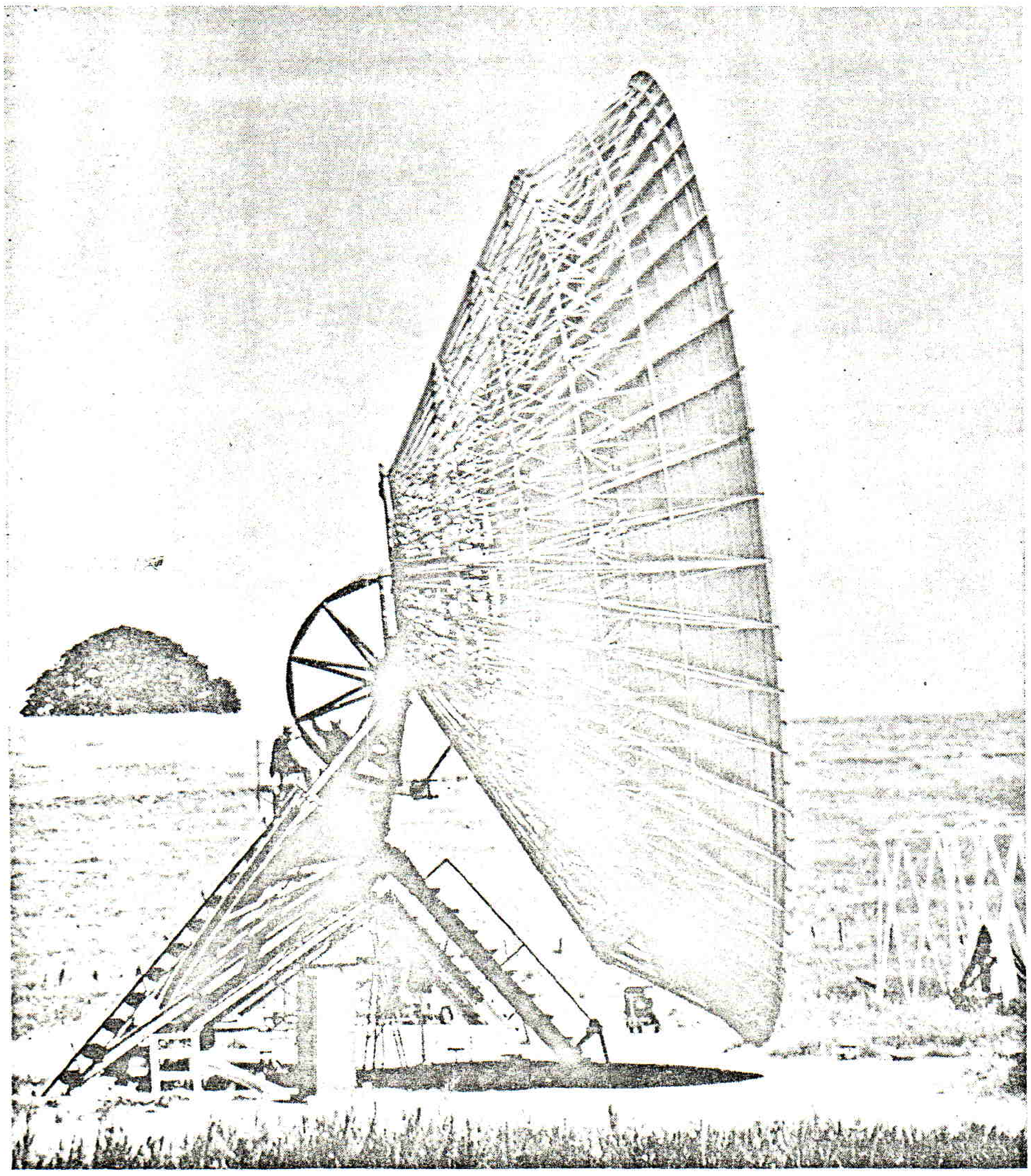
With our minimum-redundancy array, such practical difficulties are avoided, for the analogue image formation results from the way in which the signals are processed in the computer.

THE 60-FOOT REFLECTORS

A great advantage of an interferometer employing dishes of moderate size is that they can be equatorially driven to follow a source across the sky. In our case the coverage is for 10 hours, from five hours east of the meridian to five west of it. Our range in declination is from the north celestial pole to the southern horizon (−52°), covering the entire sky visible from our latitude.



