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ANTENNA OPTICS METROLOGY WORKSHOP

"History of Antenna Metrology"

By John W. Findlay

1. Introduction.

This paper covers in outline many of the various ways in which the surface shapes of reflector antennas used for radio astronomy have been measured. It is derived from about 30 years experience, and thus includes references to work done on many antennas. I have attempted to describe very briefly the methods used, and in some cases I give a reference to specific examples of a successful measurement. Where a method is to be treated by other authors later in the program I have kept my comments to a minimum. The list of references at the end of the paper is far from complete; one reason is that much work has been done by antenna designers and builders and has not found its way into the literature. But the list does include some of the earliest and the most significant published work. I have also concentrated on the task of determining the shape of a reflector surface with reference to a known coordinate system. Some of the methods I cover can be extended to measure the positions of other important points (e.g. the location of a sub-reflector) and can thus begin to lead to a determination of the position on the sky of the antenna beam - but this aspect of the task can be left to others. But it is worth noting here that the task of setting the antenna surface after it has been measured must be considered along with the measurements and this is sometimes not simple.

~~I shall divide the methods of measuring into the following five classes:~~ Range-Angle measurements; Angle-only measurements; Range-only measurements; Holographic methods and Mechanical-Optical methods. The problems which arise in practice due to the changes of shape which will occur during the measuring and setting tasks can be serious but here we can only note that in making and recording measurements speed can be at least as important as precision.

2. Range-Angle Measurements.

Figure 1 shows this method in its classical form. All methods essentially measure the angle Θ and the range from V to P. T is usually a theodolite and the range is most simply got from a tape under tension or laid along the surface. The direction VF may be a reference line to a point near the focal point or a gravity vertical. Instead of a simple theodolite one that photographs the target and transmits the angle data electronically may be used. A variant can be to use a precise level at T, set at various measured heights above the vertex. Instead of measuring the angle Θ it can be chosen by using a pentaprism for each ring of targets; also the range VP can be measured by modulated laser ranging. The method has been used successfully many times over the years. But it can be slow, and angle meassurements can suffer when made through an atmosphere which is irregular or stratified in its refractive properties. In Table 1 below are references to some of the many telescopes which have been measured and set by range-angle measures.

Table 1. Some Range-Angle Measurements.

Telescope	Reference	Method	Accuracy
Efflesberg 100-m	A. Greve (1)	Tape and photo-theodolite	First measure to about 0.3 mms later about 0.1mm
Parkes 210-foot	M.J. Puttock and H.C. Minnett (2)	Tape and target photos via tiltable mirror	About 0.5 mms improved later
Raisting 25-m	C. Kühne (3)	Tape and first use of pentaprisms	About 0.3 mms
Nobeyama 45-m	N. Kaifu and K. Akabane (4)	Computer controlled optical angle and ranging to 700 corner cubes.	Perhaps 70 microns
Algonquin 46-m	M.H. Jeffrey (5)	Theodolite could read when tilted	About 0.25 mms
IRAM 30-m	J.W.M. Baars et al (6)	Theodolite sent laser beam to XY position sensor on targets.	About 70 microns
		Range by tape.	

The measurements in Table 1 need some comments. First, the estimates of precision are only rough, and in some cases were improved later in the life of the telescope. The Nobeyama measurements were made with a specially designed machine and were aided by the ability to move the panel supports by remote-controlled motor-driven devices. The ability to tilt the instrument in the Algonquin measurements allowed the shape of the surface to be measured with the telescope tilted away from the zenith. The IRAM measures were compared with holographic measures and later the final surface was set using holography.

3. Angle-only Measurements.

Figure 2 shows this method in its simplest form, measurements of the two angles from elevations separated by a known vertical distance can locate the target. The similarity to many terrestrial range-finding systems is clear. I believe that originally the Haystack antenna was to have been set by this method, but I do not believe it was used.

However, the use of photogrammetry can be described under this heading. It is to be considered later in the program - here I will only note that it has been applied to several antennas, including two at Green Bank. See (7) which describes the results of measurements made by DBA Systems Inc., of Melbourne Florida. The measurement accuracies achieved were adequate at the time, but if the intervening thirty years have improved techniques, the method should still be valuable. Its chief advantage was the speed at which the raw data (in the form of photographs) could be taken; an additional advantage was the possibility of measuring all the antenna features with the antenna at its normal working angles.

