25 METER - MILLIMETER WAVE TELESCOPE

MEMO # 27

NATIONAL RADIO ASTRONOMY OBSERVATORY
Charlottesville, Virginia

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MEMORANDUM

To: Barry Turner

From: J. W. Findlay

Subj: Surface Measuring for the 25-meter Telescope

I feel we have reached a point in the development of the Payne, Hollis and Findlay surface measurer where I need guidance—insofar as the future use of the system for a 25-meter telescope is concerned. The method in its present stage has been tested on the 36-foot and Payne has since made considerable use of it in work designed, perhaps, to improve that telescope. However, there are three outstanding questions which require answers before one would adopt it (without adding other techniques) to measure a 25-meter telescope. These are:

(a) What is the absolute accuracy of the method, when used over distances of 12.5 meters?

(b) Can the RMS errors of the method be reduced to give an average RMS measurement error of < 0.04 mm over the 25-meter telescope?

(c) What means should be adopted to make the method work well on a surface with gaps between panels and will it maintain its accuracy on such a surface?

I attach as an appendix to this memo the pages from the draft paper (P,H&F now being written) which deal with the error problems.

I feel that, if we need hard answers to these three questions, the only good way will be via experiment. My plan for such experiments is outlined below. At the outset, however, let me say that the amount of work involved for me, almost single-handed, to carry through this work is considerable. When I see the areas in the 25-meter project which lack decision, I am led to wonder whether it is worth the effort and money to push further on the measurement problem at the present time. It is on this question that I should value guidance.

To answer the three questions requires full-scale measurements, under controlled conditions, over a 12-1/2 meter track. J. Ralston has re-designed a cart which should (mechanically) ride panel gaps satisfactorily. The shops are just finishing the cart fabrication. The experiment would be to run this cart over a test-track and record data digitally to the required accuracy; then compare the results with the track geometry.

My present plan would be to concentrate on measuring the accumulated error at the end of a 12-1/2 m track. To do this the cart would be started from and stopped on two flat level glass or metal plates at the ends of a track--which could be a strip of aluminum-laid on the floor.

The elevation difference between the end plates could be measured to about 0.03 mm (either with a good level or by a water manometer). The method should consistently give the same answer. Modifications to the track (insert gaps, etc.) would be made to test the effects on the overall accuracy.

Data would be recorded digitally. A new stepping-recorder is on its way to me for the calibration experiment. I would record on this, via a 14 or 15 bit A/D converter and an interface. I would need electronics help (and money) to get the A/D converter and interface.

I would do the experiment indoors (along a wall in the Green Bank auditorium for example) where temperature and mechanical vibration are not a problem.

I have addressed this note to Barry since, as far as I know, he is still responsible for the 25-meter task. However, I should welcome comments from all on the circulation list.

JWF/pj

cc: D. S. Heeschen
H. Hvatum
D. E. Hogg
W. E. Howard
S. Weinreb
J. Payne
J. Ralston
S. von Hoerner

APPENDIX

Pages from the first draft of a paper by Payne, Hollis and Findlay.

4. ESTIMATES OF ACCURACY

The overall accuracy of the method will depend on a number of factors; we will discuss these here in a simple way. The accuracy achieved in the experimental tests of the system is described later.

For simplicity, consider the cart being moved along an almost-flat surface, starting on a perfect flat and ending on a perfect flat. Let the surface to be measured be N x L/2 in length. When the cart starts with the depth sensor at n = 0 (all three contact points on a perfect flat), let the depth sensor read d_0. It should, of course, read zero but we take the case where a small zero point error exists. Move the cart so that the depth sensor is at n = 1 and let Z_o, Z_1 .... be the Z coordinates of the surface at n = 0, 1, ...

$$\begin{aligned} \text{At } n = 1 \quad & Z_2 = 2Z_1 - Z_0 + 2\ (d_1 + d_0) \\ n = n \quad & Z_{n+1} = 2Z_n - Z_{n-1} + 2\ (d_n + d_0) \end{aligned} \tag{5}$$

The value of Z at the end of the cart travel is Z_{N+1} and this can be got from the set of equations (5) as

$$Z_{N+1} = 2 \sum_{n=1}^{n=N} n(d_{N=n+1}) + d_0) \tag{6}$$

Equation (6) can be used to discuss the systematic and random errors to be expected in the measurement system.

