NATIONAL RADIO ASTRONOMY OBSERVATORY

25-Meter Millimeter Wave Telescope Memo No. 94

TESTING THE STEPPING METHOD ON THE 140 FOOT

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1. INTRODUCTION

Memos Nos. 68, 70 and 82 described the method of measuring telescope surfaces by stepping along a radius with a bar of known length and measuring the inclination of the bar to the vertical at each step. The method has now been tested on one radius of the 140-foot telescope with good results. This memo describes the method and the results of the tests. It seems very likely that the method will be accurate enough to measure the 25-meter telescope.

2. THE INSTRUMENTATION AND ITS CHARACTERISTICS

(a) The measuring bar

A bar (Fig. 1) was made to carry the LSOC inclinometer. Since the LSOC measures over the range ± 14.5° it was mounted on a wedge at the bar center so that it would read about -14° at the first step, near the telescope center, and about +14° near the telescope edge. Contact surfaces for the LSOC and the wedge were machined. The bar length L (nominally 650 mm), was defined by having the bar rest on two 12.7 mm diameter steel spheres. One of these was attached to the bar; the other could slide a small distance lengthwise. In its final form it was intended that the small changes in L required when the bar was used would be sensed and recorded by a length sensor. As we say later, this system was not used in the present tests.

(b) Data collection and processing

The voltage output from the LSOC (which varied between ± 5 volts) was read by a digital multimeter (DVM) with the following characteristics:

Maker: Data Precision Corporation, Wakefield, Mass. 01880
Range used: ± 10 volts
Accuracy: About ± 100 microvolts on 10 volt range
Least significant digit: 100 microvolts on 10 volt range
Interface: Direct to HP9825A computer
Read time: 250 milliseconds

The HP9825A interface allowed the DVM to read in, at its own rate of 4 numbers per second, any desired block of readings. For all the present telescope tests, blocks of 20 were used. The HP9825A was programmed to accept and store all the raw data on its cassette tape and to take and print the means and RMS values of each data block, after converting the voltage values to angles.

(c) Tests of the data system

As was discussed in Memo No. 82, the method of sampling and averaging the LSOC voltage might be important, so tests were made to see what averaging took place in the DVM. (Although a study of the instrument design could give this information, a practical test was more useful.) Accordingly the LSOC output voltage (with the inclinometer on a stable base) was read as described in Memo No. 82, into the IBM 360 and also, via the DVM, into the HP9825A. The read rates were about 40 and 4 per second, respectively. Thus blocks of 6400 numbers went to the IBM 360 and 640 to the 9825A. The RMS voltage was then derived for:

(i) The voltages read by the IBM 360, taken in blocks of 200.
(ii) The voltages read by the 9825A, taken in blocks of 20.

The RMS values from (i) would be expected to show no integration effects--they were instantaneous values sampled, held and read. The values from (ii) should show the integration effects of the DVM. In all the above by RMS we mean, for n observations of x_i,

$$\mathrm{RMS} = \left\{ \frac{\sum_{1}^{n} (x_i - \bar{x})^2}{n - 1} \right\}^{1/2}$$

The results of one test of the several made serve to show the DVM integration effects:

(i) RMS from 15 IBM blocks of 200 values each = 351 microvolts.
(ii) RMS from 15 9825A blocks of 20 values each = 50.1 microvolts.

We may thus conclude that a single DVM reading alone would be adequate to reduce the inherent LSOC noise to 50 microvolts (equivalent to an angle of 0.5 arc seconds). In all the following work we used 20 DVM readings, since we were to be limited by telescope-induced noise while on the 140 foot.

3. TESTS ON THE 140-FOOT TELESCOPE

(a) The chosen radius

A line of holes was drilled in the telescope surface along a radial line at an azimuth of about 12° E of N. This line was chosen so that it was not far from the edge of the panels in the center and outer rings. It then, of course, went almost through the center of the inner ring panel.

Pilot-holes were first drilled through the surface plates and then, using a centering bit, the holes were counter-sunk to give a hole of uniform depth shaped to fit the steel spheres. It was important that the bar rested in these holes, even when it was on the almost 30° slope of the upper part of the radius. The telescope was held in the zenith with all brakes on.

In a separate test the bar was used to measure the hole separation. For this, a micrometer was mounted on the bar (Figure 1). There were 33 holes, the inner one being at a nominal position of x = 1574.90 mm, z = 33.91 mm. (The xy coordinates lie in a horizontal plane passing through the telescope surface vertex and z is vertical.)

Although it may be that the L values changed with time over the 8 days of the tests, only one set of measurements was taken and used throughout. In a real measurement of a telescope the bar would be arranged to measure L and record it, as well as the angle, at each step. The 32 values of L were all close to 650 mm, the largest difference being 1.30 mm. In reducing the results the measured L value for each step was, of course, used.

(b) The bar and its cabling

The voltage output from the LSOC was taken via about 25 meters of shielded twin cable to the telescope cabling near the Cassegrain house. From there it went to the control room, where the DVM and 9825A were placed. Despite this long cable run the voltage at the DVM appeared to be clean. It was monitored by an oscilloscope to watch for stray voltages.

Power (± 15V DC) to the LSOC was similarly sent over 25 meters of shielded twin, with the shield as the zero voltage conductor.

A transverse spirit level and a levelling screw were fitted to the bar, since at each step it was important that the transverse axis of the LSOC should be level to a few minutes of arc. Thus, to take a reading, the bar had to be placed with its two spheres in the holes and levelled transversely. The operator would then step away and command "read". The 9825A would read 20 times and the operator would move the bar to the next position.

(c) Tests and measurements

The 140 foot was out of use for a number of equipment changes to be made for a large part of May. The following Table 1 summarizes the times spent on the measuring tests:

Table 1. Schedule of tests and measurements

Date and time (EDT)	Activity and Result
May 4 - a.m. 1400-2000	Holes on radius measured by JR. Installing and cabling. Tests of stability with bar near telescope center.
May 6 - p.m.	Program writing and testing.
May 7 - 1000-1500	First trial run, weather wet and calm. LSOC scale wrong. Reject run.
May 8 - 1000-1300	Second trial run. Results fair but heavy rain allowed only one run. LSOC mount and level need modification.
May 12 - 1400-1600	Three runs completed, JNR and S. Smith operated measuring bar. Windy and sunny weather. Time per run about 20 minutes.

