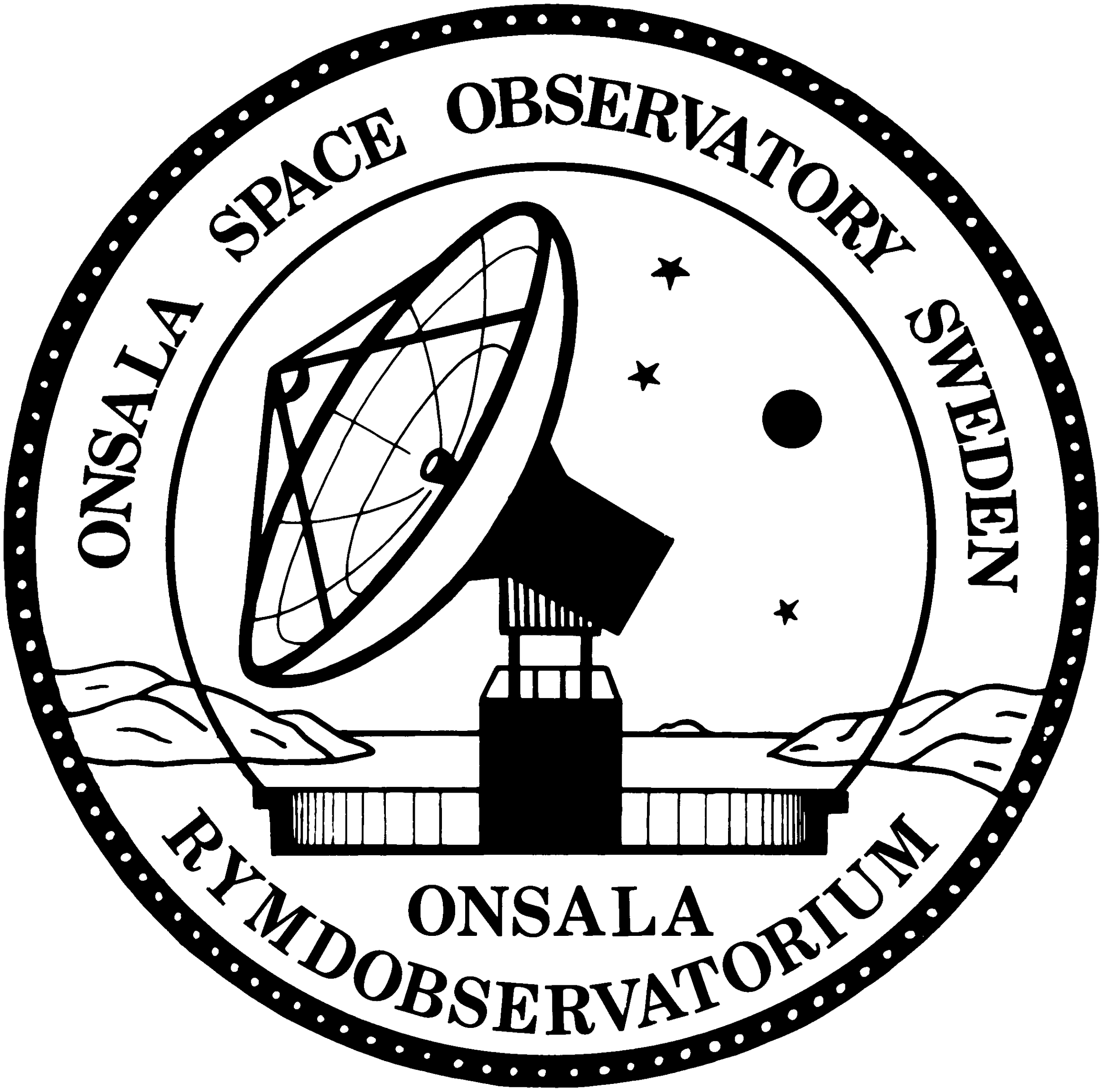

CHALMERS TEKNISKA HÖGSKOLA

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Report #9

THE ONSALA 20-METER TELESCOPE STABILITY TESTS

by

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March 1981

This paper is also published in the series of 25-meter Telescope Reports by the National Radio Astronomy Observatory, Charlottesville, VA, U.S.A. as Report No. 9.

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1. Introduction

The 20-meter diameter radio telescope at the Onsala Space Observatory is a precise instrument, located in a radome and intended to work at wavelengths of a few millimeters. It was dedicated in 1976 and since that time has given good results at frequencies as high as 115 GHz. The instrument is described by Menzel (1976). It was designed by ESSCO† and erected by that company and by the staff of the Observatory.

The present work may be the first step in a program to measure the shape of the reflector surface to a high precision and perhaps, if it is needed, to adjust it. However, before such a program is followed it is desirable to find out how stable in shape the telescope reflector is, since this can be a decisive factor in choosing the measuring method to be used. A simple method was adopted by which one ring of targets, located in the reflector surface close to the reflector rim, could be studied to see if possible changes of the reflector shape occurred. Within a radome it can be expected that changes in the thermal environment will be the main causes of reflector shape changes.

2. The Measuring Technique

(a) Instrumentation

Figure 1 shows the geometry of the telescope. With the dish fixed in the zenith position the levels of a number of the rim targets were to be measured by a precise optical level mounted at the correct height above the dish vertex. Figure 2 shows how this level was mounted to keep their weights from disturbing the measurements.