After the 305-m Arecibo antenna was resurfaced, the positions of the support points for the surface panels were measured using angle-only sets of measurements made from three precision theodolites mounted on firm supports around the antenna rim. The positions of these instruments were well-determined so a few hundred points could be surveyed to an accuracy of about 3 mms. The panels between these reference points were then adjusted using a mechanical reference jig. This process and the plans to use modulated laser-beam range measures is described in (8)

4. Range-only Measurements.

It is perhaps worth noting that when working through average variations of atmospheric refractive index, it is usually true that range measurements are less likely to be sybject to errors than are angle measures. This is due to the fact that the chief properties of the refractive index which have to be allowed for are the existence of rather small-scale irregular changes in index and the fairly stable vertical gradients which exist. In fairly recent years the use of ranging instruments for precision work in surveys has grown. Instruments which measure the range to a target by using a modulated light beam are derived from the method used by Bergstrand (9) in 1949 to measure the velocity of light. These early experiments used incoherent light sources, and fairly low modulation frequencies, but even so achieved absolute range accuracies of a few parts in a million. In recent years laser light beams and modulation frequencies of 10 GHz (a wavelength of 3 cms) have come into use and the resulting systems can measure distances of hundreds of meters with sensitivities measured in tens of microns. At such sensitivities the atmospheric effects are far from negligible; the final performance of such systems will depend on how well these effects can be compensated. However, the advantages of speed in measuring and entering data into a computer make these systems very attractive.

One of the earlier instruments built to test the ranging method was built by Payne (10) which showed that a measurement precision of about 45 microns could be achieved over a distance of 60 meters. Somewhat later similar instruments were built as part of the effort to measure the Arecibo surface and the IRAM 30-m dish. The plans for the new Green Bank 100-meter telescope now include the use of modulated-laser ranging for surface and structural measurements. Later papers in this workshop will certainly provide more information on this and other range-measuring devices.

Two other ranging methods which have been applied to telescope metrology should be mentioned, although both are suited mainly to measuring changes of range. Swarup and Yang (11) devised and used a method of using a 3-cm wavelength radio signal to set the phases of the antennas in a centimetric-wave array. The radio wave travels over the path to be measured and is returned to the sending end from a transponder at the end of the path. This transponder is arranged to modulate the amplitude of the signal it returns so that the return signal can be recognised and compared in phase to the transmitted wave. However, to use such a system to measure distance meets two difficulties. The phase repeats for each wavelength of path travelled, but this in principle can be overcome if the path length is fairly well known. However, if there are any scattering objects in the field illuminated by the wave, the scattered signals introduce noise into the receiver; this may be amplitude modulated if the scattering objects are moving, and spoil the phase of the received signal. Attempts to use the method as a distance measurer have been made without success, but Findlay and Payne (12) used it to measure the way in which the structure of the Green Bank 140-foot telescope deformed as the telescope tilted.

The second precision instrument which has played a part in metrology is the well-known Hewlett-Packard Laser Measurement System. This of course works essentially by counting light wavelengths. It need not be described in detail, but it has been used in several reflector measuring systems. These will be referred to in the later paragraph on Mechanical - Optical Systems.

5. Holographic Methods.

The technique which is now known as "Microwave Holography" has taken its place as being the most useful for measuring both the phase and the amplitude distribution over a wavefront which leaves the antenna system after originating from a point source at the system focus. A considerable part of the time at this workshop will be devoted to study of the various techniques and their application in practice, so in this paragraph I will only write briefly of the way the subject started.

It is well-known in optics that if we know the amplitude and phase of a wavefront over an aperture then the angular distribution of the radiated power from that aperture is also known. I have not read Born's "Optics" in the original German, but I am sure it is in that book. I certainly heard it in detail just after WWII when J.A. Ratcliffe lectured on diffraction problems in Cambridge. In reference to the beginnings of holography, both Ryle and Bracewell were in Ratcliffe's audience, and I have seen both quoted as originating holography. But I suggest the credit goes to those who made it work first, and to my knowledge these are Bennett et al. (13) and Scott and Ryle (14). From these beginnings the method has been widely used and developed so that "phaseless" holography is now used also. Only one of the earlier suggestions (that measuring the field in the focal plane would work) has not in fact succeeded, chiefly I believe to the way the sensors distort the field.

One comment (not intended to diminish the value of holography) is to remind the user that when the antenna shape is known it is still not a trivial task to correct the shape. The group at Texas have been very successful at doing this by shaping the sub-reflector.

6. Mechanical-Optical Methods.

(a) The Leighton Machine. (Figure 3).

For about 20 years R.B. Leighton at CalTech (15) has been designing and building reflectors for mm-wave work; his telescopes have been installed and are in use at the Owens Valley site in California and on Mauna Kea on Hawaii. The reflector back-up structure is fabricated in such a way so that it can, if necessary, be dis-assembled and re-assembled in a reproducible form. The reflector surface is made of hexagonal panels of aluminium honeycomb structure coated with a thin aluminium sheet. The novelty of the technique is that the whole 10.4-m dish is mounted on a machine and rotated on an air-bearing so that a cutting tool can be moved to form the upper surface of the honeycomb to the required shape. The thin reflector surface is then fixed by epoxy to the honeycomb. The machine is designed to use the fact that the required surface is defined by the constancy of the path length from the focal point to the surface and then up to a horizontal plane. This path length is monitored by a Hewlett-Packard Laser Interferometer. There is much other innovative metrology in the system, including the use of the surface of a tank of oil to check the level of the horizontal reference surface. Reflectors have been made by this method with RMS accuracies approaching the 10 micron level.

