Y-12

**OAK RIDGE
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MARTIN MARIETTA

**CRADA Final Report
for
CRADA Number Y-1293-0224**

**Spatial Measurement Accuracy Tests Of The
Laser Ball Bar**

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August 26, 1994

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under contract DE-AC05-84OR21400

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FOR THE UNITED STATES
DEPARTMENT OF ENERGY**

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United States Government

Department of Energy

Oak Ridge Operations

memorandum

DATE: December 20, 1994

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ATTN OF:

SUBJECT: FINAL REPORT FOR CRADA NO. Y1293-0224 WITH TETRA PRECISION, INC.

TO: Judy Gilmore, OSTI

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for
Robert M. Poteat, Chief
Office of Intellectual Property Counsel
and Technology Transfer

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Final Report

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December 14, 1994

Mr. Peter D. Dayton
Director, Procurement and Contracts
Department of Energy, Oak Ridge Operations
Post Office Box 2001
Oak Ridge, Tennessee 37831-2001

Dear Mr. Dayton:

Final Report for CRADA No. Y-1293-0224 with Tetra Precision

The subject CRADA has been completed and enclosed is the Final Report for this project.

This report does not contain proprietary information or Protected CRADA Information.
Neither Energy Systems nor the participant object to public distribution of this report.

If you have any questions, please feel free to contact me.

Very truly yours,

Brian Bovee
Business Manager
Office of Technology Transfer

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Executive Summary

A series of tests were performed to evaluate the spatial and length measurement accuracy of the LBB. The length measurement accuracy tests consisted of using the initialized LBB to measure the distance between two magnetic sockets. While the LBB was installed in the sockets, the M-60 probed the spheres at the LBB ends and computed their coordinates. The deviations between the LBB predicted length and the M-60 predicted length ranged from +56 to -21 μ in. The mean value of the length measurement errors was +21.5 μ in. with a standard deviation of 10.5 μ in.

The spatial measurement accuracy test consisted of commanding the M-60 to move to selected points in its workspace, and using the LBB to measure the coordinates of these points. The LBB measurement error is defined as the difference between the LBB predicted coordinates and the commanded coordinates. The data were normalized to a point which was in the center of the measurement zone (i.e. the LBB coordinate system is assumed to be coincident with the M-60 coordinate system at this point). Three complete sets of measurements were taken. The range of LBB measured coordinate errors over the three data sets was +32 to -47 μ in. in X, +59 to -21 μ in. in Y, and +36 to -47 μ in. in Z.

No meaningful statement about the repeatability of the LBB measurements can be made due to the low number of tests (three). However, the maximum spread over the three tests between the measured X coordinates at any test point was 45 μ in. with a standard deviation of 25 μ in. The maximum spread in Y coordinates was 27 μ in. with a standard deviation of 14 μ in. The maximum spread in Z coordinates was 32 μ in. with a standard deviation of 18 μ in.

The LBB exhibited a systematic hysteresis associated with approaching the measured point from opposite directions. The hysteresis error tended to lie along the line of approach and had a mean magnitude of 34 μ in. in X, 42 μ in. in Y, and 20 μ in. in Z.

Based on these results, it appears that the length measurement uncertainty of the LBB is approximately $\pm 21\mu$ in. at the 2σ level. The error of any coordinate measurement over distances of 19 X 21 X 15 inches was found to be within $\pm 40\mu$ in.

SPATIAL MEASUREMENT ACCURACY TESTS OF THE LASER BALL BAR

SUMMARY OF RESULTS OF TESTS CONDUCTED ON THE
M-60 COORDINATE MEASURING MACHINE
AT THE OAK RIDGE METROLOGY CENTER

OAK RIDGE CENTERS FOR MANUFACTURING TECHNOLOGY
MARTIN MARIETTA ENERGY SYSTEMS, INC.
Y-12 PLANT
OAK RIDGE, TENNESSEE

AUGUST 22-26, 1994

Final Report for CRADA No. Y-1293-0224 between
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Introduction

The effectiveness of the laser ball bar (LBB) as a spatial measurement device was evaluated on the Moore M-60 coordinate measurement machine at Martin Marietta Energy Systems, Inc. Y-12 Plant in Oak Ridge, TN during the week of August 22-26, 1994. The measurement volume and accuracy of the M-60 make it suitable for assessing the LBB's measurement accuracy.