The level chosen was the Wild N III precision level (Wild Heerbrugg Ltd., Switzerland). This is a well-known and well-tested instrument. It can measure level differences over a range of ± 5 mm; it can be leveled and read to a precision of 10 microns (see Figure 3).

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* JWF is with the National Radio Astronomy Observatory, which is operated by Associated Universities, Inc., under contract with the National Science Foundation.

† The Electronics Space Systems Corporation of Concord, Massachusetts.

The practical reading accuracy depends on distance. In a series of tests made by A. Greve* of the Max Planck Institute for Radio Astronomy before our measurements he concluded a (1σ) precision of 50 microns at our range of 10 meters should be achieved.

The ring of targets observed were all quite closely at the same radial distance (9675 mm) from the dish axis. For our tests of stability we did not need to measure this distance since we were studying only the (possible) vertical motions of the targets. Four target positions were obliterated by feed legs, so 44 of the 48 targets were available to be measured.

The targets themselves (see Figure 4) were already fixed to the dish and were therefore used by us. They were very ill-suited to their task. We used three observers, and it soon became clear that we could not agree where the target "center" was. In fact, the designer of this target appears to have had in mind the creation of an optical illusion.

(b) Observing method.

The dish was positioned, with the brakes on, in the zenith position (azimuth reading was -15.52°) and the level mounted and leveled to a first order. After checking that all targets fell within the level measuring range, a series of tests were made to see if men moving on the observing platform or on the structure near the tower affected either the level stability or the telescope position. All was well.

Since it was possible that the telescope tilt might change during a run around the ring, the following target measuring schedule was adopted. (For convenience, we number the targets 1 through 48; 1 was target (22,16), 47 was (21,16). Targets 12, 24, 36, and 48 were not measured because of the feed legs.) We measured Nos. 1, 17 and 33 before starting round the ring. On reaching No. 17 we measured No. 33, No. 1 and No. 17 before continuing. On reaching No. 33 we measured Nos. 1, 17 and 33 and then continued to the end, testing closure by measuring Nos. 1, 17 and 33 again. The readings on these three targets 120° apart would have allowed us to correct for a change in telescope tilt during a ring of readings.

It soon became clear that no such effects were present, and later we checked only that the ring readings closed within the reading errors.

The targets needed good illumination--this was supplied from a hand-held spotlight.

(c) Measurements

The log of measurements is given in Table 1. All three authors observed. The temperature at various points on the structure and in the outside air were

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* Dr. Greve helped in planning the tests but could not be present for the measurements.

TABLE 1. THE ONSALA 20-METER TELESCOPE

Log of Measurements

Run #	Date Nov. 1980	Local Time	Observer	No. of points	T_s in °C Start to end	Mean Elevation mms
1	20	1310	JWF	44	0.9 - 1.6	5.925
2	20	1700	BH	44	4.6 - 6.2	6.352
3	21	1000	JE	44	8.9 - 9.4	6.374
4	21	1610	JWF	44	8.9 - 8.8	6.064
5	22	1205	JWF	12	8.9 - 8.9	6.058
6	22	1450	JE	12	9.2 - 9.3	5.838
7	22	1520	BH	12	9.3 - 9.3	5.977
8	22	1720	JWF	12	9.5 - 9.5	6.023
9	22	1740	BH	12	9.5 - 9.5	6.010
10	22	1810	JE	12	9.5 - 9.5	5.947
11	23	1150	BH	12	9.9 - 10.3	6.080
12	23	1220	JE	12	10.4 - 10.6	6.130
13	23	1255	JWF	12	10.7 - 10.8	6.272
14	23	1410	JE	12	10.6 - 10.4	6.136
Telescope azimuth changed by 90°						
15	23	1500	JE	12	10.1 - 9.7	6.086
16	23	1520	BH	12	9.7 - 9.3	6.164
Telescope tilted to 5° elevation and back						
17	23	1620	JE	12	About 9.3	5.889
18	23	1640	BH	12	About 9.3	5.918

recorded during the runs. In Table 1 we have given this temperature as T_s, which itself is a mean value of the temperatures measured at three typical points on the telescope. We have preserved all the temperature measurements, but we shall not discuss them in detail here.

The first four runs of 44 measured points each took from one to two hours to complete. As we shall describe later, the results of these showed good agrement, and so the measuring schedule was shortened to observe targets Nos. 1, 5 ... 45 and No. 1, giving a ring of 12 targets with closure. Using this 12-point schedule we measured 14 more times. We moved the telescope 90° in azimuth (to an azimuth of +75°) before runs Nos. 15 and 16. Finally, we tilted the telescope to an elevation of +5° and back before making runs Nos. 17 and 18.

The leveling screws of the N III were left untouched during runs Nos. 5 through 16. The level was demounted for the telescope tilt and was then releveled for runs Nos. 17 and 18.

We attempted to measure the height from the line-of-sight of the level to the vertex of the dish. For this we used four sections of an invar measuring rod with a micrometer end. This was in an attempt to see whether our measuring instrument remained at a fixed elevation. We will discuss these measurements later.