(b) The James Clark Maxwell Telescope. (Figure 4).

This 15-meter telescope has now been operating for some years at a site on Mauna Kea. The original plans for measuring and setting the surface were to employ a mechanical-optical system again relying on the use of the laser interferometer to establish the changes of length of a light path which travelled from a line set by the beam from an alignment laser to the end of a probe which rested on the telescope surface. This method was replaced by holographic work later; I am not sure of the degree to which the original machine was used.

(c) Measurements of Reflector Curvature.

This method was devised to measure the shape of the 36-foot (11-m) diameter antenna which had been built by the Rohr Corporation for N.R.A.O and installed in an astrodome near the summit of Kitt Peak. The original reflector surface was made on a specially-built machine in the Rohr plant at Chula Vista, so that the reflector shape was determined by the mechanical accuracy of the machine. The reflector had a long focal length (8.8-m) and so was quite flat by most standards. Originally its surface was good for use at frequencies below 85 GHz but after a few years the bipod feed legs had fallen and made quite a deformation at places near the edge of the dish. In the hope that it might be possible to map the worst areas of the surface, the curvature method was devised. It is, of course, similar to the use of a spherometer to measure a lens or mirror, and it has been applied in testing large optical surfaces. Figure 5 shows the method in principle. The curvature K_p at the point P is $d\theta/dS$ where S is measured along the surface from the vertex at O. The following integrations now give Z as a function of S and X :

$$\theta_P=\int_0^P K.dS \qquad Z_P=\int_0^P \sin\theta.dS \qquad X_P=\int_0^P \cos\theta.dS$$

In the work described in (16) the curvature was measured by a three-wheeled cart with a very precise depth sensor mounted midway between the front and rear wheels to derive values for the curvature. (See Figure 6). The distance along the surface was measured by a wheel-rotation sensor. Depth sensor voltages were read in digital format at every pulse from the wheel sensor, so tat data could be recorded in real time by the telescope computer. The integrations were also done in real time so that an (X,Z) profile was available to be stored after each cart track from the center to the edge of the telescope. It is clear that the individual measurements of curvature must be very precise, since two integrations are needed to get the profile. Also the start and end conditions for the cart along the track must be well defined. The method worked well when tested on the 11-m antenna, showing an average repeatibility of the profiles of about 40 microns. The method was tested at length along a fairly horizontal test track 12.5-m long as part of the study for the design of a 25-m telescope. These results were fairly encouraging, but the small distortions of the track under the cart's weight and the tendency of the cart to wander in its travel introduced problems. I believe this technique was considered (but not used) by the IRAM group building the 15-m interferometer antennas. Their plan was to measure curvature both radially and circumferentially with a device not resting on the surface but carried above it.

(d) Measuring by "Stepping".

It is possible to avoid the double integrations needed in the cart method by adopting the principles used by surveyors in precision levelling. Figure 7 shows how to measure the shape of a reflector radius by this method. A bar of length L is placed step-by-step along the radius and the level of the bar (θ) with respect to gravity measured for each step by a precise electronic level. It is clear that if we are careful to step between clearly defined points we shall be able to derive the values of X and Z along the radius. The ends of the steps can be defined in several ways. The bar shown in Figure 8 was used when the ends of the bar rested in holes drilled in the surface to measure. The bar length was measured at each step by the micrometer. On the Green Bank 43-m telescope plastic locators glued to the telescope surface allowed the steel tooling balls defining the ends of the bar to rest on the surface without the bar sliding away. The bar length was variable and read by an electronic sensor. Both the length and tilt angle values were read in digital form to a mini-computer.

This stepping technique has been used in several surface setting projects; it will be referred to again in the work on the NRAO 12-m telescope on Kitt Peak. It has been shown to be very reproducible; one quite severe test was to compare three separate measures made on one radius of the NRAO 43-m telescope, which showed point-by-point agreement as good as 60 microns. The inclinometers used can be read easily to 1 arcsecond; they were tested and calibrated by comparison with an inductosyn.