4. RESULTS OF THE TESTS

(a) Telescope stability

The first thing to be tested was clearly whether the 140-foot would remain steady, with respect to gravity, over periods of 30 minutes or so and whether the LSOC on the telescope would develop higher noise levels due to mechanical interaction between the telescope and the inclinometer. (See Memo #82, paragraph 4(c).) Accordingly on May 4 and again on May 7 the bar was placed on the telescope and the LSOC performance measured. On both days the wind was less than 8 km/hour and the sky was overcast with some rain. Table 2 below summarizes measurements taken on these two days. In Table 2 we give the (1σ) standard deviation of the mean of 20 observations, in arc seconds, as a measure of the overall noise in the telescope and the LSOC.

Table 2. Stability tests of May 4 and 7

Date and bar position	EST	Recorded mean angle in degrees and 1σ value (arcseconds)
May 4. Bar on first step.	1603-1612	-11.5493° ± 0.68"
	1810-1830	-11.5507° ± 0.53"
Bar removed at 1850 and replaced	1835-1850	-11.5511° ± 0.83"
	1851-1900	-11.5512° ± 0.80"
May 7. Bar on step #24	1200	+7.2912° ± 0.98"
	1215	+7.2911° ± 0.85"
	1306	+7.2897° ± 1.69"

The weather conditions, although wet, were good on these days. The May 4 results suggest that either the 140-foot or the LSOC and bar moved by about 7 arc seconds in three hours. For both days the angular noise is excellent--below our required figure of 2 arc seconds.

(b) Reproducibility of results

Three runs were made on May 12 over the test radius. The weather was bright, sunny and windy, with occasional readings of the wind speed indicator of 20 km/hr. The telescope was not stable; throughout the run the TALYVEL level on the declination axis was recorded and it showed peak-to-peak movements of 16 to 20 arc seconds. Nevertheless the three runs were carried through; each took about 20 minutes. The operators had neither used the measuring bar previously. The measuring bar was returned to position #1 at the end of each run and that measurement was repeated.

Table 3 below summarizes the angles measured for each of the 32 steps on each run, and gives the 1σ value for the mean for each angle. The numbers can be compared with those in Table 2 to show how much more angular noise has been produced by the wind. The mean value of the standard deviations in Table 3 is 5.27 arc seconds, while in Table 2 it is only 0.91 arc second. There is no apparent drift with time of the angles recorded in Table 3. A rough straight line has been put through the angles at each step and the mean slopes of all these lines is close to zero. However, the measured angles at various steps do change randomly with time. We suspect that these changes were due to actual movements of the telescope surface in the sun and wind.

Table 3. The angles and their errors for the three runs of May 12.

Step No.	Run #1 Angle in degrees	Run #1 1σ in arc secs	Run #2 Angle in degrees	Run #2 1σ in arc secs	Run #3 Angle in degrees	Run #3 1σ in arc secs
1	-13.8544	4.0	-13.8469	3.2	-13.8432	7.6
	-12.7868	4.0	-12.7803	1.9	-12.7838	2.7
	-11.8144	8.1	-11.8180	2.7	-11.8103	6.9
	-10.7516	6.0	-10.7448	2.8	-10.7489	5.4
5	- 9.6646	5.0	- 9.6628	1.8	- 9.6592	10.0
	- 8.8205	5.3	- 8.8225	2.4	- 8.8211	3.2
	- 7.8454	4.2	- 7.8461	2.8	- 7.8483	3.0
	- 6.8112	2.2	- 6.8083	2.5	- 6.8095	6.7
	- 5.8637	2.9	- 5.8693	4.7	- 5.8622	2.4
10	- 4.8663	3.2	- 4.8546	2.7	- 4.8581	1.2
	- 3.9154	3.3	- 3.9459	2.9	- 3.9435	1.5
	- 2.9740	4.5	- 2.9817	3.6	- 2.9771	1.1
	- 1.9574	5.4	- 1.9596	5.9	- 1.9575	2.1
	- 1.1668	3.0	- 1.1674	3.0	- 1.1685	1.7
15	- 0.3355	1.3	- 0.3440	2.0	- 0.3374	1.6
	0.6770	1.9	0.6769	6.1	0.6784	1.7
	1.5953	2.3	1.5928	4.5	1.5946	0.83
	2.3396	3.1	2.3517	6.3	2.3372	1.4
	3.3539	10.0	3.3568	12.4	3.3474	1.3
20	4.0106	3.7	4.0133	3.3	4.0141	2.6
	4.9487	9.7	4.9518	2.2	4.9470	1.3
	5.7754	6.5	5.7808	21.6	5.7710	1.1
	6.4150	4.3	6.4135	6.3	6.4143	1.5
	7.2688	3.9	7.2568	5.0	7.2568	9.7
25	8.0649	7.8	8.0632	4.1	8.0621	3.8
	8.8289	4.9	8.8288	14.4	8.8263	17.9
	9.5764	5.3	9.5791	7.4	9.5782	17.9
	10.3110	7.2	10.3080	5.2	10.3126	12.4
	11.0143	4.2	11.0201	5.6	11.0205	14.0
30	11.6472	2.8	11.6532	6.2	11.6577	6.4
	12.3334	9.9	12.3342	6.1	12.3439	10.4
32	13.1522	14.4	13.1590	6.1	13.1623	8.8
1	-13.8475	8.6	-13.8409	6.6	-13.8388	5.1

The mean value of the (1σ) error is 5.27 ± 0.7 arc seconds.

