12 METER MILLIMETER WAVE TELESCOPE
MEMO No. 187

MEASURING THE REFERENCE JIG--PHASE 1

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1. Introduction

We have now made two sets of measurements of the dowel positions on the R/J. This note will first describe the coordinate systems used for the R/J and for the telescope, and then it briefly describes the two, fairly independent, measurement methods. We hope to continue R/J measurements by other methods at a later time.

2. The R/J and its Coordinate Systems

(a) The design of the R/J.

The R/J was designed to meet the following conditions:

(i) Twelve dowels would be used; these would be contacted by the 12 template (T/P) sensors.

(ii) The R/J would carry the center ball, the edge ball, and the plate to support the T/P correctly on the R/J.

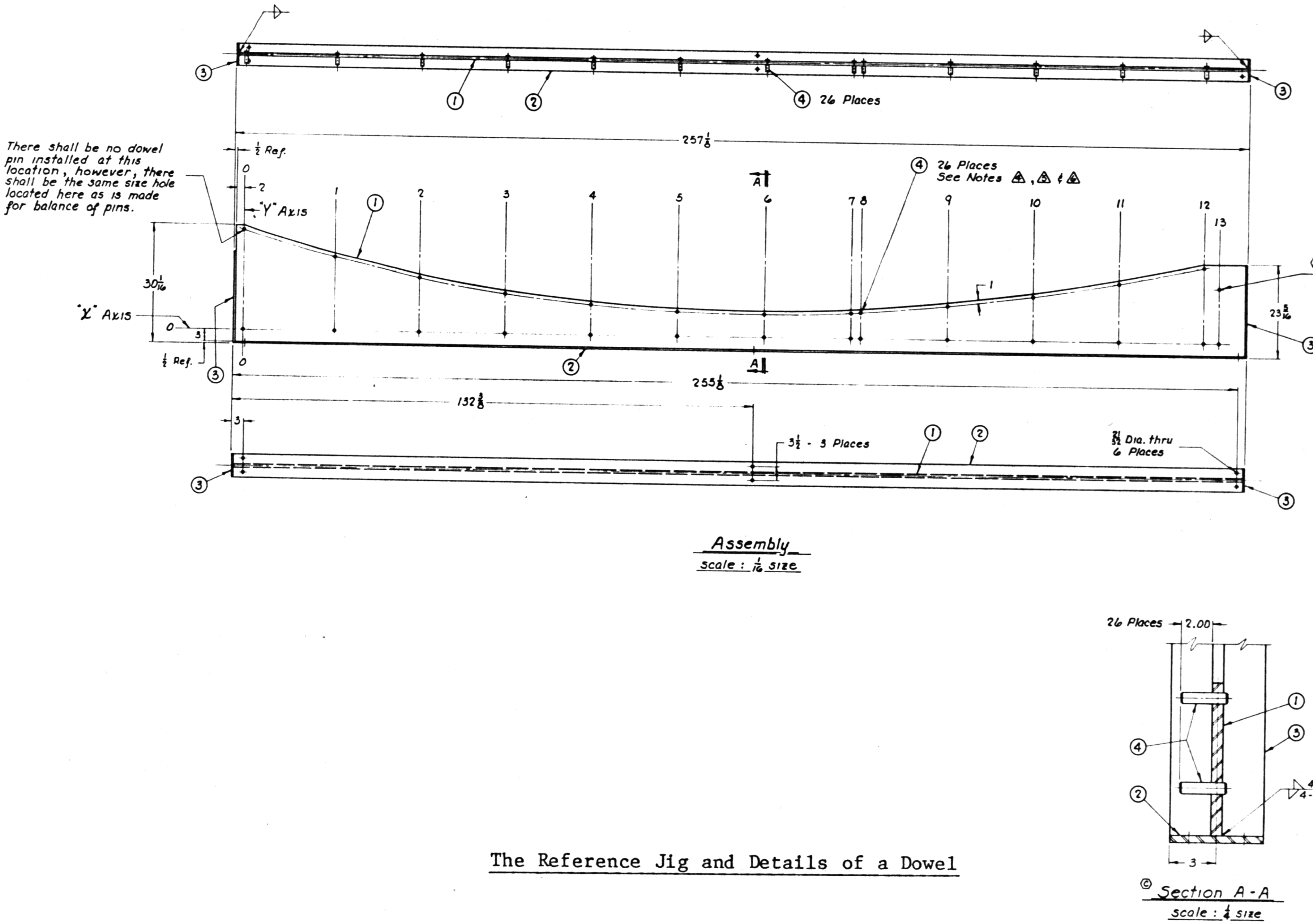
(iii) The 12 dowels would be positioned so that their coordinates could be measured using a stepping-bar of between 556.5 mm and 559.5 mm in length.