3. Data Reduction

The data for each run was in the form of level readings in millimeters for each target. It was recorded and hand-entered into a HP-65 desk computer. It should be noted that the level inverts, i.e., a high value for the level reading means that the target is below the reference line. The following steps were then taken:

(a) Compute the mean value of the N ring reading. N is either 48 or 12.

Note here that, for computing simplicity, we entered interpolated values for the four missing targets in the 48 point run. These mean elevations are given in Table 1.

(b) Subtract the mean value from the N ring values and then fit a sine curve to the resulting N values.

This step determines the angle of tilt of the best-fit plane through the ring values. The value of this tilt angle and its phase show the tilt of the target ring axis away from the gravity vertical (Appendix A gives the method of fitting a sine curve.) We printed out the amplitude and phase of this fitted curve for each run.

(c) Subtract the fitted sine curve at each of the N points to give Δz values for the departure of the N points from the best fit plane. Plot Δz vs N.

(d) Form the RMS of the N Δz_i values.

$$\mathrm{RMS} = \left\{ \frac{\sum_{i=1}^{N} (\Delta z_i)^2}{N} \right\}^{1/2} \tag{1}$$

and print the RMS in microns.

4. Discussion of Results

(a) The 44-point runs (Nos. 1 through 4)

The results of these four runs are plotted in Figure 5 as the departures of each point (Δz) from the best-fit plane through the points. Two deductions are clear from a study of Figure 5:

(i) The agreement between the four runs is very good.

(ii) The RMS of each run (264 to 280 microns) is about what would be expected. The whole telescope is believed to have an RMS departure from a paraboloid of about 210 microns, when the telescope is at 90° elevation. We return to this point in paragraph 5.

To examine the agreement between the four runs, we derived a figure for the RMS departure of the readings from the mean. We did this as follows: At each of the 44 points we took the mean Δz ($\overline{\Delta z}$) over the four runs. We then computed the RMS as:

$$\mathrm{RMS} = \left\{ \frac{\sum (\Delta z - \overline{\Delta z})^2}{4 \times 44} \right\}^{1/2} \tag{2}$$

where the sum is taken over each of the four ($\Delta z - \overline{\Delta z}$) values at each of the 44 points. The result, shown also in Table 2, is that the RMS = 39 microns.

Table 2. The RMS of the measurements, taken in groups.

Run Numbers	No. of Values	RMS in Microns
1, 2, 3, & 4	176	39
5, 6, 7, 8 & 9	60	31
10, 11, 12, 13 & 14	60	30
15, 16, 17,& 18	48	35

In view of our estimate of the repeatability of N III readings at this (10-meter range) this result is rather low. We shall return to this point later.

Three other quantities can be derived from these four runs. The mean z values we will reject; the N III leveling screws we altered during these runs. The amplitude and phase of the "tilt" sine wave were computed. We give here only the mean results and their RMS of the four values from the mean.

Tilt amplitude = (1.306 ± 0.090) mm

Tilt phase = (88.5 ± 1.4) degrees

The small RMS numbers associated with these measures of the telescope tilt again show the stability of the structure over a period of 27 hours.

(b) The 12-point runs (Nos. 5 through 18)

The four runs already described had demonstrated the repeatability of the shape of the edge of the telescope when referred to a mean plane put through the edge points. We therefore turned our attention to measuring as well as we could the stability of the elevation of this mean plane. This was a more difficult task since the z-direction stability of our mount for the N III (Figure 2) now entered the measuring loop. To watch this level stability we tried from time to time to measure from a fixed point on the underside of the tripod to a point in the plane of the telescope reference ring—a distance of about 2.6 meters. We used an invar steel rod in four sections with a micrometer device* reading to 0.001 inch (25 microns). However, since the

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* A Starrett inside micrometer.

observers had to climb through the reference ring we had to use a demountable reference point on the ring and this surely introduced errors. However, four readings were taken, as follows:

Table 3. Readings of the Micrometer on the Distance Rod

Local Time and Date	Approximate T_s	Micrometer
1540 Nov. 21	8.9° C	12.903 mm
1200 Nov. 22	9.0° C	13.106 mm
1430 Nov. 23	10.6° C	13.233 mm
0900 Nov. 24	5.0° C	13.157 mm

Mean = (13.100 ± 0.071) mm where 71 microns is the s.d. of the mean.

We used the distance rod measures to give an elevation, above the (believed) location of the dish vertex, for the mean plane through the edge targets, and arrived at z (edge) = 2614.5 mm.

The average value of x for these targets was known from earlier measures to be x (edge) = 9675.0 mm. If we accept these values, the focal length of the dish at the edge is found to be 8950.6 mm. The nominal value is 8966.7. This is probably satisfactory agreement.

For runs Nos. 5 through 16, we were able to observe without altering the coarse level screws of the N III on the tripod. Thus we could avoid altering the level height. By measuring only 12 points we could observe quickly (a run took 15-20 minutes). Results were reduced exactly as for the 44-point runs. Figure 6 is a typical result, and Tables 1 and 2 summarize all the runs. We can draw the following conclusions from these results:

(i) The agreement between the values of Δz for all the runs is again excellent. In Table 2 we have grouped the runs into blocks of 5 and got the RMS exactly as we did for the 44-point runs. The results show RMS values of between 30 and 35 microns.

(ii) The RMS of the targets themselves is lower (about 230 microns instead of about 270 microns) for these as compared to the 44-point runs.