(c) Reduction of the results

The results of Table 3 have been reduced as follows. First, to arrive at the angles of Table 3 the Schaevitz calibration of the LSOC has been used. This is well fitted by a line:

$$\sin \theta = (0.0071 - \text{Voltage}) \times 5.0104 \times 10^{-2}$$

where θ is the inclinometer angle. There is one adjustable constant--the angle θ_o that the LSOC would read when the bar rests on a horizontal surface. Checks suggest that this angle is about -16.77°, but it cannot be measured since it is out of the LSOC range. We therefore have, in the present tests, adjusted this angle to give the best fit of the measurements to a perfect parabola of focal length (F) of 18288 mm. The 140-foot surface has been set to this focal length. Similarly, we have assumed that the innermost hole on the surface has x = 1574.90 mm, z = 33.91 mm--a point on this perfect parabola. The HP9825A then calculates the x,z values of each new point by:

$$x_{N+1} = x_N + L_N \cos \theta_N$$

$$z_{N+1} = z_N + L_N \sin \theta_N$$

and computes Δ_N for each point by

$$\Delta_N = x_N^{\,2}/4F - z_N.$$

Finally it computes $\Sigma\Delta_N$ so that a best-fit can be found by varying the value of θ_o. It then plots Δ_N for each run--see Figure 2.

This process for the three runs of May 12 yields the following result:

(i) A single value of θ_o (-16.769) gives a best-fit for each of the three runs.

(ii) The RMS of the surface errors along the measured radius of the telescope is 0.67 mm, a value in good agreement with the radiometrically measured value of about 0.8 mm for the whole dish at the zenith. (One would expect a somewhat lower RMS for a single radius than for the whole dish.)

(iii) The 3 runs of May 12 shown in Figure 2 can be used to give an estimate of the measurement accuracy of the method, shown in Figure 3. In that figure we have computed D from the 3 z values at each x:

$$D = \sqrt{\frac{\Sigma(z-\bar{z})^2}{6}}$$

i.e., D is an estimate of the accuracy of the mean of the three plots of Figure 2.

(iv) The mean value of D over the 32 points is 66 microns.

5. COMMENTS AND CONCLUSIONS

(a) Error sources not investigated

This test was intended to find out how well the method would reproduce results on a real telescope. Thus, for example, we accepted the Schaevitz calibration of the LSOC. It should be calibrated over $\pm$ 14.5° to one arc second, but such a task is not easy. However, if we had a millimeter-wave telescope we would use its elevation indicator to calibrate the LSOC.

The surface may bend slightly under the bar. This effect is not going to be serious, the bar weighs 2.8 kgrm, and could easily be corrected for.

The readings of the LSOC did not seem to drift with time, but the effects of temperature changes should be examined.

No attempt was made to measure the depth of the holes below the surface. Again, it is easy to make such measurements to the required accuracy.

(b) Suggestions

The method adopted may not be the best for a specific problem. For some telescopes a longer bar (or more than one bar) might be used. Steps around circles as well as along radii could be made. For a full telescope survey the bar might be turned into a cart, with automatic transverse levelling, and stopped each time to read θ at specific S values read from the wheel encoder. A good survey needs a common cart or bar start-point, at the nominal surface vertex.

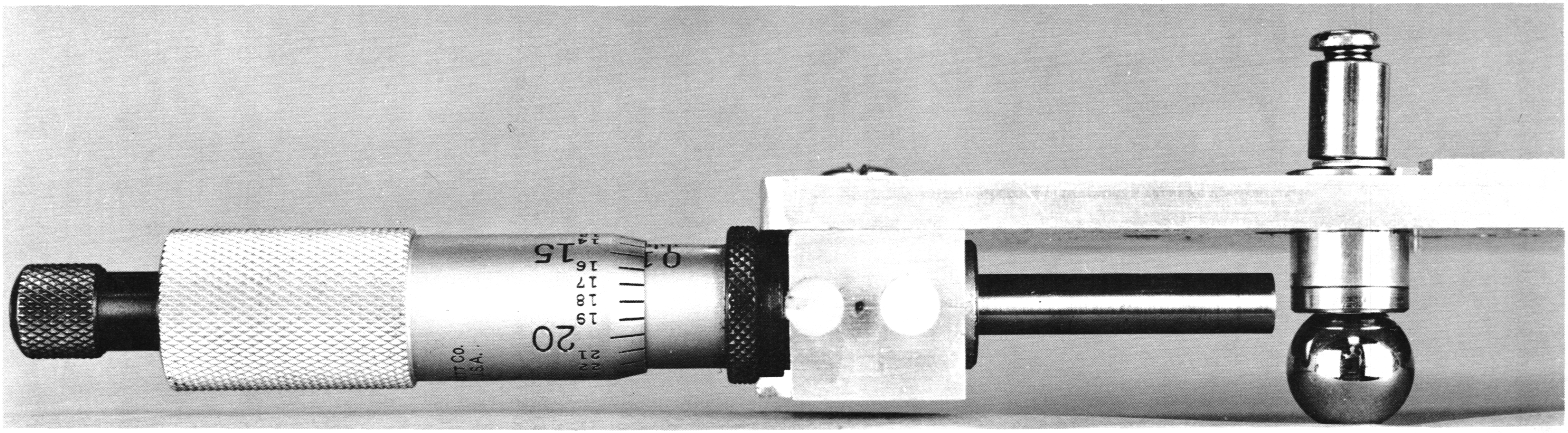
(c) Conclusions

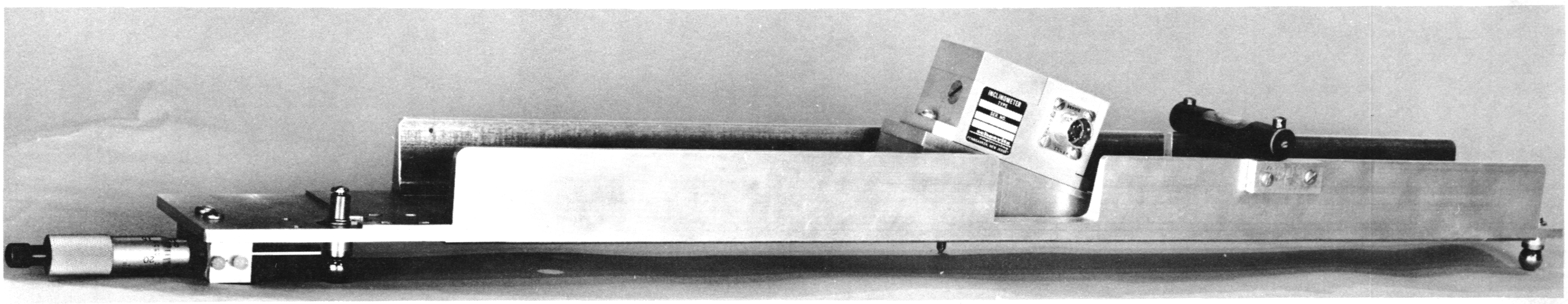
Even in this elementary form the method measured 32 points to better than 100 microns in 20 minutes on a shaky telescope. It seems quite reasonable to say that, with sensible development, it could measure the nine rings on the 25-meter surface to our required 40 micron accuracy. It may be somewhat slow, but that may not be vital for a method to be used in an astrodome with a controlled environment.