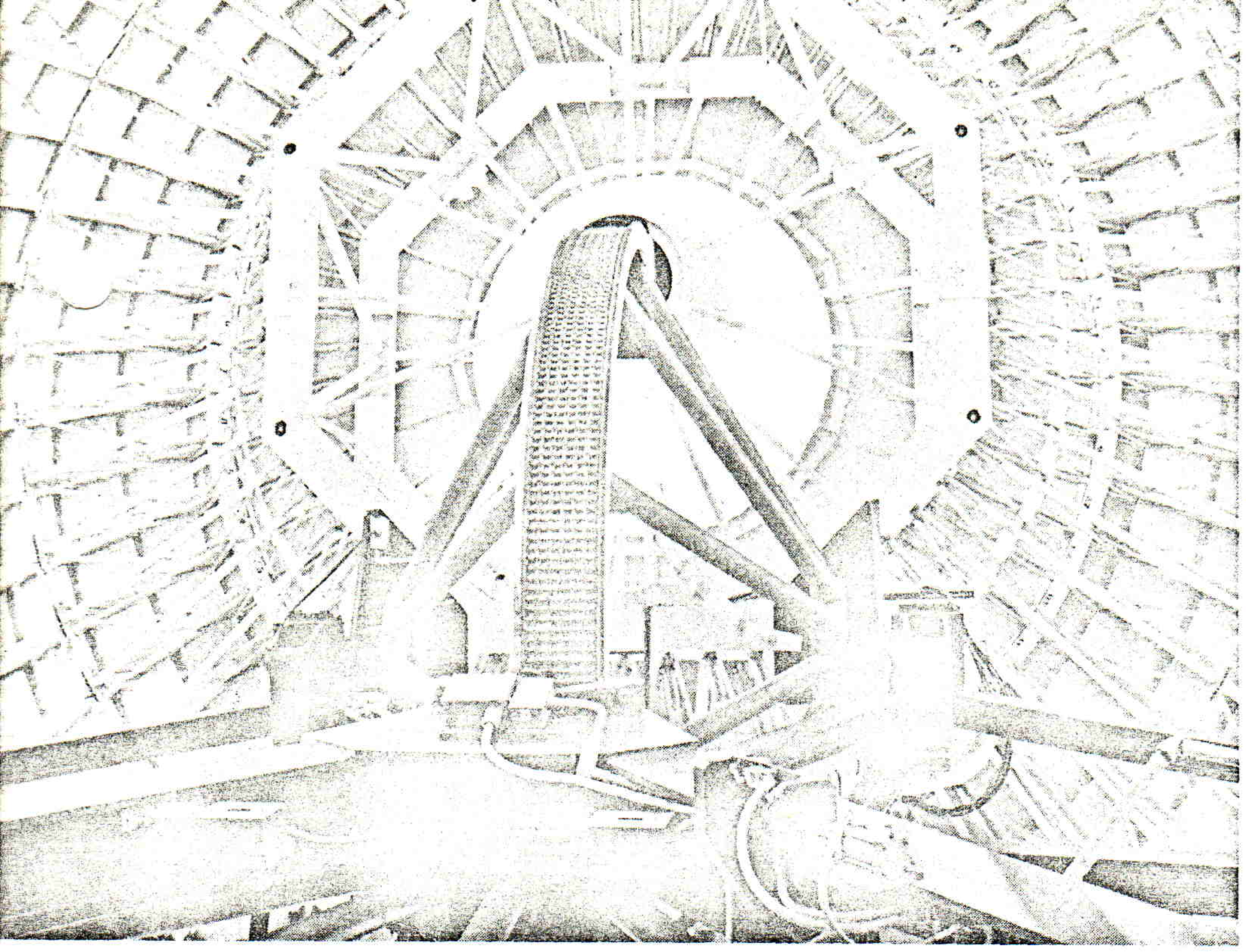
Above, in a view from the north, the yoke and hour wheel are already installed on a base frame, while the dish and declination wheel are being lowered into place. Below, a view from the west shows how offsetting the hub permits the dish to clear the ground when turned fully south for servicing.



The diagram gives a north-south cross section of one of our 60-foot reflectors. The base tripod has one leg due south, the other two widely split toward the north. As shown on page 3, each of the latter is double, to form the upper and lower supports of the stubby polar axis. This is already installed in the picture of the dish with the declination assembly attached (above) being lowered into place.