(a) Systematic Errors

The zero-point error in the depth transducer may be as a first approximation thought of as incorporating the uncertainty in the other instrumental constant, L, the cart wheel separation. In practice, with care, the transducer can be set to read zero, with the cart on a flat plate, to about $\pm 5 \times 10^{-3}$ mm and L can be measured to about $\pm 10^{-2}$ mm. Neither of these errors is small enough to allow of the absolute calibration of the instrument in this way. For example, on the 11-meter telescope the cart travelled about 16 half-cart lengths. A zero-point error of 5×10^{-3} mm has, after this distance, accumulated to an error in Z of 11.4 mm—an unacceptably large value. We return later to this point, but, in practice, we have chosen the cart constants to give the expected Z values at the edge of the telescope. All runs on the telescope have used these same cart constants, so that if there is a systematic error in our Z measures it is the same in all radial measures.

A further source of systematic error in the measurements on the 11-meter telescope was the uncertainties of the conditions at which the cart started each of its radial tracks. These tracks ideally should have started with the cart center over the telescope center and with the cart on a good flat at the center. Practical considerations--the center of the 11-meter telescope is a hole surrounded by obstructions--prevented such a perfect experimental situation and some systematic errors must have resulted. In practice, each radial run was started at a carefully measured distance from the (assumed known) telescope center. In evaluating the integrals (2),(3) for each track identical initial values of θ and Z were used--these values were the design values for the telescope..

It is not easy to determine the effect of this approximation on the systematic error. An uncertainty in Z at the start appears only as an equal uncertainty at the end. The uncertainty in θ (which is similar to having $d_0 \neq 0$) cannot have been large, since the values found at the edge of the telescope corresponded reasonably with those found by less precise methods of survey (a tape and theodolite).

(b) Random Errors

We can return to equation (6) to estimate the effects of random errors in measuring d on the resulting values of y. Suppose each d reading has an rms error σ_d . The resulting error in Z_{N+1} will be

$$\sigma^2_{N+1} = 4 \sum_{n=1}^{N} n^2 \sigma_d^{\,2} \tag{7}$$

and roughly

$$\sigma_{N+1} \simeq \sqrt{\frac{4N^3}{3}} \quad \sigma_d \, . \tag{8}$$

These errors increase roughly as $N^{3/2}$ and, for our measures N = 16. Thus

$$\sigma_{N+1} \simeq 75 \; \sigma_d . \tag{9}$$

The transducer used has a repeatability of about 10^{-4} mm so from (9) we might expect edge errors of 0.0075 mm.

The random errors in measuring S amount to a fraction of the wheel-transducer interval, say 0.2 mm. Thus, on the 11-meter telescope, corresponds to an error in Z of 0.05 mm at the edge.

5. EXPERIMENTAL TESTS OF REPEATABILITY

The first set of experiments was designed to test on a radio telescope the repeatability of the measurements made using the method described. The NRAO 11-meter (36-foot) millimeter-wave telescope on Kitt Peak was chosen for these tests. The reflector had been originally machined as a single surface and thus was well suited to test the method. The reflector is shallow (the f/D ratio is 0.8) and the fact that the whole instrument is in an astrodome made it possible to reduce the effects of wind and sunlight in distorting the reflector.

It was not possible to use the center piece of the reflector, since there is a hole and mounting brackets for electronics in the central area. It was necessary to set up well-defined start conditions for the cart. This was done by fixing a machined ring to the reflector. Its diameter was ____ m and start marks were scribed around this ring at 15° intervals. To start a radial run the cart was backed up against this ring (the back of the cart was shaped to fit the circular ring) and a mark on the cart aligned with the start mark. A pulley was fixed to the reflector edge, aligned with the end of the desired radial track, and a thin flexible steel towing cable went from a centrally mounted winch over the pulley and back to the cart (see Figure 5). A radial run was completed by towing the cart at a fairly constant speed (about 10 cm per second) from its start position to a point near the edge of the dish.

The depth sensor, which develops an analog voltage between $\pm$ 5 volts, was read at every pulse from the wheel sensor. The analog voltage was converted by a 15 bit A/D converter and each binary value was read into the telescope data computer. One binary bit corresponded to 6.17×10^{-5} mm movement of the depth sensor. To ensure that the correct number string was recorded, the following observing routine was followed:

(a) Set the cart in the start position.

(b) Arm the computer to take data when the wheel pulses start to arrive.

(c) Start the cart moving by turning on the winch.