(d) Acknowledgements

We thank R. Fisher for help in arranging to read our results into the HP9825A.

List of Figures



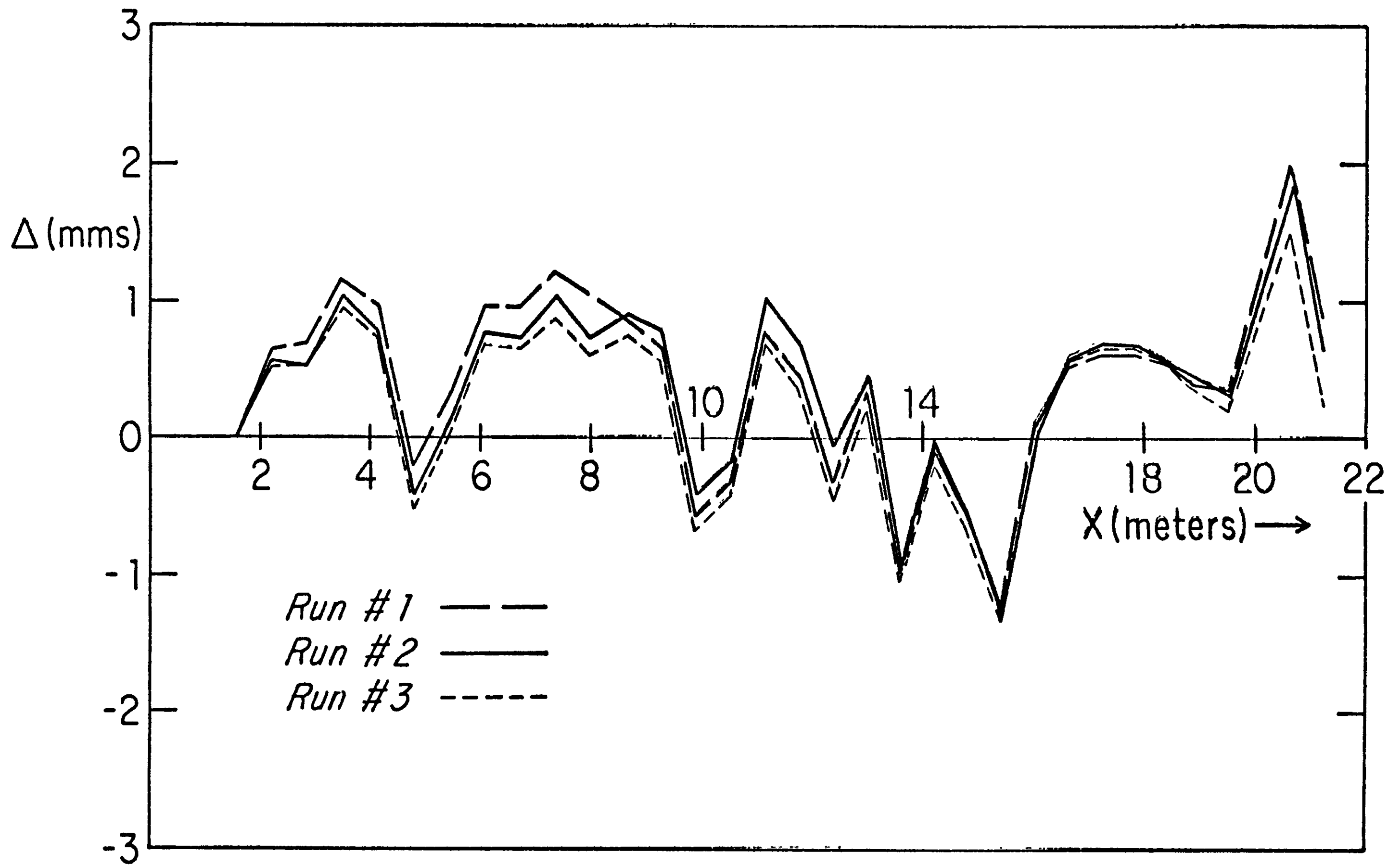


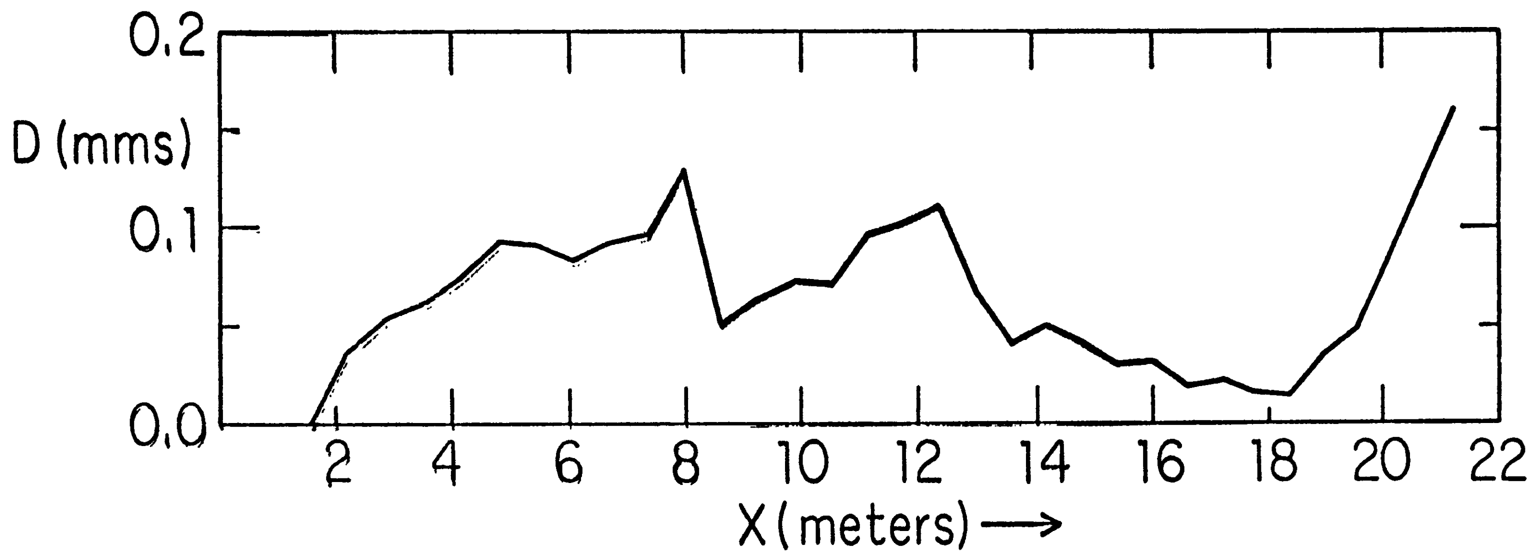
The inclinometer and bar used for the stepping method.