(e) The NRAO 12-meter Telescope. ([17])

In the spring of 1982 work was started to re-build the original 11-m telescope on Kitt Peak to have a new surface, 12-m in diameter, with a shorter focal length (f/D = 0.43). A new steel structure to carry a new surface of 72 ESSCO panels was designed to be placed, with new sub-reflector support legs, on the elevation axis of the original telescope Figure 9 shows the new structure in the astrodome before the new surface was emplaced. We were fortunate in being able to buy from ESSCO the panels needed for a 12-m dish (the astrodome door would not permit a larger size) and get an f/D very close to that of other NRAO telescopes without having to accept the cost of new tooling. Figure 10 shows the arrangement of panels in the inner and outer rings and also shows the location of the surface mounting points and the points at which the surface would be measured. The panels supplied by ESSCO were all measured in plant and all passed the requested RMS value of 45 microns. Of course, the ESSCO panel has to be mounted and adjusted correctly to perform well on the telescope.

Although it was always expected that the final telescope performance would be checked by holography, the measuring and setting machine was planned and designed to meet the following requirements:

- (i) The machine could be allowed about 30 to 40 microns in the surface error budget.
- (ii) The surface should be measured above every panel support point and also at many intermediate points.
- (iii) The machine should measure the whole surface in a few hours and all data should be taken and recorded in the computer.
- (iv) The surface itself, not targets, should be measured.
- (v) The machine should give a direct read-out to a technician working at an adjustment screw.
- (vi) The machine should be easily installed and removed.

All these needs were met. Under the best conditions 1430 points were measured in less than two hours. Two sets of measurement data taken one year apart were compared point by point and the RMS value of the difference was 28 microns. This demonstrates the stability of both the telescope as well as the machine. The need for control of the adjustment process was well-met; when a particular adjusting screw was being worked, the voltage reading of the machine sensor at that screw was sent to the technician's digital volt-meter together with the statement of the required voltage he should achieve. After a full adjustment the best-fit surface could be computed in a few hours, together with the position and direction of the axis of the reflector and its focal length.

The main steps by which this machine performance was achieved can be outlined as follows:

- (i) The coordinate system for the measuring machine was defined by a steel tooling ball positioned close to the vertex of the dish and by 144 steel tooling balls mounted around the edge of the support structure. The template (Figure 11) which carries the sensors was supported kinematically on the center ball and an edge ball.
- (ii) The required profile of a radius was built into the "Reference Jig" (Figure 12) to which the template could be "mated" and the sensors read. The RJ profile was measured in several different ways to confirm its shape.
- (iii) A complete measurement required that the template, after being checked on the RJ, was lifted into the dish using hoists from the astrodome to place it in position. One operator below the dish center and two or three in a cherry-picker at the edge positioned the template and told the computer to read. Each radius was plotted and displayed at the computer before the template was moved to the next radius; this was brought to the edge crew by rotating the dish in azimuth.

The whole process of bringing the telescope into use involved many steps of detail. The elevations of the edge balls had to be measured and checked as time passed. Precise levelling by a Wild level, stepping (as in (d) above) and even the use of a mercury manometer were used. The RJ temperature was monitored, and so also were the temperatures at several points on the telescope structure. The RJ profile was measured by several methods, including using a Wild level, stepping and even tri-lateration using the H-P interferometer. The final success of the whole project came about after holographic measurements made with the help of the group from Texas University, but the measuring machine is kept so that if panels get damaged (as has already happened) they can be quickly replaced.

7. Conclusion.

This paper has been prepared rather rapidly and may not have the most up-to-date facts about some of the antenna measurements described. In particular, the later holographic work on the telescopes on Mauna Kea, the 30-m IRAM telescope and the 15-m telescopes of the IRAM array are not reported. So there are perhaps quite a number of errors and omissions.

May 15th 1991.

Figures.

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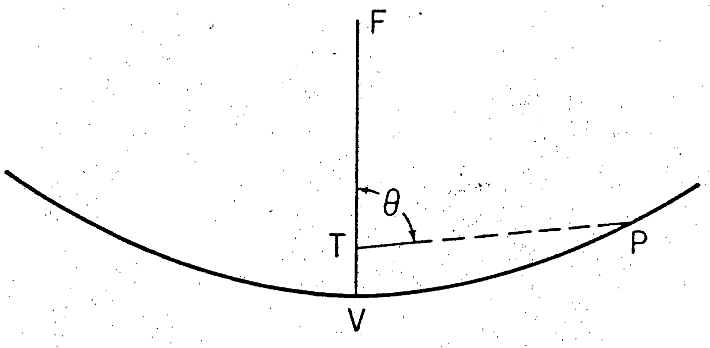