(iv) And, they would also be positioned so that 7 of the 12 sensors would be close to points above the 7 surface plate adjustment screws.

(v) Finally, the points of contact of the sensors and the dowels would also lie (nominally) on the perfect telescope surface. The origin of this surface would lie on the top center of the center reference ball.

(b) Coordinate systems and transformations

Figure 1 shows the R/J and Table 1 gives the nominal X_c and Y_c values for the centers of the dowels, the center of the center ball, and the edge ball center. Note that by "nominal" we mean the coordinates which would satisfy (v) above. These coordinates are in the R/J axis system No. 1.



The Reference Jig and Details of a Dowel

Figure 1

The axis system No. 1 (AS#1) has its origin 647.700 mm vertically below the center ball center. Its X-axis is parallel to the line through dowels Nos. 1 and 12.

We have computed the X,Y values for the nominal contact points in the following manner. Transform the dowel centers to points in the dish axis system (DAS). This system has its origin at the <u>top</u> of the center ball and its X-axis rotated through $\theta = 17.88595°$ from the X-axis of the R/J. I have made this coordinate transformation in two steps, for reasons which will appear later.

The first step transforms AS#1 into AS#2, which has its origin at the <u>center</u> of the center ball and its X-axis parallel to that in AS#1. I shall use the symbol YY for this movement of the X-axis. In the perfect case now being discussed, YY = 647.700 mm. Later, when I discuss the real R/J, I propose to adopt a value for YY which is derived from my R/J measurements.

So, for the present, we move from AS#1 to the coordinates (X_{cp} Y_{cp}) of the dowel centers in the DAS by using:

$$\left.\begin{aligned} X_{cp} &= X_c \cos\theta - (Y_c - YY)\sin\theta \\ X_{cp} &= X_c \sin\theta + (Y_c - YY)\cos\theta - r \end{aligned}\right\} , \qquad (1)$$

with YY set equal to 647.700 mm, and r, the dowel radius, = 9.525 mm.

Next we transform to get the coordinates X_p, Y_p (in the DAS) of the points of contact. In Figure 2, we see the sensor probe contacting a dowel (in the DAS) at an angle ϕ to the Y axis. Note that we have set the sensors to contact the reflector normal to the surface.

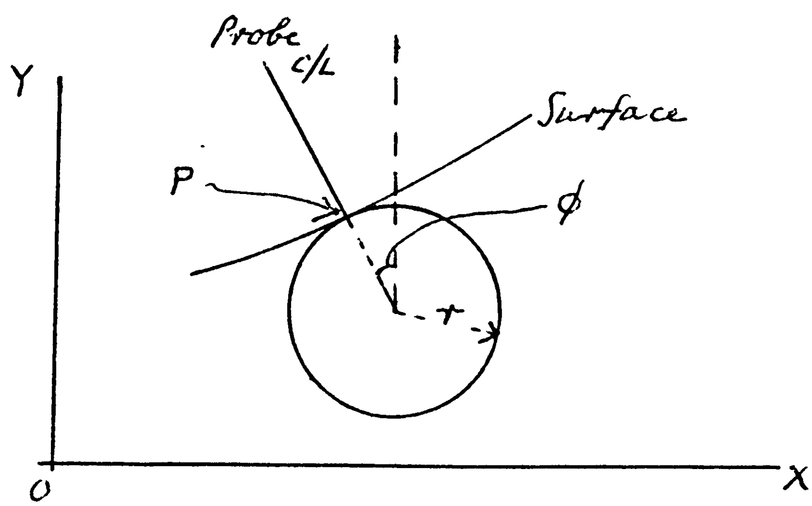


Figure 2 - A probe contacting a dowel in the DAS.