This is clearly due to the fact that the 12-point runs by chance missed several of the "bad" targets.

(iii) The mean elevations for run Nos. 5 through 16 show variations which seem to be random. Runs Nos. 17 and 18 cannot be used since the N III was demounted and remounted for the telescope tilt. However, the mean of all elevation measures (Nos. 5 through 16) is:

$$\text{Elevation} = (6.060 \pm 0.033)\ \text{mm}$$

where the 33 microns is the standard error of the mean of 12 values.

We present this result with the comment that a part of the scatter in the mean level measured was most probably due to the difficulty of every observer agreeing on the target "center" (see paragraph 2(a)). However, we cannot say how big this error contribution might be.

5. Comparison with Earlier Surface Data

The surface of the 20-meter telescope was originally set and adjusted using a Wild T2 theodolite. This was, however, not stable enough to adjust the surface to its stability limits. Figure 7 shows a comparison between the values obtained after the final surface adjustment in February, 1976 and the average of optical level measurements No. 1-4 in November, 1980. The theodolite curve of Figure 7 is the actually measured curve of the outermost ring at an elevation of 90°. At that elevation the estimated RMS of the outer panels then was 260 microns. The surface was set at an elevation of 90°, with a precalculated offset in order to obtain the best surface at an elevation of 60°. The RMS deviation from the best fit paraboloid at this elevation was found to be 170 microns. The general appearance of the curves shows a close similarity, although some supports may have changed their position by as much as 0.3-0.4 mm. The RMS of the difference between the curves is 0.184 mm.

6. Conclusions

We conclude that both the telescope and the measuring system were remarkably stable throughout the tests. We cannot be sure of the absolute errors which might limit a subsequent attempt to set the telescope more precisely, but we suggest the telescope and measuring system stability might contribute as little as 50 microns to the error budget for such a task.

We saw no signs of hysteresis as a result of rotating or tilting the telescope.

References

Menzel, D. H. Sky and Telescope, 52, 241-242, October, 1976.

Figures

1. The telescope geometry.
2. The tower to carry the level and the observers.
3. The Wild N III level.
4. A target.
5. Runs Nos. 1 through 4.
6. A typical 12-point measurement.
7. The 48 edge targets measured by theodolite in February, 1976 and the mean of runs 1 through 4, November, 1980.

APPENDIX A

To fit a sine curve to N points equally spaced in angle over 2π radians. Note -- we knew our targets were at equal azimuth angles from measurements when the telescope was built). Let the N elevations be $z_1 \ldots z_N$. Compute

$$A = 2/N \sum_{i=1}^{N} z_i \sin \frac{2\pi i}{N}$$

$$B = 2/N \sum_{i=1}^{N} z_i \cos \frac{2\pi i}{N}$$

Then the best-fit sine curve is

$$\sqrt{A^2 + B^2} \sin \left\{ \frac{2\pi i}{N} + \text{arc tan } B/A \right\} .$$