Figure 1

Range-Angle Measurements

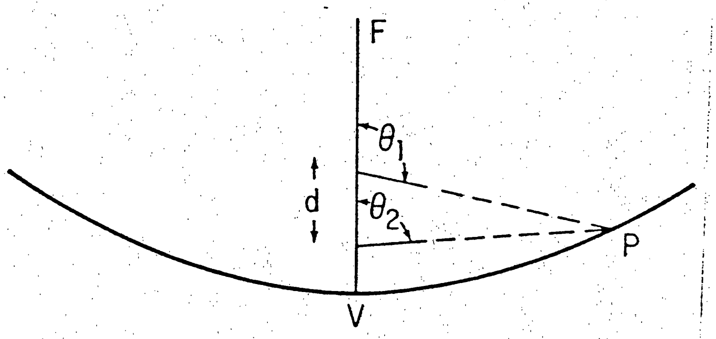


Figure 2

An example of Angle-only Measurements

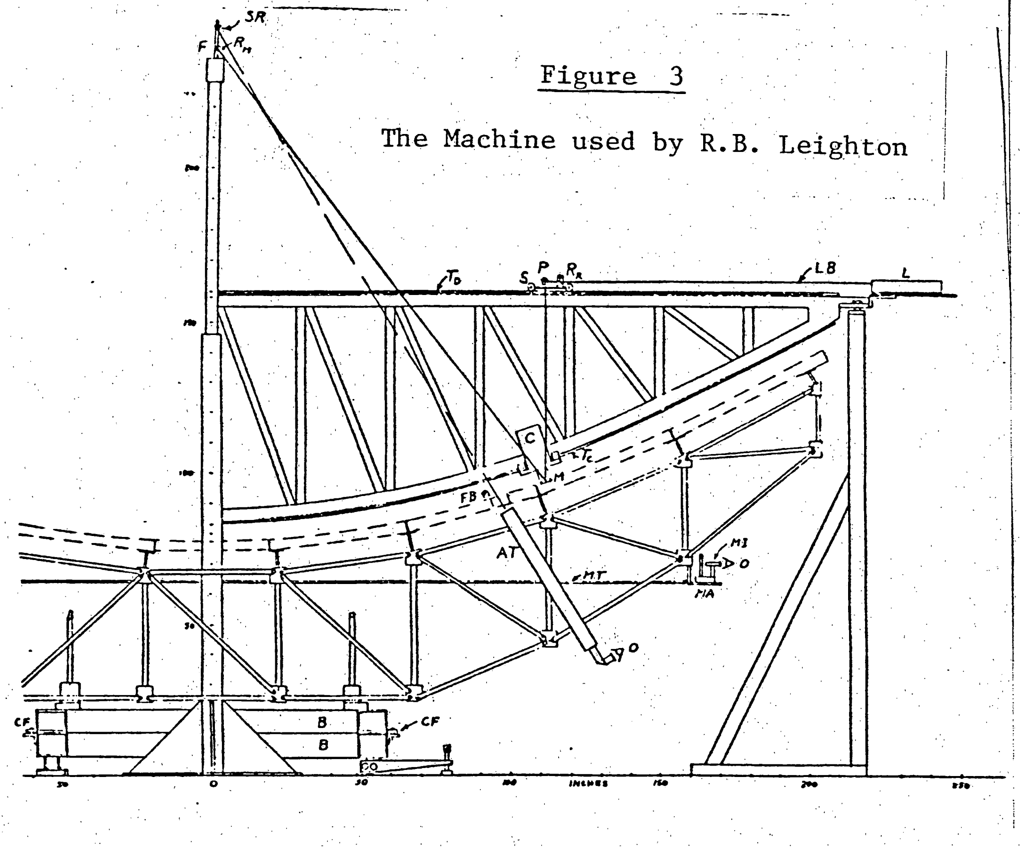


Figure 3

The Machine used by R.B. Leighton

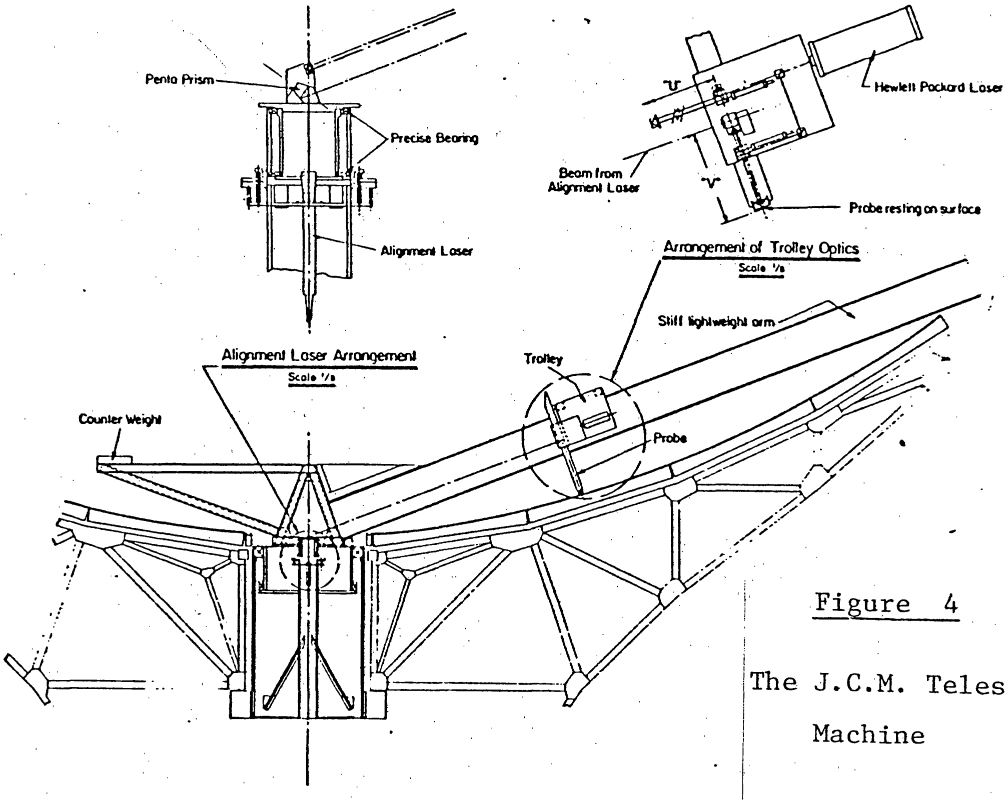