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

Figure 2

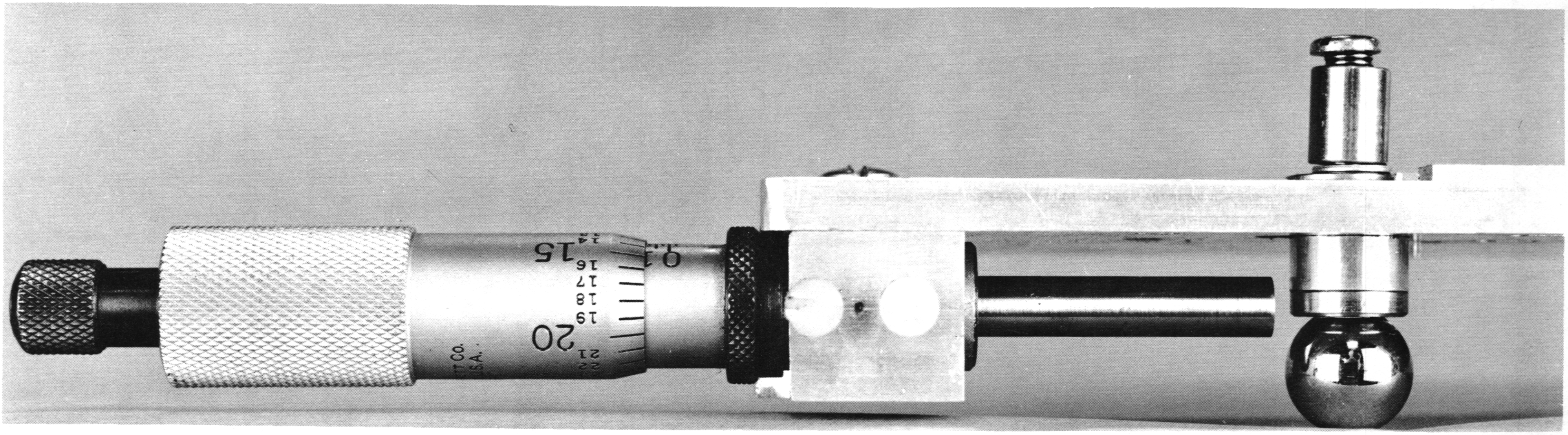
Deviations from the design parabola for the 140-foot for the three runs of May 12th.

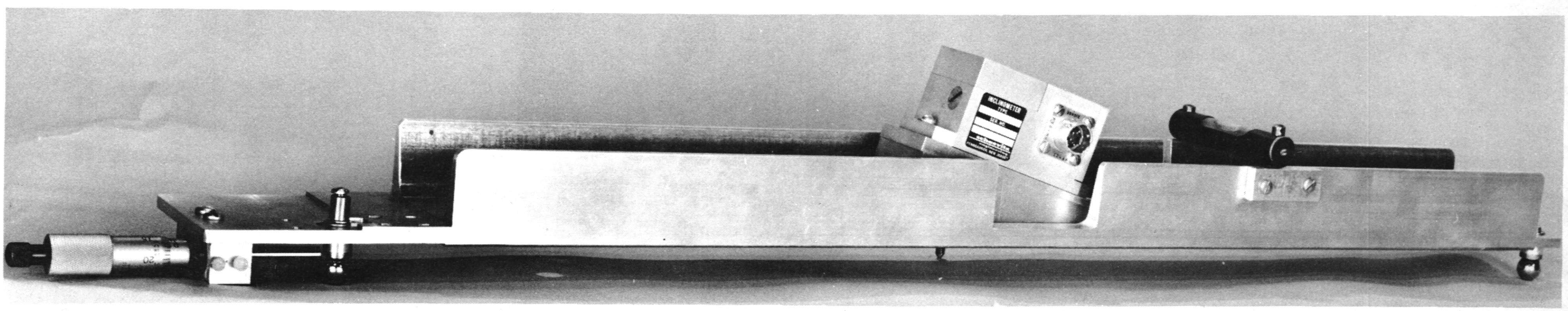




<u>Figure 3</u>

The estimated measurement error for the three runs of May 12th.