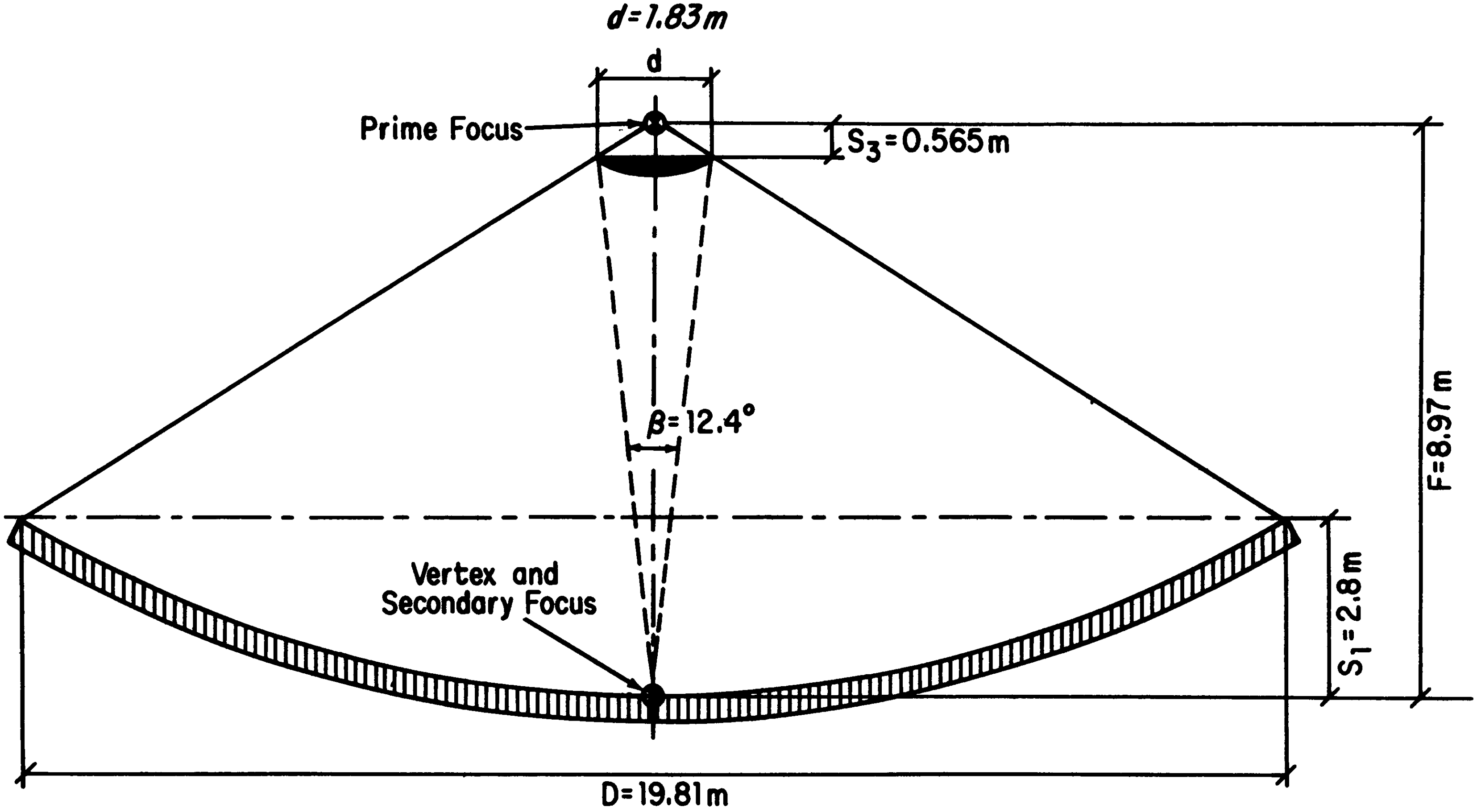


Figure 1. The telescope geometry.

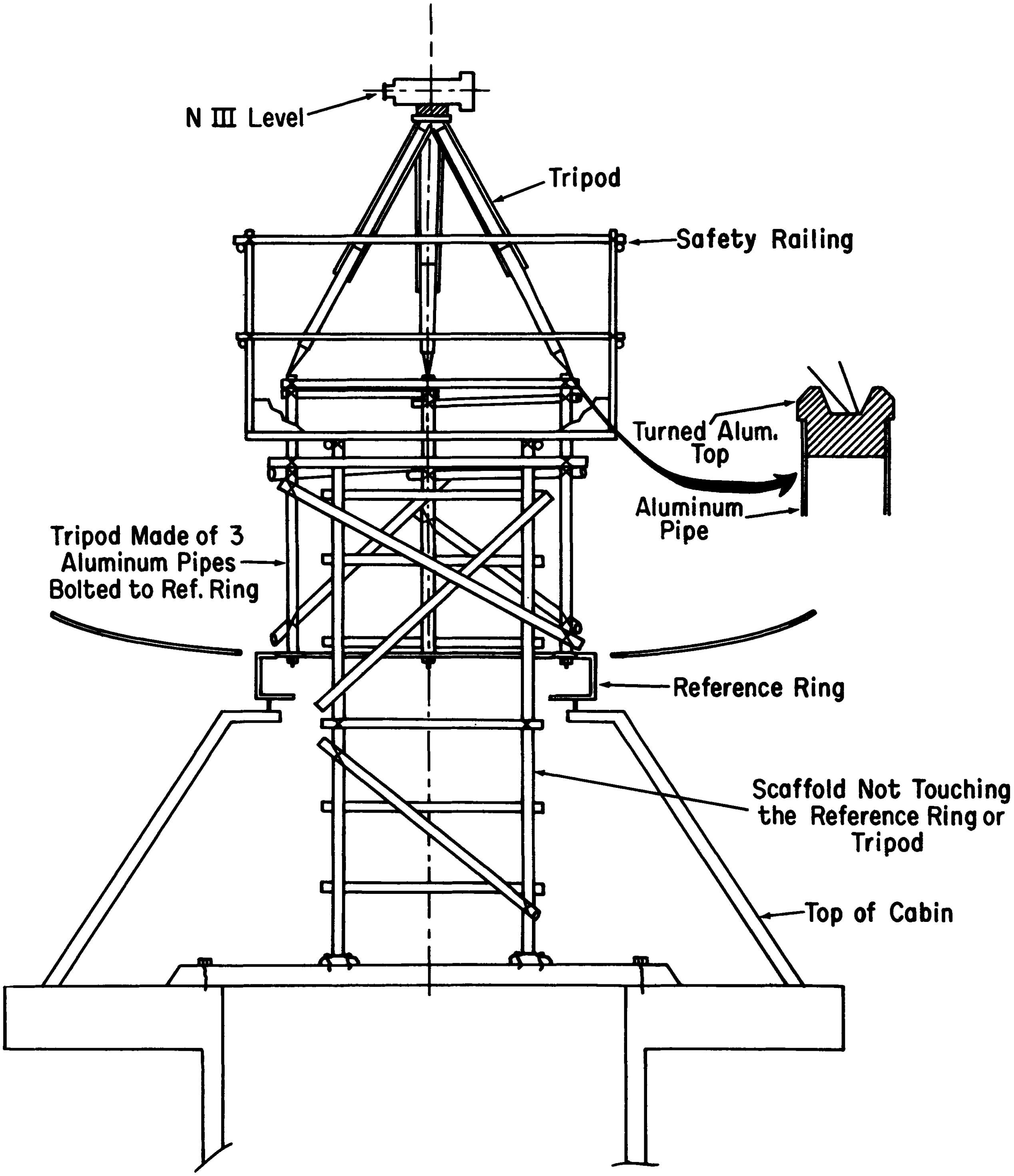