In each case, motion about the axis is by means of a large half-wheel around which a roller chain wraps. The hour-angle wheel is 30 feet in diameter and the declination wheel 15 feet. The chain passes over two idler sprockets and a drive sprocket to which a motor is connected through a gear reducer. Walter S. Scott designed the drives and C. C. Lee supervised the mechanical construction up to mid-1969.

The dish construction is seen in several photographs and in the drawing. Its framework is cantilevered from a central octagonal steel box frame that also carries the supports for the antenna-feed assembly at the focus of the paraboloid. Note particularly that the dish is offset half the width of the box frame to the north of the declination pivots. This permits lowering the declination axis by about six feet, yet the reflector does not strike the ground when it is turned to the fully vertical position for servicing (pointing due south). Were the reflector center-mounted on the box frame, a much taller,



The central hub (light tone) is seen in this view of the back of a dish. The six-strand chain of the declination drive is about 10 inches wide.

more massive tripod would be required. The weight of the reflector and parts that move with it is 21,000 pounds, but counterweights were omitted on the grounds that drive, bearings and structure all must accept wind loads that considerably exceed the dead load.

An eight-legged structure similar to the tube of some optical telescopes supports the feed. This permits the feet to stand on the steel octagon, whereas the more usual three or four-legged support would require the feet to be well out in the flimsier aluminum panel structure. However, the greater number of legs means more loss of signal by shadowing. The focal length is 18 feet and the focal ratio is 0.3.

Antenna Feed and Electronics

Each antenna has a feed horn that is rotatable to permit polarization studies. Receiving equipment is located in a front-end box mounted immediately behind the feed horn and also in a ground box at the foot of the south leg of each antenna.

The front-end box contains a tunnel diode preamplifier, a mixer and IF preamplifier, the local oscillator and noise calibration components. In addition, it is possible to throw a wave-guide switch in the front-end box that brings into operation a Dicke switch, so that the antenna can be operated as a single unit for pointing corrections and other adjustments. The local oscillator signals at each antenna are derived from a master oscillator (2673.25 MHz) in the control room, thus assuring that the signals from all antennas will be in synchronism. An automatic phase-lock system is used to assure this.