We can now compute the coordinates of the nominal contact points (P) in the DAS from the values of the angles ϕ at which the probes are set, using the equations:

$$\left.\begin{aligned} X_p &= X_{cp} - r \sin \phi \\ Y_p &= Y_{cp} + r \cos \phi \end{aligned}\right\} , \tag{2}$$

These $(X_p Y_p)$ points are given in the RH columns of Table 1. They all lie on the parabola

$$X_p^2 = 4 \times 5080 \times Y_p \tag{3}$$

The values given in Table 1 are within ± 1 μm of those in my Memo No. 86 of October 8, 1981. This has thus been a useful check of the various computations leading to the R/J design, which started from equation (3) and went backwards to the dowel centers.

(c) The edge balls

Finally, we transform the coordinates of the edge-ball center from the R/J in AS#1 to the DAS. This gives us the elevation of the edge-ball centers above the top of the dish center ball. We shall adjust all edge balls to this elevation.

Let (X_{ce}, Y_{ce}) be the nominal values of the edge ball in the R/J. Table 1 shows these to be X_{ce} = 6289.426 mm and Y_{ce} = 350.815 mm.

Using (1) and YY = 647.700 mm, we get in the DAS

$$X_{pe} = 6076.637 \text{ mm} \qquad Y_{pe} = 1639.568 \text{ mm} \tag{4}$$

Later we shall use a "real" value for YY and recompute (4).

3. Measurements of the R/J

(a) NIII and length measures

(i) NIII elevations - The first attempt to measure the dowel elevations was spoilt by NIII problems. The NIII was returned to Wild, and on June 23/24 JWF and SS made a set of elevation measures on dowels No. 0 (the center ball) through No. 13 (the edge ball). The R/J was levelled, as measured by the elevations of dowels No. 1 and No. 12. This was good to about 10 μm.

The NIII readings taken by both observers agreed to about ± 10 μm.

Table 1. Geometry of the Reference Jig

Dowel		Nominal centers (AS #1)		Nominal dish contact points (DAS)	
#	Contact angle	X_c	Y_c	X_p	Y_p
0	0.000	0.000	647.700	0.000	0.000
1	3.472	592.971	476.006	616.467	18.702
2	6.572	1135.779	352.085	1170.587	67.434
3	9.616	1684.444	257.452	1721.298	145.811
4	12.579	2237.303	191.712	2267.144	252.949
5	15.444	2792.773	154.178	2806.833	387.712
6	18.194	3349.396	143.906	3339.272	548.756
7	20.820	3905.867	159.761	3863.567	734.604
8	21.163	3980.327	163.802	3933.134	761.298
9	23.652	4537.791	207.990	4449.702	974.402
10	26.007	5092.870	275.697	4956.805	1209.150
11	28.228	5644.779	365.506	5454.129	1463.955
12	30.319	6192.901	476.006	5941.519	1737.285
13		6289.426	350.815		

Notes: All dimensions in mms, angles in degrees.

Dowel #0 is the center ball.

Dowel #13 is the edge ball.

AS #1 is axis system #1 in the R/J.

DAS is the dish surface axis system.

These level values were first referred to dowels No. 1 and No. 12 and set to the nominal value of 476.006 mm (AS#1) at those dowels. The "best" Y values for the other dowels were then put into file No. 81*. However, we still do not have a good value for the relative elevations of dowels No. 0 and No. 1, so the value chosen for No. 0 must be improved.

(ii) Measured step lengths - The lengths of the steps were measured using calipers by JNR and W. Monk on March 14, 15 and 18. They have recently been remeasured, but these later results are not considered here. The lengths are in file No. 77 as an average of three separate sets of readings. I did not know the R/J temperature at that time, but it was most likely 21° C ± 1° C.

(b) Stepping measurements

(i) The method and its calibration - The R/J was designed so that stepping could be used to determine the relative positions in AS#1 of dowels No. 1 through No. 12. The first step, from the center ball to dowel No. 1 could not be included--nor, of course, could the step from No. 12 to the edge-ball.

Tests of repeatability of stepping have been made for some time, but the method could only be used in an absolute sense when the length of the stepping bar had been calibrated. Accordingly, a standard step was built in such a form that its length could be measured accurately and also so that it could carry the stepping bar to calibrate the length of the bar. We sent this standard step--which I shall now call Baker's Bar (BB) -- to BNL where Sam Baker measured its length†. I have adopted from his results the value:

Length of BB at 68° F or 20° C = 557.982 ± 0.002 mm
The coefficient of expansion is 6.5×10^{-6} per °F.