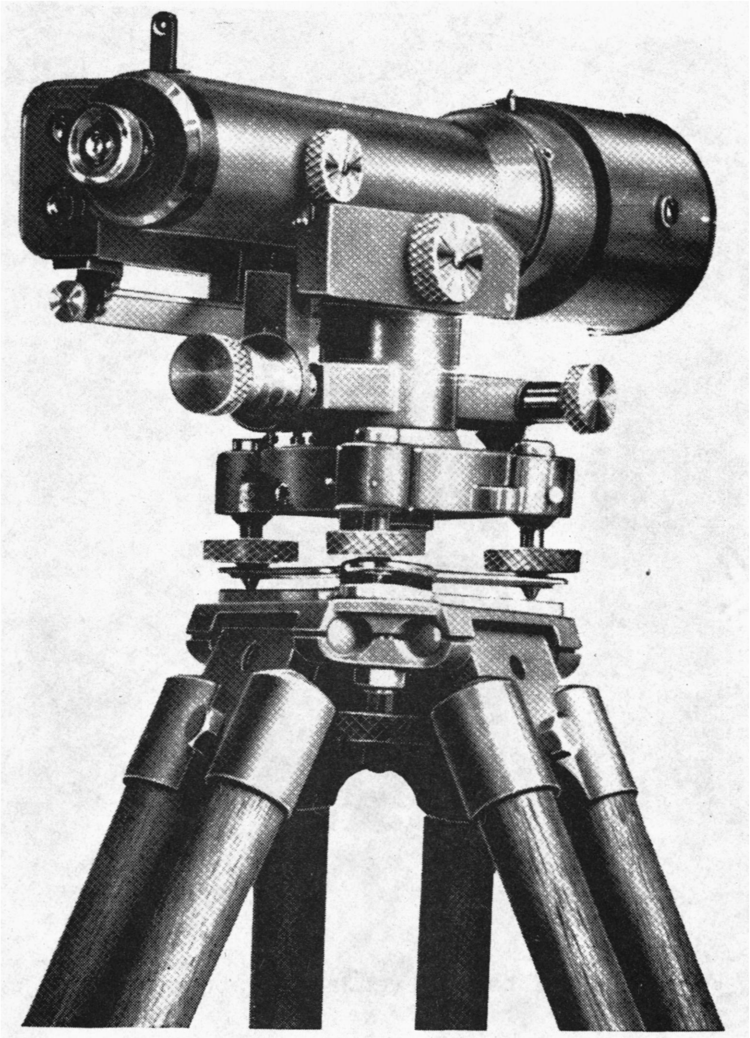
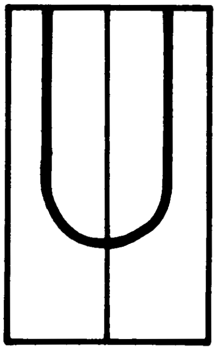
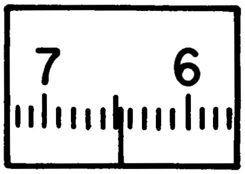