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Lower: The bar, inclinometer and tranverse level.
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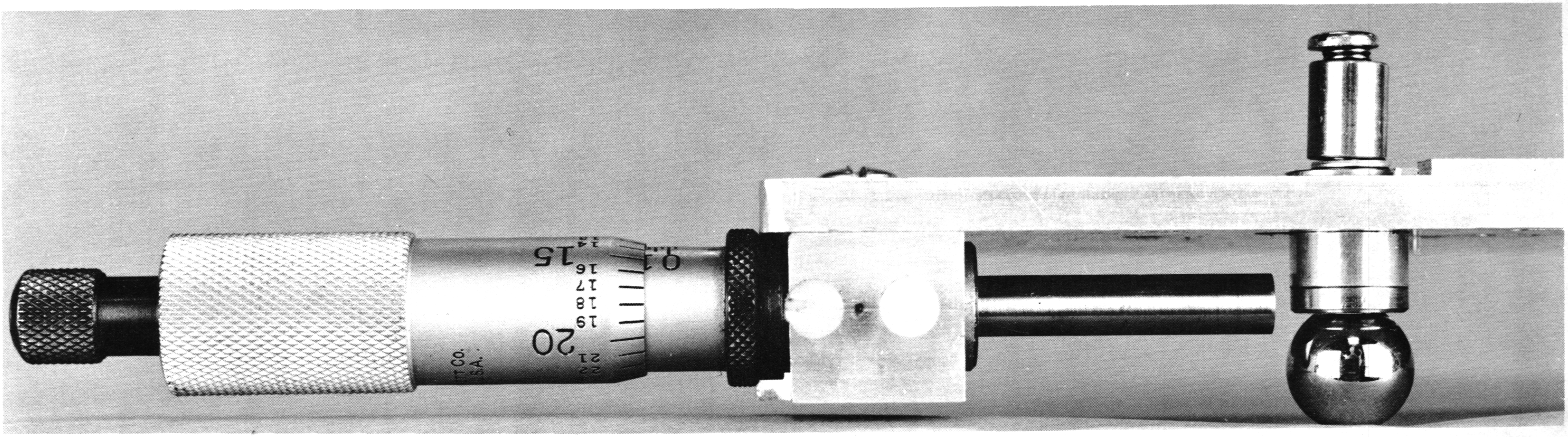

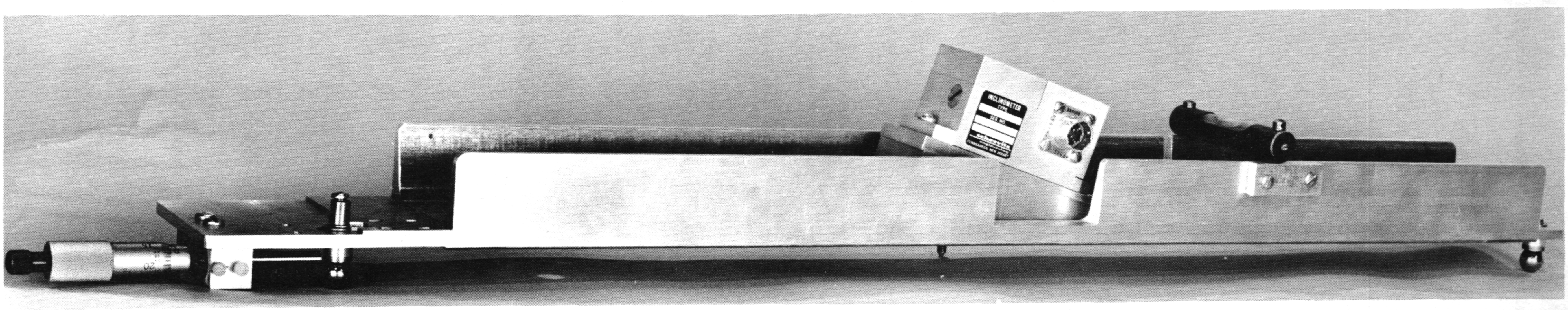

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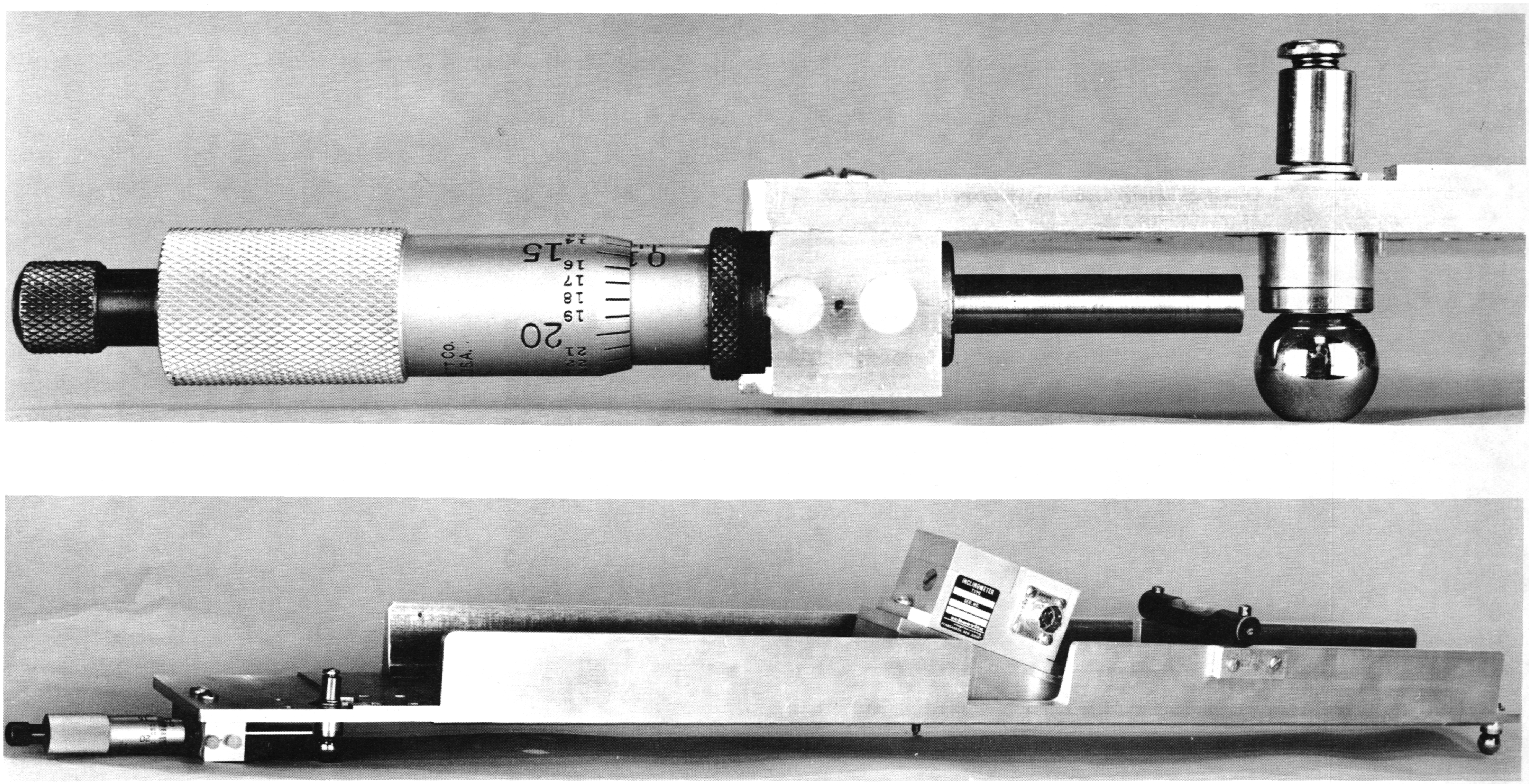