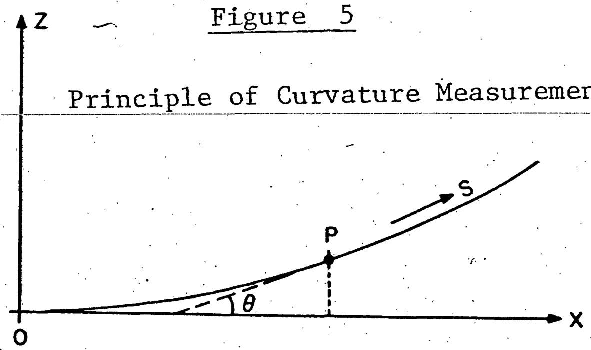


Figure 4

The J.C.M. Telescope Machine

Figure 5

Principle of Curvature Measurement



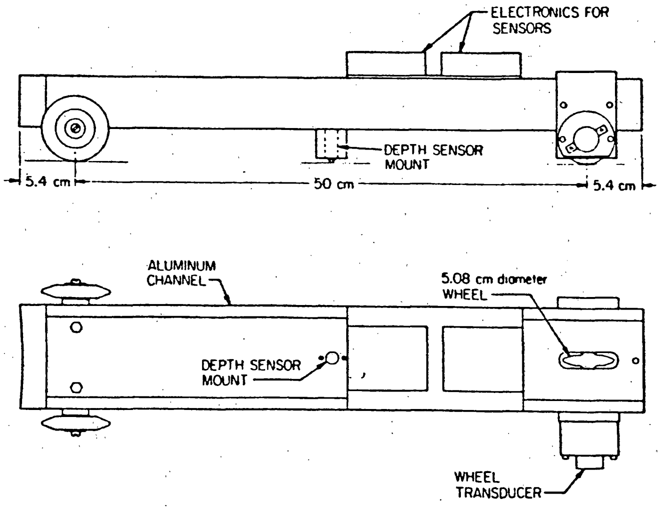


Figure 6

The Cart used to measure Curvature

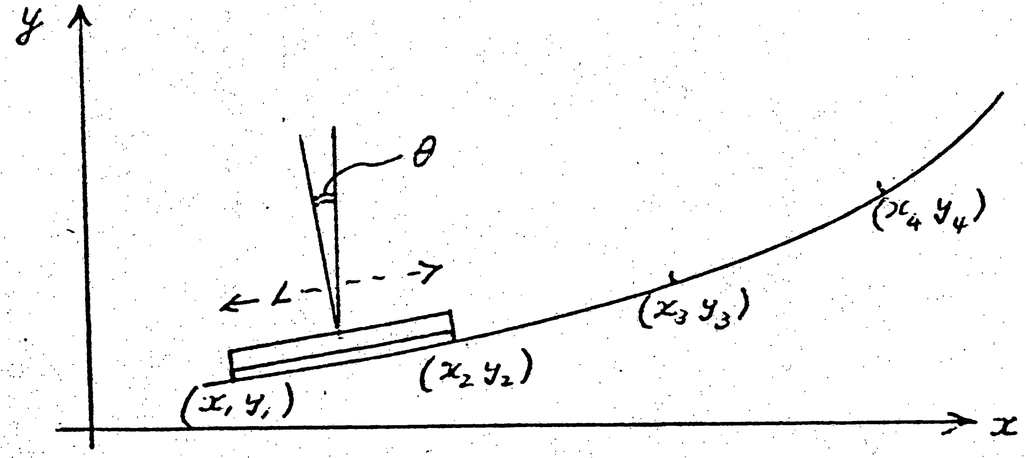


Figure 7

Measuring by "Stepping"