Figure 2. Tower to carry level and observers (scale about 1:30).





The split bubble, when centered.



Scale reading 6.47 mms.

Figure 3. The Wild N-III level.

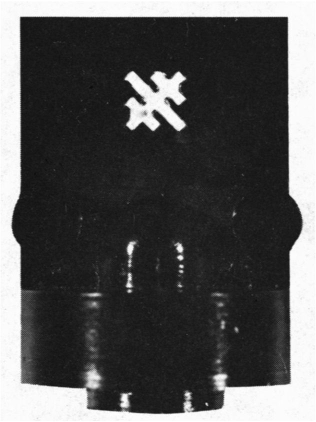


Figure 4. A target (enlarged about 4 times).

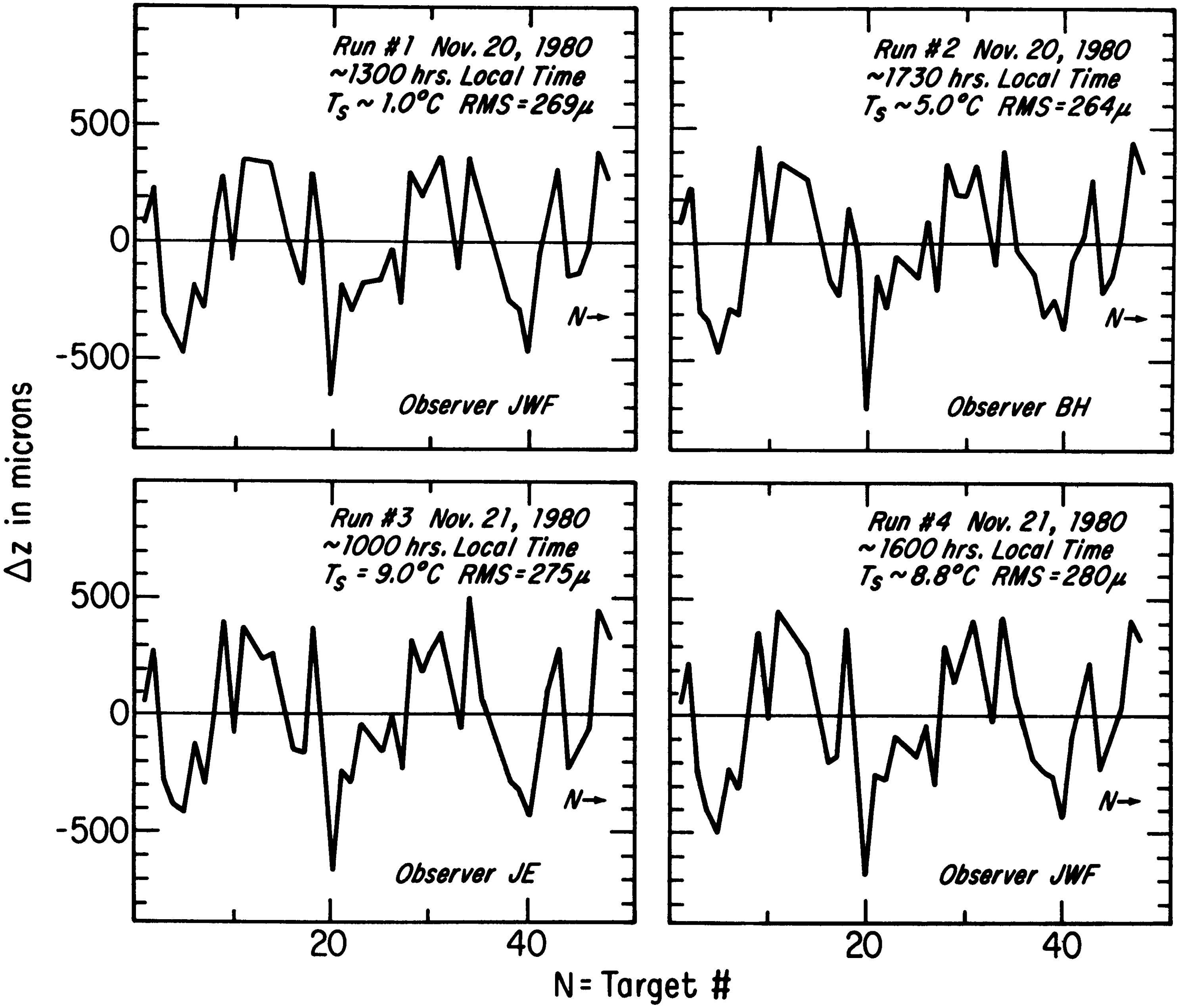


Figure 5. Runs 1 through 4.