The Schaevitz angle sensor had been calibrated by me against an inductosyn about three years ago. However, it was known that its calibration constant was not entirely temperature independent. Accordingly, I devised a way of measuring this dependence and arrived at an expression:

$$\text{Calibration constant at } T^\circ\text{ C} = \{(T-23) \times 7.71 \times 10^{-5} + 1\} \times \text{the constant at } 23^\circ\text{ C} \qquad (7)$$

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* References to files are to 9825A Cassette No. 2, Track No. 1.

† We are indebted to Sam Baker, of the BNL Isabelle Project, for this help.

At 23° C I adopted the relation between angle θ° and voltage output (V volts)

$$\sin\theta = -\left\{V \times 0.0500105 - 9.5\times10^{-7}\, V^2\right\} \qquad (8)$$

(ii) Stepping runs on the R/J - With the stepping bar calibrated by BB and the above angle sensor data, I did stepping runs on August 13, 14 and 15. It will be understood that stepping starts at dowel No. 1 and continues to No. 12. The short step between No. 7 and No. 8 is fitted by adopting the nominal values:

$$X(8) - X(7) = 74.504 \text{ mm}$$
$$Y(8) - Y(7) = 4.041 \text{ mm}$$

Each run was, in effect, the average of four separate stepping runs. In Table 2, I have summarized the results. Note the following:

- I have forced each run to give Y(1) = Y(12) as it should. However, I give the value in microns of C = (Y(12) - Y(1)) computed before forcing Y(12) to equal Y(1).

- I have put ΔX and ΔY in the table to keep numbers small.

$$\Delta X = (\text{Observed } X - \text{Perfect } X)$$
$$\Delta Y = (\text{Observed } Y - \text{Perfect } Y)$$

Both are in microns. So the scatter in one run in ΔX,ΔY is mainly a measure of the perfection of the R/J drilling, but across the runs the scatter of ΔX,ΔY is a measure of the repeatability of the stepping process.

4. Discussion of the Results

(a) The step from the center ball to dowel No. 1

I discuss this first since it is the least well-known number at present. It does not occur in the stepping measures. From NIII levels and direct caliper measures, I can get

$$\left.\begin{aligned} X(1) - X(0) &= 593.048 \text{ mm} \\ Y(0) - Y(1) &= 171.597 \text{ mm} \end{aligned}\right\} \qquad (9)$$

The nominal values (Table 1) are 592.971 mm and 171.694 mm.

I have not enough measurements to assess errors in these figures, so:

(i) I accept these as nominal values, and since I keep Y(1) = 476.006 mm in my stepping runs, I put Y(0) = 476.006 + 171.597.

Table 2. Four stepping runs -- all values in microns.

Dowel #	Aug. 13 1130 -1410		Aug. 14 1400		Aug. 15 0940		Aug. 15 1330	
	ΔX	ΔY	ΔX	ΔY	ΔX	ΔY	ΔX	ΔY
1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	-86.5	-71.6	-86.6	-70.4	-87.9	-77.2	-93.9	-71.7
3	-100.6	-70.6	-96.6	-65.5	-100.0	-74.5	-115.0	-66.8
4	-127.8	29.7	-129.9	37.9	-128.7	25.1	-148.1	31.9
5	-147.0	102.5	-151.0	108.7	-148.9	96.2	-173.1	102.5
6	-143.7	152.4	-151.1	156.3	-143.6	142.2	-176.3	150.8
7	-138.6	143.6	-150.0	146.5	-135.6	137.8	-173.5	149.0
8	-94.1	189.6	-105.5	192.5	-91.1	184.1	-129.0	195.5
9	-113.3	-8.1	-128.2	-9.3	-107.0	-10.3	-154.7	-7.1
10	-99.6	-23.3	-116.9	-26.3	-92.2	-28.0	-151.7	-23.3
11	-107.1	-43.4	-130.3	-44.0	-96.4	-49.7	-165.0	-51.7
12	-101.6	0.0	-130.2	0.0	-89.8	0.0	-171.0	0.0
	C = 33.3 microns		C = 31.1 microns		C = 14.3 microns		C = -0.8 microns	

Notes on Table 2

These results are discussed in paragraph 4.

$$Y(0) = YY = 476.006 + 171.597 = 647.603 \text{ mm} . \quad (10)$$

(ii) And, I note that these step No. 1 measures need to be improved. However, this will be easier when the R/J is in Tucson in its elevated position.