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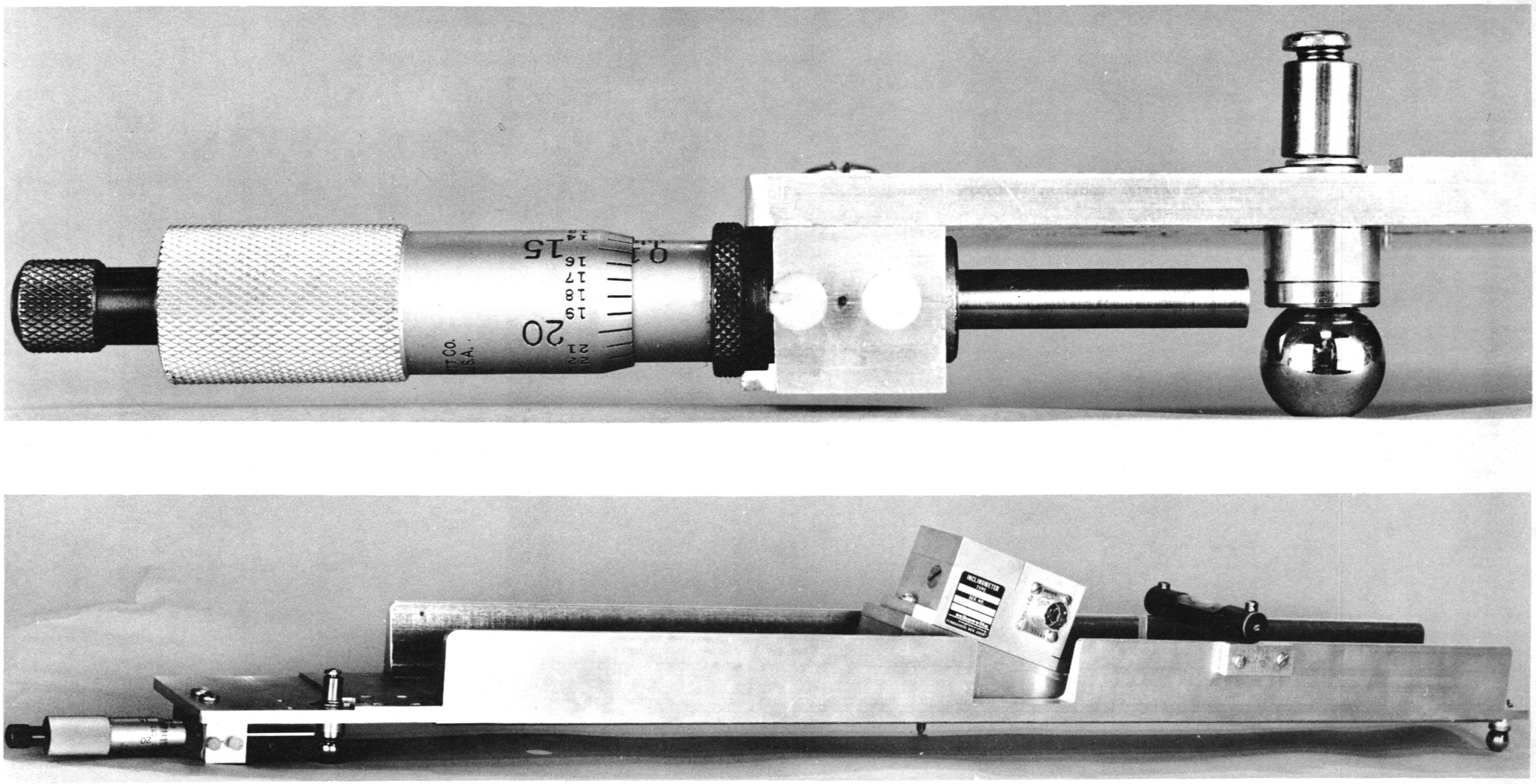