(d) Record depth data sensor and count wheel pulses.

(e) When wheel pulse count equals the preset value (usually 6500) disarm the computer and stop recording.

(f) Stop the cart and return it to the start position.

The depth sensor data as a function of wheel count (and thus essentially a measure of curvature as a function of S) was thus immediately available in the computer memory, and could be displayed and reproduced on the computer hard-copy output. Figure 6 is such a display of the raw data taken along a radial track.

It will be clear from Figure 6 that the depth sensor readings vary considerably with position on the surface. To give an immediate look at the reproducibility of the raw data, at least two runs were made over each radial track. Since both were stored point-by-point on the computer disk, it was possible to display the point-by-point difference between two such runs. Figure 7 is such a comparison, it shows that the main features of Figure 6 do in fact reproduce very well. The "noise" on Figure 7 has a peak-to-peak value of about 400 counts, equivalent to 0.025 mm (0.001 inches) movement of the depth sensor. The main source of this noise is believed to be small-scale irregularities in the machined aluminum surface.

The computer was also able to evaluate the integrals (2) and (3) in real time (the ΔS interval was small, 0.6384 mm, so that the integrals could be directly evaluated as sums). Thus, if needed, plots of θ or of Z as a function of S could be made. Figure 8 shows the difference between the values of Z derived in two successive runs made about 10 minutes apart in time over the same radius; it shows that the value of Z near the edge of the dish had changed by 0.1 mm (0.004 inches). Part of this may have been due to temperature changes, and part is due to the system errors.

To establish a measure of the reproducibility of the measurement system this first experiment was to measure 23 radials on the telescope, to make each measurement twice with only a small time interval between and then, after reducing the data, to compare point-by-point the Z values obtained in the two separate sets of measurements.

The work was done on one day in July 1974. The ambient temperature rose steadily at about 1° C per hour for six hours and then levelled off for the last three hours. At the end of the measurements and first step reductions, two sets of (Z,S) data were available, each consisting of 21 values of Z along each of 23 radial lines of known azimuth. For each radius these (Z,S) values were transformed to (X,Y,Z) values. (The Z-axis is parallel to the reflector axis and the X,Y axes lie in the plane of the reflector aperture.) This transformation was made using the relationship between S and (X,Y) for a true paraboloid and does not introduce any serious error.

6. THE MEASUREMENT REPEATABILITY

To estimate the repeatability of the measurements the results were analyzed as follows. For each measurement point (483 in all) the difference (ΔZ) between the Z values on run 1 and run 2 was calculated. The time interval between runs 1 and 2 was about 10 minutes. The values of ΔZ will be a measure of the repeatability of the observations, but it may also be that the telescope itself changed shape somewhat between the runs. Accordingly the values of ΔZ were averaged for each ring of points at a constant radius. The mean ΔZ, if different from zero, will show if there is a shape change in the telescope. The standard deviation of ΔZ will be a measure of the repeatability of the system.

Table I summarizes the results of this analysis.

Table I. Values of ΔZ, the Change in the Measured Z, Between Two Sets of Telescope Measurements

Radial distance	Mean ΔZ and S.d.of Mean	S.d. of a Single ΔZ Measure
5.16 m	0.074 $\pm$ 0.019 mm	0.090 mm
4.97	0.070 $\pm$ 0.016	0.075
4.78	0.064 $\pm$ 0.013	0.062
4.59	0.057 $\pm$ 0.012	0.058
4.40	0.051 $\pm$ 0.011	0.052
4.21	0.044 $\pm$ 0.010	0.046
4.02	0.047 $\pm$ 0.007	0.034
3.63	0.031 $\pm$ 0.007	0.032
3.24	0.023 $\pm$ 0.004	0.021
2.85	0.011 $\pm$ 0.005	0.025
2.46	0.008 $\pm$ 0.004	0.020
2.07	0.003 $\pm$ 0.003	0.016

Table I could not be carried into points nearer the dish center since the measurements showed $\Delta Z = 0$ (to the final computer LSB which was 0.026 mm) inside the 2-meter radius. The table showed that there was a mean change in dish shape between the runs--a point near the edge changed by 0.074 mm. This is not inconsistent with what is known about temperature change effects on this telescope.

The final column shows that the measurement repeatability gets worse as the radius increases. If we take a mean value of the final column (weighted approximately to give an equal area to each point) we get:

<u>Standard deviation of ΔZ = 0.038 mm</u>