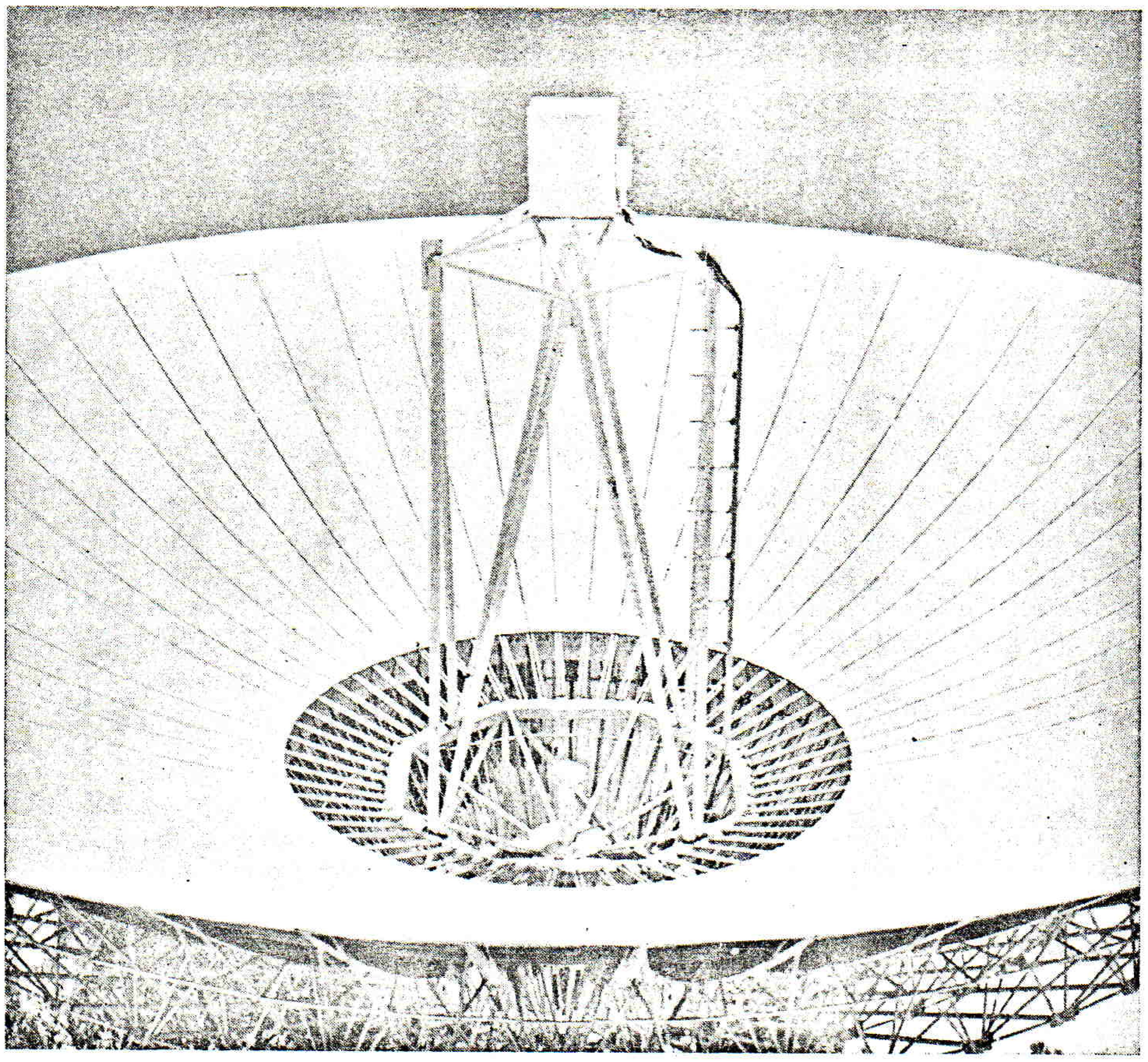
The X-band signals are converted in the mixer to an intermediate frequency band of 10 to 70 MHz. Because of this wide bandwidth (for increased sensitivity), compensation is needed for the antennas being at different distances from a given source. This is done by switching into each circuit varying lengths of cable, which act as delay lines. As the earth rotates, the relative distances change, so the delays have to be adjusted. For each antenna there are 512 possible values.

A small on-line computer calculates when it is necessary to change the delays and selects the appropriate values. It also samples the 10 multiplier outputs and performs an initial averaging of the data. Data is read into the computer 50 times per second, stepping sequentially from one multiplier to the next. Every five minutes the computer records on magnetic tape the average values of the amplitude and phase of the 10 fringe patterns. Thus 15,000 data samples are compressed into 20 values, greatly decreasing the cost of subsequent processing.