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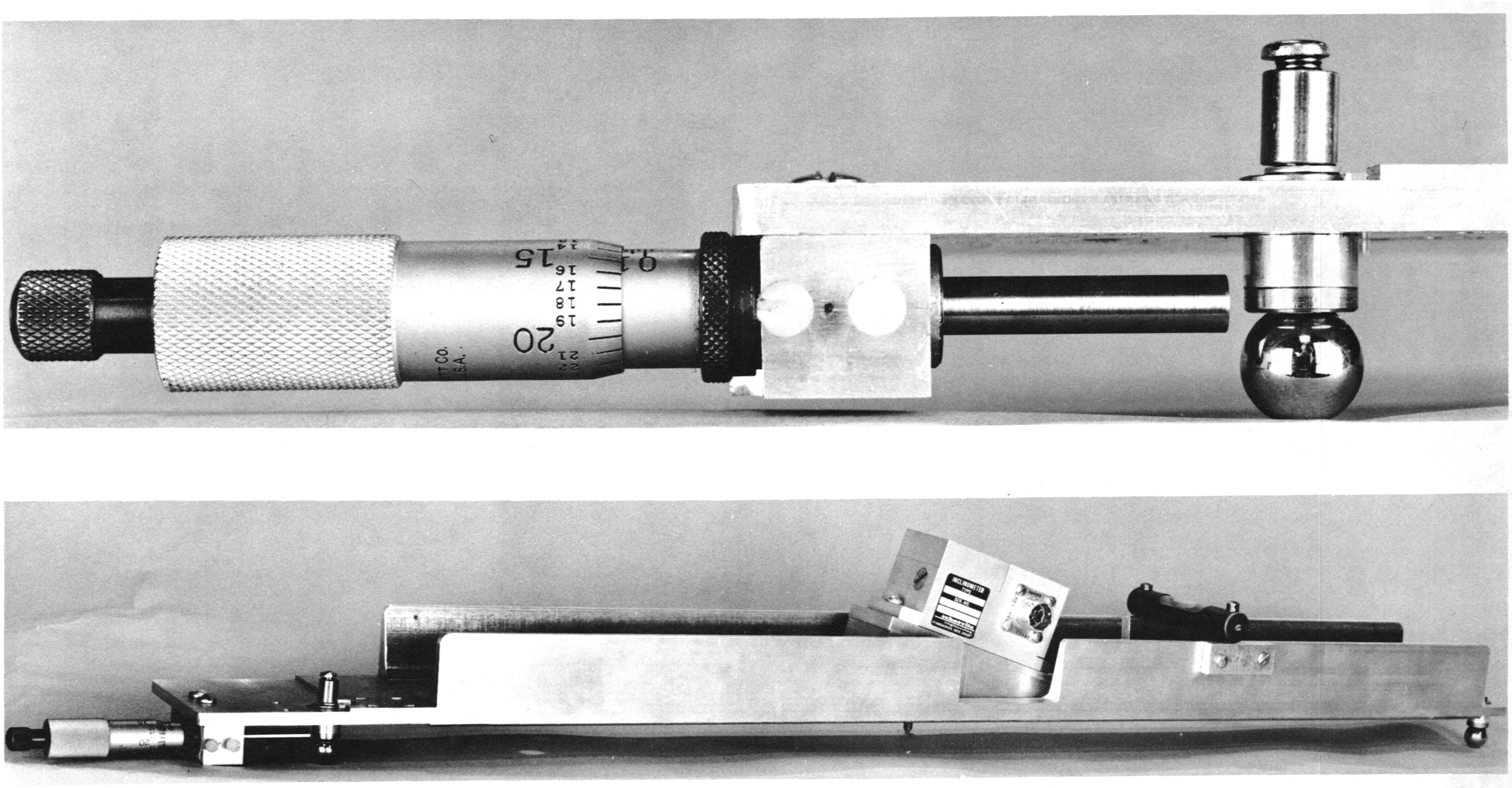

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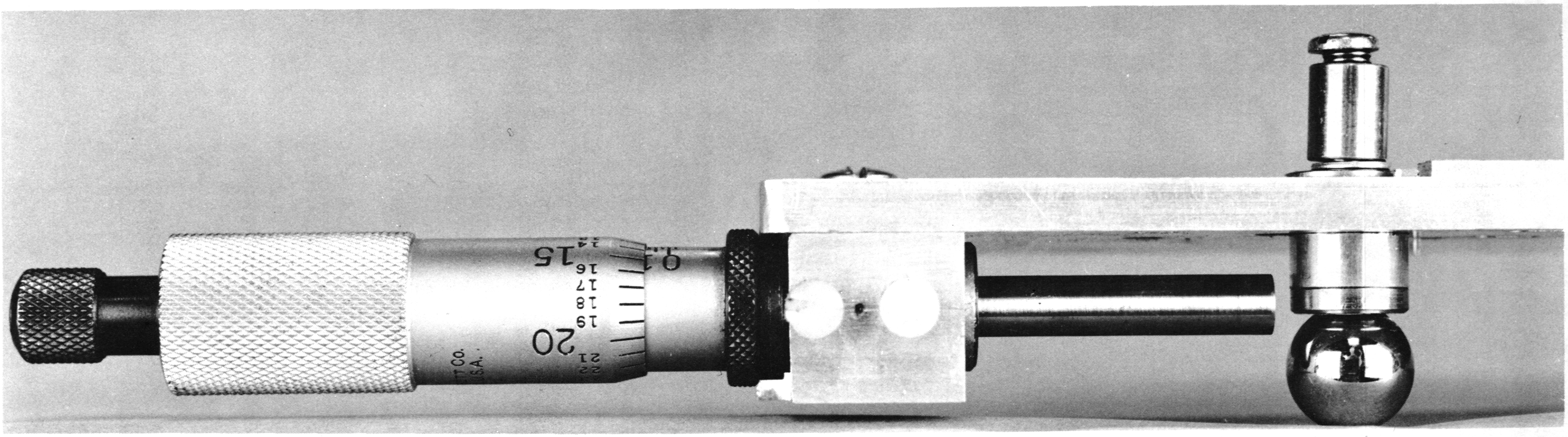

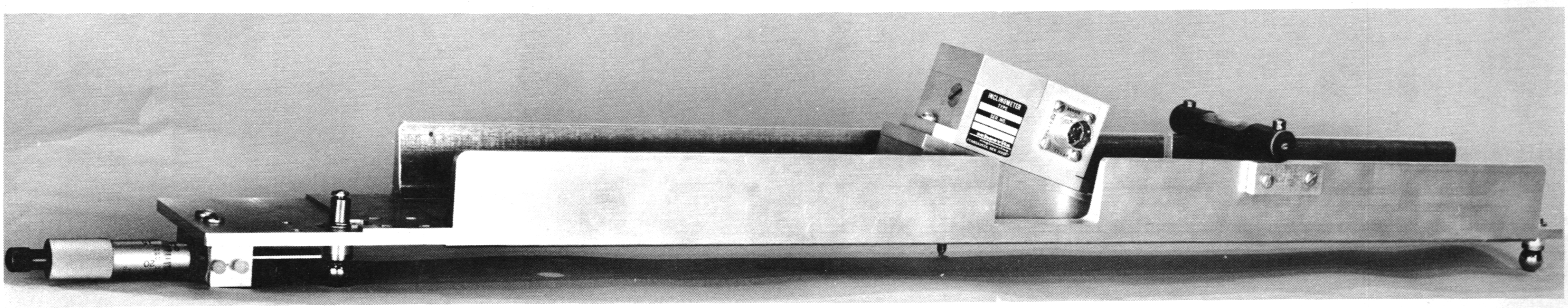

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