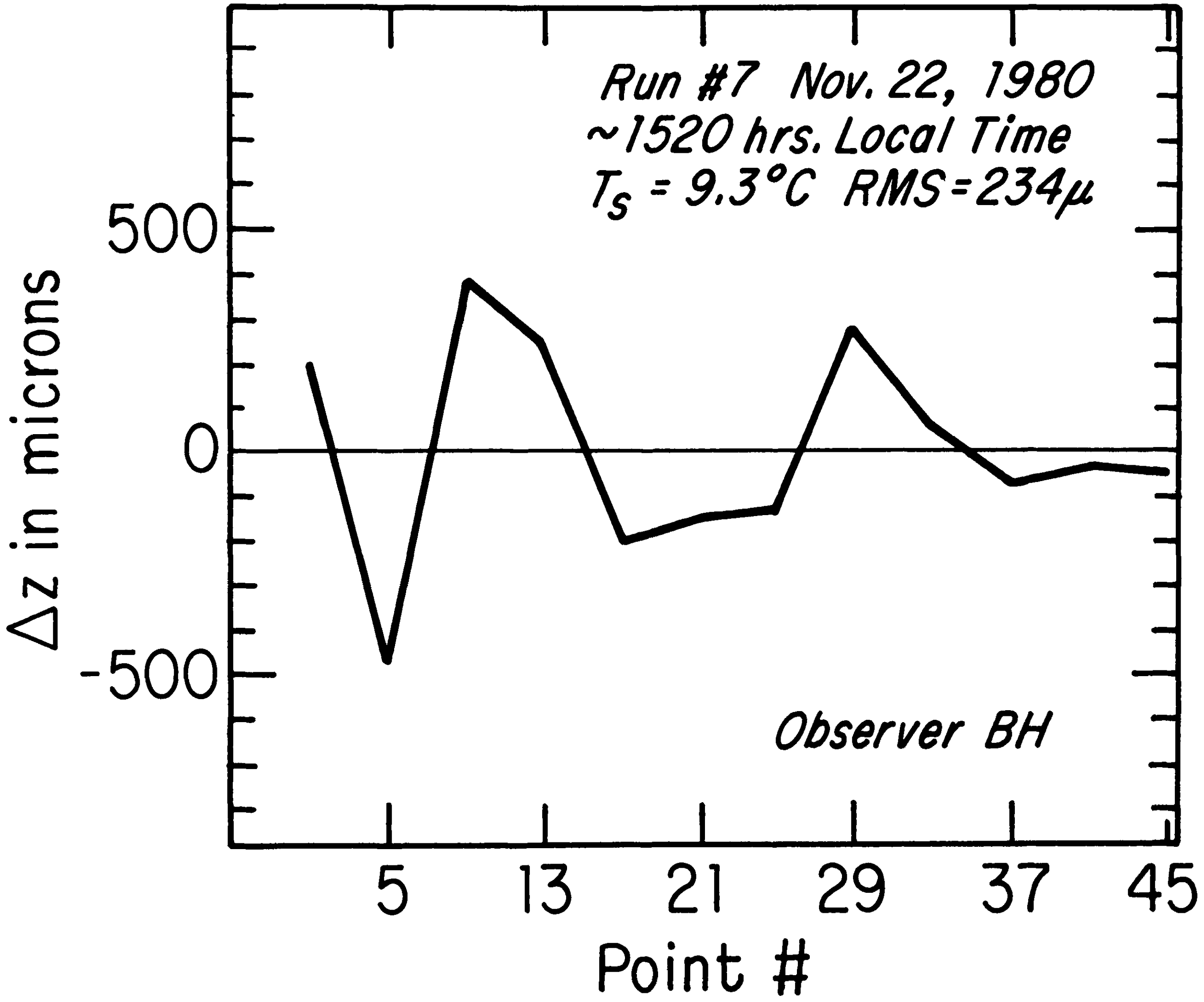


Figure 6. A typical 12-point measurement.

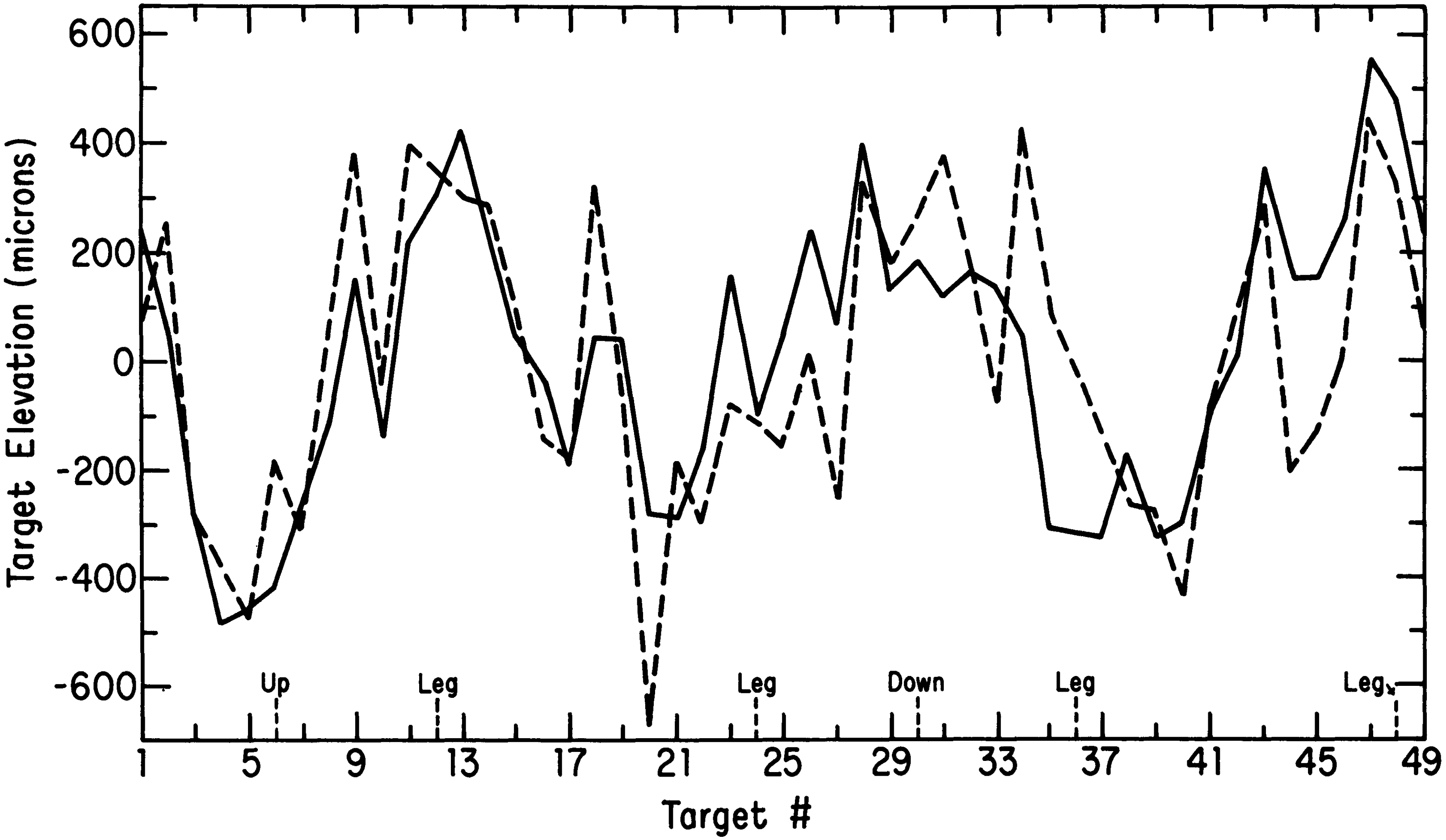


Figure 7. The 48 edge targets measured by theodolite in February 1976 (solid line) and the mean of runs 1 through 4 November 1980 (dotted line).