(b) The step from dowel No. 12 to the edge ball

As above, I have somewhat better measurements which give:

X(13) - X(12) = 96.492 mm (Nominal = 96.525 mm)
Y(12) - Y(13) = 125.212 mm (Nominal = 125.191 mm),

and I shall use both these values for the present.

(c) The "best" R/J from NIII and caliper measures

Table 3 gives my present best values for X_c and Y_c from the measurements described in 3(a), using my values chosen in 4(a) and 4(b) for steps 0 to 1 and 12 to 13.

(d) The "best" R/J from stepping

Table 2 shows the results for steps from No. 1 to No. 12. Two things can be seen at once:

(i) The agreement in ΔY for the four runs is remarkably good. The average RMS of ΔY for the ten dowels is 3.1 microns. Even the values of C, which show the total end errors and include possible tilt changes of the R/J with respect to gravity, are impressive.

(ii) The ΔX agreement is less good. However, the ΔX values seem to show an effect of temperature differences. We note that the results of stepping should be independent to a first approximation of ambient temperature provided that:

- The angle sensor is thermally compensated.
- The expansion coefficients of the stepping bar and the R/J materials are the same.
- No temperature differences exist between the bar and the R/J.

During the run at 1330 on August 15, we noted the stepping-bar temperature and the mean R/J temperature and found the R/J to be 1.5° C cooler than the bar. Using a coefficient of expansion for steel of 1.0×10^{-5} per °C per unit length, we see that all measured lengths should be increased by 1.000015. When this is done, the final column of Table 2 changes, as is shown in Table 4.

Table 3. The Reference Jig from N III and Caliper measures.

Dowel #	X Coordinates			Y Coordinates		
	X Measured	X Nominal	ΔX Microns	Y Measured	Y Nominal	ΔY Microns
0	0.000	0.000	0	647.603	647.700	-97
1	593.068	592.971	97	476.006	476.006	0
2	1135.850	1135.779	71	352.034	352.085	-51
3	1684.498	1684.444	54	257.384	257.452	-68
4	2237.339	2237.303	36	191.730	191.712	18
5	2792.813	2792.773	40	154.280	154.178	102
6	3349.463	3349.396	67	144.048	143.906	142
7	3905.954	3905.867	87	159.908	159.761	147
8	3980.459	3980.327	132	163.996	163.802	194
9	4537.918	4537.791	127	207.969	207.990	-21
10	5093.035	5092.870	165	275.689	275.697	-8
11	5644.962	5644.779	183	365.472	365.506	-34
12	6193.092	6192.901	191	476.006	476.006	0
13	6289.587	6289.426	161	350.794	350.815	-21

Notes on Table 3

Dowel #0 is the center ball.

Dowel #13 is the edge ball.

X, Y in mms. ΔX, ΔY in microns

5. The Two Methods Compared

(a) Comparison

Let us compare $\Delta X,\Delta Y$ from Table 3 (the NIII (caliper measures)) with the mean of four runs in Table 4. The following results are immediately apparent:

(i) The ΔX agreement is poor. We return to this.

(ii) The ΔY agreement is good. We take (NIII - Stepping) for dowels Nos. 2 through 11 and get:

Mean (NIII - Stepping) = +3.5 microns
RMS (NIII - Stepping) = 11.2 microns,

which is well within our expectations since we estimated our NIII precision at about ± 10 microns.

Why are the ΔX values so far apart? I prefer the stepping numbers because we believe each step to be measured to about 2 microns. Each caliper reading is only good to 25 microns (perhaps not as good as that), so an accumulated X error of 100-200 microns is easily possible.

To test this belief, I have returned to the Ralston March measures of step lengths and compared them with the best stepping measures--which are in turn based on BB.

I find (my notebook for August 20 and 21) that all the JNR measures are 20 ± 3) microns too large. This is entirely reasonable in a length of 558 mm (an error of ~4 in 10^5). So I have used these adjusted JNR step lengths (File No. 143) to show in Table 5 what is now my "best" set of R/J coordinates.