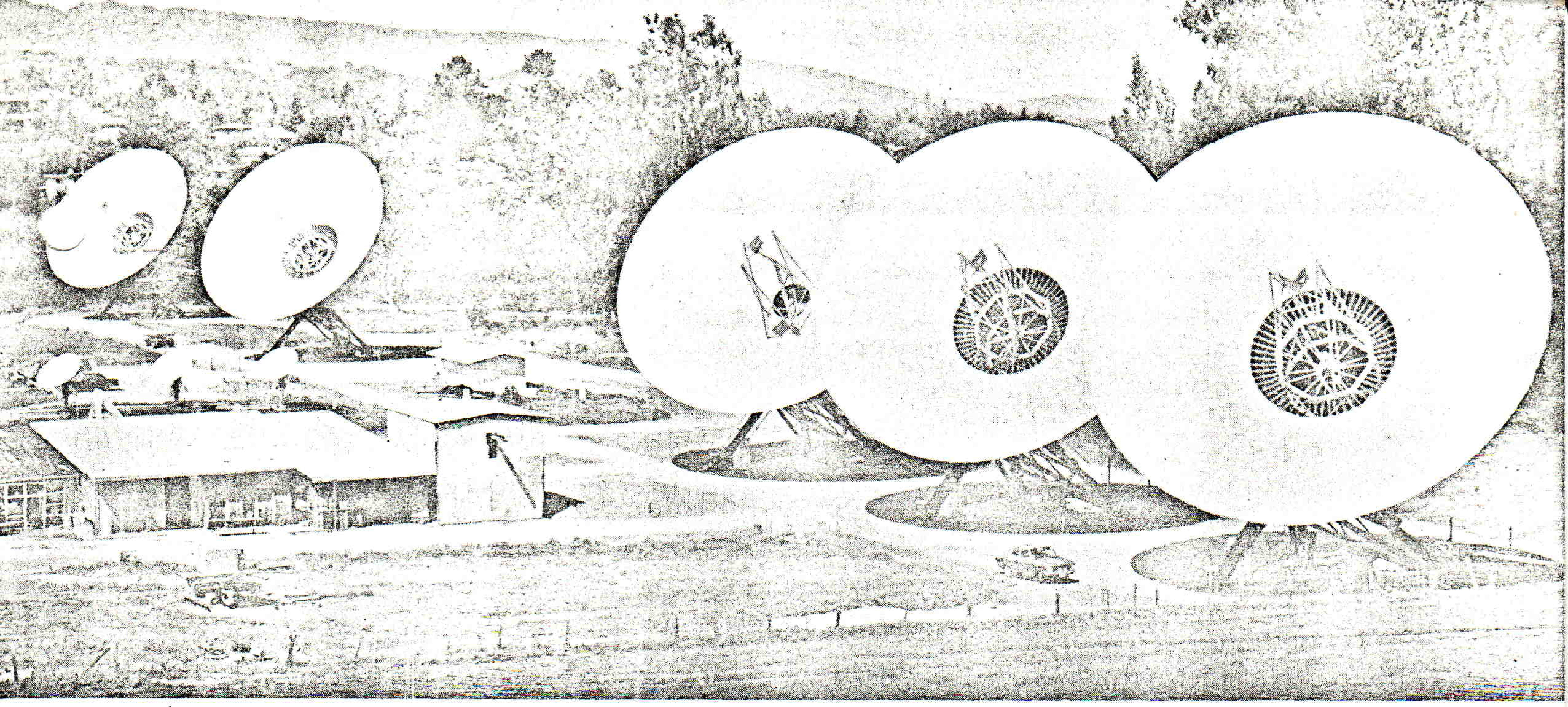
The antennas are driven in declination by independently controlled motors, but the hour-angle drive motors are connected to operate the array as a single unit. The antenna readouts and controls are located in the observing room and the latter are interconnected with a system of boundary and limit switches.

The Observing Program

Testing of the antennas is now under way. It includes correcting the readout indicators and resurveying of each reflector's surface. Phase measurements of



The feed box at the focus of a dish is reached by a ladder on the supporting truss. Each of the 56 panels contains about 100 accurately placed 1/16-inch holes, which are targets for a theodolite set up on the little platform at the dish center. The holes form tiny spots of light that must align properly as the theodolite scans them to check the figure of the paraboloid.



A view with the dishes pointing high in the southeast. Some of them have unfilled central sections, to allow convenient access for men and materials, but they will be filled in for regular observing.

the entire transmission system have begun, and the computer-controlled variable delays have been tested under automatic operating conditions with two antennas connected as a two-element interferometer. Both the readouts and the delay lines were designed by Alec G. Little. Since we are working to an accuracy of about one millimeter, we expect to find that corrections will be needed for ambient temperature changes, antenna position, and other effects.