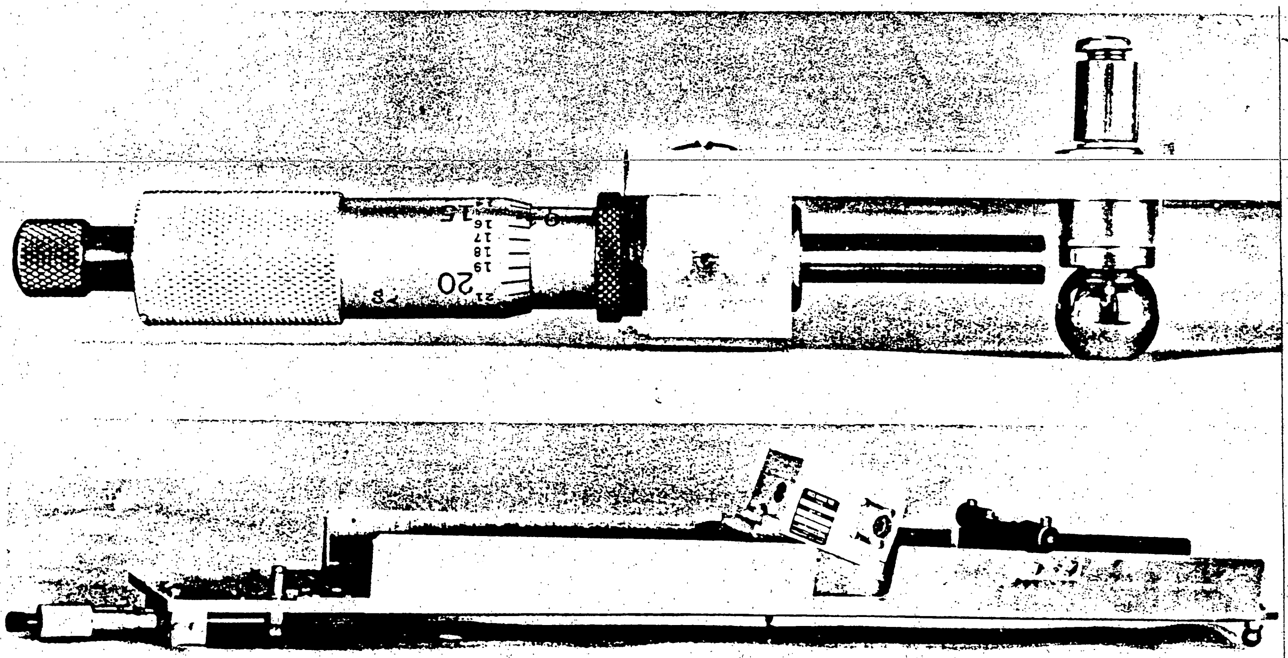


Figure 8

The inclinometer and bar used for the stepping method.

Lower: The bar, inclinometer and tranverse level.
Upper: Micrometer used to measure the step length.