In deriving the means of $\Delta X,\Delta Y$, I have given stepping four times the weight of NIII/JNR.

6. Comments and Conclusions

(a) Comments:

(i) The eventual agreement between NIII/JNR and stepping in both X and Y is very good. However, remember we have adjusted the caliper step lengths by 4 in 10^5 to get this agreement in X.

(ii) The NIII/JNR agreement in Y is less suspect. The Y measures with the NIII rely mainly on high-quality "white-faced scales" and also on the NIII itself.

Table 4. The "best" R/J from stepping. All values in microns.

Dowel No.	1330 Aug. 15 revised		Mean of 4 runs		RMS of 4 runs	
	ΔX	ΔY	ΔX	ΔY	ΔX	ΔY
1	0	0	0	0	0	0
2	-85.7	-73.6	-86.7	-73.2	0.8	2.6
3	-98.7	-70.1	-99.0	-70.2	1.5	3.2
4	-123.4	27.7	-127.4	30.1	2.5	4.8
5	-140.1	97.7	-146.7	101.3	4.1	4.9
6	-135.0	145.8	-143.3	149.2	5.7	5.5
7	-123.8	144.3	-137.0	143.1	9.3	3.2
8	-79.3	190.8	-92.5	189.3	9.3	3.1
9	-96.7	-11.2	-111.3	-9.7	11.4	1.2
10	-85.4	-26.4	-98.5	-26.0	11.7	1.7
11	-90.3	-53.4	-106.0	-47.6	15.3	4.1
12	-88.1	0.0	-102.4	0	16.9	-

Notes on Table 4: The mean RMS of ΔX = 8.0 microns.
The mean RMS of ΔY = 3.4 microns.

(b) A "best" set of R/J coordinates

Table 5. The "best" coordinates, in AS#1. All vlaues are in "rounded" microns, with ΔX,ΔY in the sense measured-nominal.

Dowel No.	ΔX			ΔY		
	NIII/JNR	Stepping	Mean	NIII/JNR	Stepping	Mean
0	+77?	--	+77?	-97?	--	-97?
1	0*	0*	0*	0*	0*	0*
2	-81	-87	-86	-51	-73	-69
3	-97	-99	-99	-68	-70	-70
4	-127	-127	-127	+18	+30	+28
5	-148	-147	-147	+102	+101	+101
6	-141	-143	-143	+142	+149	+148
7	-140	-137	-138	+147	+143	+144
8	-95	-93	-93	+194	+189	+190
9	-117	-111	-113	-21	-10	-12
10	-96	-99	-98	-8	-26	-22
11	-100	-106	-105	-34	-48	-45
12	-101	-102	-102	0†	0†	0†
13	-134?	--	-134?	-21?	--	-21?

Notes on Table 5: * Indicates that the nominal values in AS#1 have been adopted.

† The measurements have been forced to close at dowel No. 12.

? Values which need more work.

(iii) The excellent agreement in Y between the four stepping runs is encouraging. However, in X it is clear that small thermal differentials must be watched. They can (and do) result in accumulating X errors.

(iv) Although we have not relied on the R/J manufacturer, it is interesting to note that I find his maximum errors to be 140 μm (0.0055") in X and 190 μm (0.0075") in Y. He evidently machined in two stages, judging from the change in ΔY from dowels No. 8 to No. 9.

(b) Conclusions

(i) Will Lee King please review this work in some detail? I may use Table 5 to derive the corrections to be made to the template transducer readings for our "first look" at the surface setting.

(ii) I must improve the metrology on the steps from dowels No. 0 to No. 1 and from No. 12 to No. 13. Also, I must remeasure the (small) No. 7 to No. 8 step. I shall do these on Kitt Peak.

(iii) I hope on Kitt Peak to be able to use stepping on the R/J with it tilted to the correct angle. However, I should welcome an estimate from Lee King on its probable deformations due to the tilt (but not at a very high priority yet until the receiver mounting is clear).

(iv) With J. Payne, I am looking at a tri-lateration method using a rented H-P interferometer. This would be very good, but laborious and expensive. (JMP says H-P rental possible.) I estimate total cost $5k to $6k, but I could get the R/J really fixed for all time.

(v) With JNR and Martin Barkley, I am trying out what I hope will be an improved stepping bar. But if it is not improved, I can revert to the existing design.