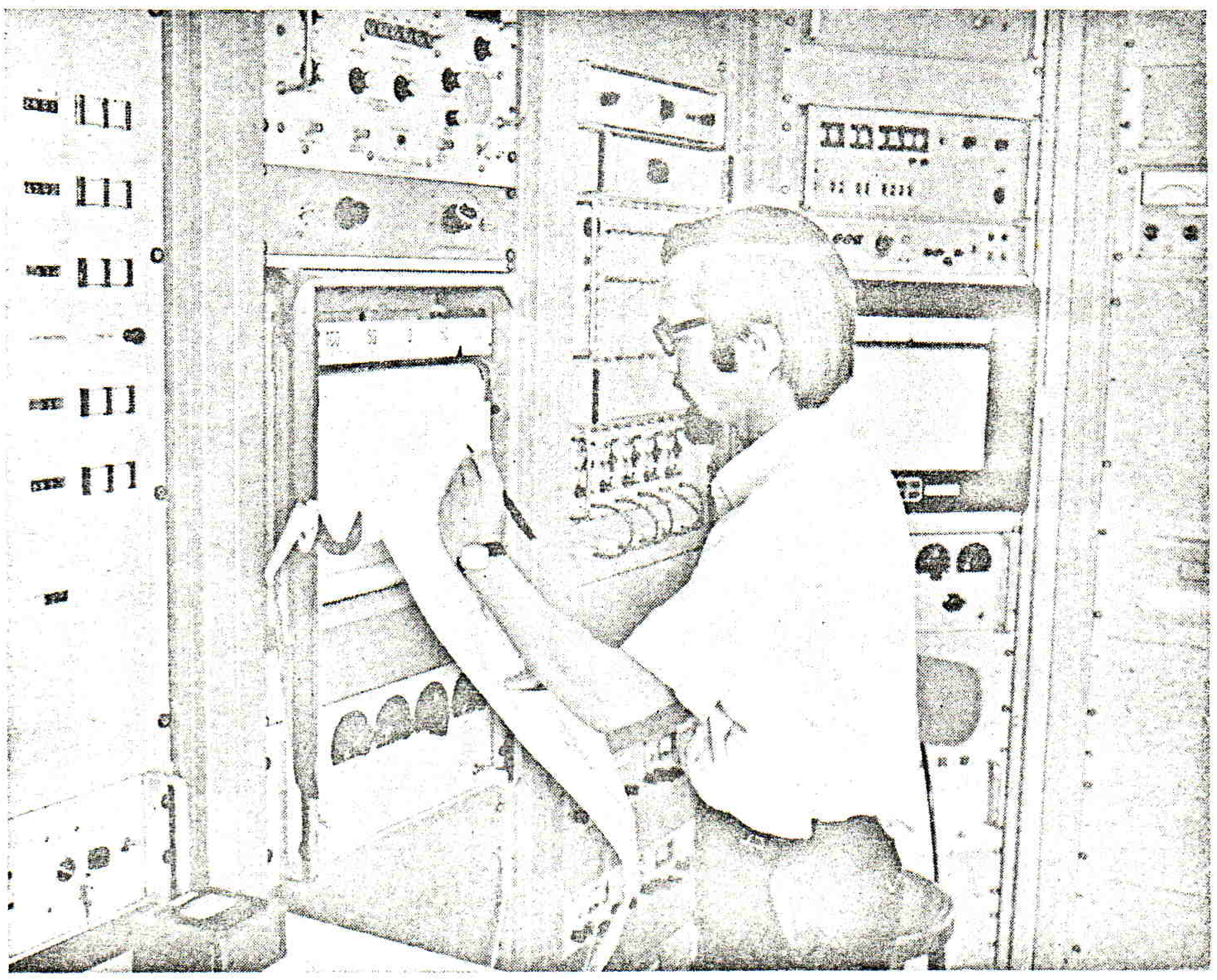
When all the two-element channels are working satisfactorily, the entire system will be operated in the rotation-synthesis survey mode for which it is intended. As we gain experience, a gradual transition will be made to observational programs, but the system is very complex and must be brought into adjustment with care.

The astronomical program will cover a variety of objects. We wish to study the structure of H II regions in the galaxy and planetary nebulae, and to compare the profiles of the latter with optical observations. Our array will be capable of detecting and measuring positions of small unresolved sources down to a flux density of a few hundredths of a flux unit; therefore the array will be more suitable than large single reflectors for surveying large numbers of small nebulae in search of radio emission.

We shall also work on the mapping of nonthermal supernova remnants and radio galaxies. These observations are time-consuming if done by movable-baseline interferometry, but are well suited to a fast, narrow-beam instrument such as ours.

The sun and moon will receive attention. It is possible that active solar regions can be internally resolved and solar radio bursts localized with respect to previously mapped components of an active region. There is also the outstanding question of solar limb brightening at different wavelengths. The immediate availability of our two-dimensional maps of the sun at a wavelength of 9.1 centimeters should furnish a good basis for special observations at our new wavelength of 2.8 centimeters.

Lunar observations for a full lunation might indicate features on the moon possessing unusual thermal properties or surface texture, especially in connection with radar maps. This subject is well developed theoretically, and observations of higher resolution are needed. In our case, there is the technical difficulty that the grating lobes of the interferometer (which limit the field of view) have a separation less than the moon's diameter (see graph on page 4). This problem is less acute with the sun, because of its changing appearance with time.



Graduate student Larry D'Addario, in the control room, checks pointing corrections for the No. 3 dish. Above the chart is a standard Airborne Instruments radiometer, and at left mechanical-counter readouts. Beyond his head is a bank of 10 multipliers, and at upper right a sidereal clock.