One form of the Stepping Bar

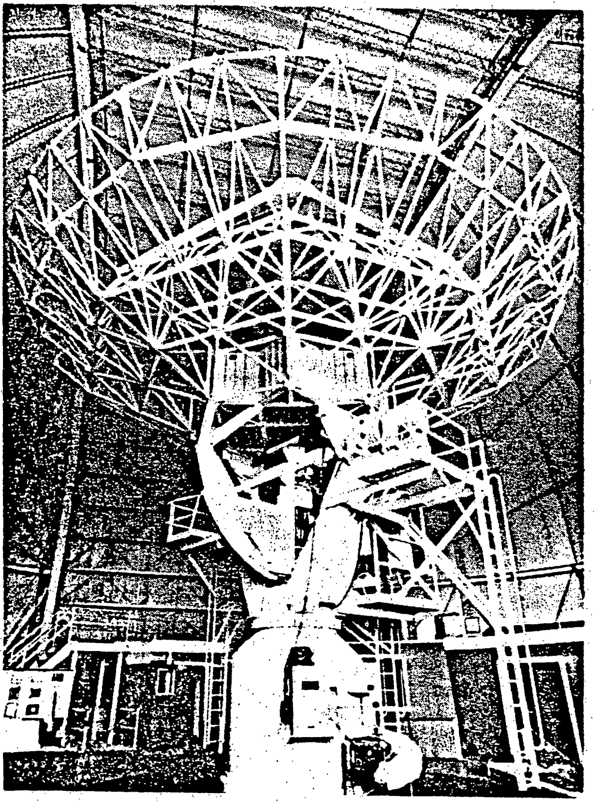


Figure 9

The 12-m Telescope Reflector Support Structure

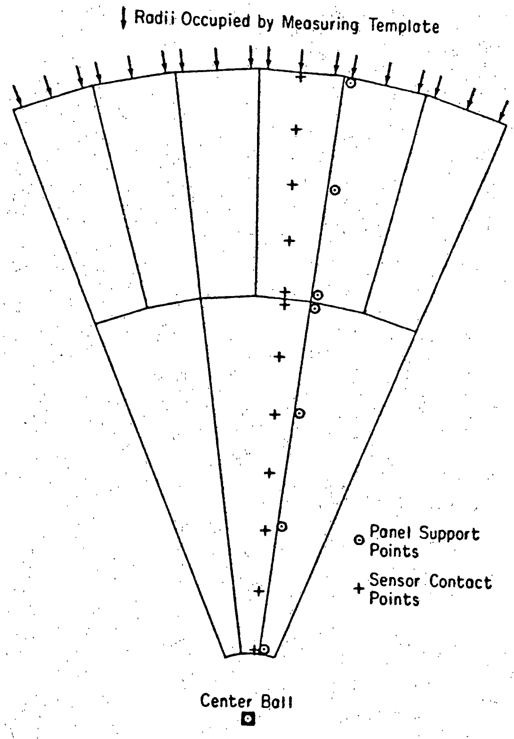


Figure 10 The Surface Panel Arrangement

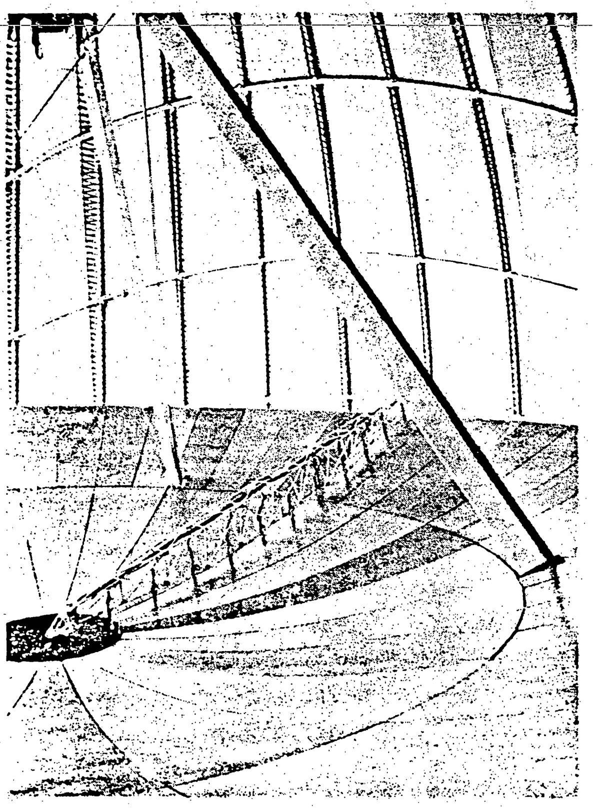


Figure 11 The Template on the Reflector Surface

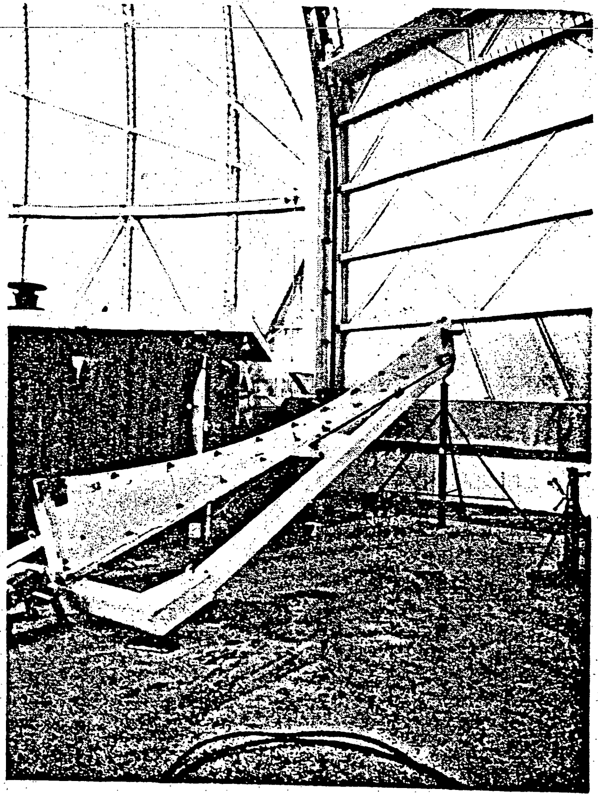


Figure 12 The Reference Jig