The laser ball bar was developed by the University of Florida Machine Tool Research Center and Tetra Precision, Inc. Tetra Precision owns exclusive rights to the LBB and is currently developing a commercial version of the instrument. The work described in this report was performed under CRADA No. Y-1293-0224 between Tetra Precision Inc. and Martin Marietta Energy Systems, Inc.

The LBB

The LBB consists of a heterodyne laser displacement-measuring interferometer whose measurement axis is aligned between the centers of two precision spheres joined by a telescoping tube assembly. It is intended to make precise linear measurements. Figure 1 shows the LBB with its components labeled. The interferometer is used to measure changes in length of the LBB. The centers of the precision spheres serve as measurement points. To know the absolute distance between the sphere centers, the LBB must first be initialized to a known length. After this the interferometer will monitor any changes in length. This initialization is accomplished with the LBB and a fixture consisting of three collinear sockets. Figure 2 shows the initialization procedure. The LBB is placed between the first two sockets and the interferometer output is set to zero. Next, the sphere in the middle socket is moved to the end socket. The interferometer in the LBB measures the distance between these two sockets. Finally, the LBB is placed between the middle and end socket and the output of the interferometer is set to the previously recorded distance. Following this initialization, the interferometer is set to the previously recorded distance. Following this initialization, the interferometer monitors any changes in length of the LBB and continuously produces the absolute distance between the spheres. The LBB can now be used to measure the absolute distance between any two sockets.

When the LBB is used to measure the motions of a machine tool, three magnetic sockets are fixtured to the worktable of the machine and a fourth is fixtured to the spindle to tool holder. These sockets form the vertices of a tetrahedron. If the initialized LBB is used to measure the lengths of the six sides of this tetrahedron, then the coordinates of the tool socket with respect to the base sockets can be computed. This procedure is known as trilateration.

Scope of Tests

The LBB by itself is a one dimensional displacement measurement instrument. When combined with an initialization procedure and the technique of trilateration it becomes a three dimensional position measurement tool. The purpose of the tests described here were to evaluate how accurately the LBB estimated its own length and how accurately it could measure spatial motions of a machine.

Test Setup

The setup for the tests is shown in Figure 3. The three magnetic sockets that form the base of the tetrahedron for spatial measurement were mounted on top of 20 inch pillars fixed

to the M-60 table. These pillars were required to raise the base plane of the LBB measurements so that the M-60 ram could reach it. The sockets labeled 1 and 2 form the X coordinate axis for the LBB and were aligned approximately with the X axis of the M-60. Socket 3 was placed to form an approximately equilateral triangle with sockets 1 and 2. The sockets were separated by approximately 22.2 inches to provide the proper LBB work volume. The index of refraction (IOR) used for the LBB was the same used for the M-60's laser scales and is computed using Edlen's formula for the initial estimate. The barometric pressure, temperature, and relative humidity for input into Edlen's formula are taken from the appropriate sensors in the M-60 facility. The fluctuations from the initial estimate are monitored by a Hewlett Packard wavelength tracker. The IOR is estimated to an uncertainty of approximately 0.1 part per million.

Length Accuracy Test

The first test involved ascertaining the LBB's length measuring accuracy. The LBB was initialized with its initialization fixture and placed between each of the three base sockets, Figure 4. For each of these three base lengths, the M-60 probed the LBB's spheres in the two sockets and determined the distance between their centers. This procedure was repeated two times. The distance as estimated by the M-60 was then compared to the readout from the LBB at each of the three base lengths. Table 1 shows the results of this test. LB1 is the distance between sockets 1 and 2, LB2 is the distance between sockets 2 and 3, and LB3 is the distance between sockets 1 and 3. The maximum deviation from the six samples is 56 to -21 μin (1.4 to -0.5 μm). This is close to the worst case estimated length accuracy of the LBB, $\pm 55 \mu\text{in}$ ($\pm 1.4 \mu\text{m}$). The mean value of the length measurement errors was 21.5 μin with a standard deviation of 10.5 μin .

Spatial Measurement Accuracy Test

The purpose of this test is to determine how well the LBB can measure the three dimensional motions of a machine using the technique of trilateration. To determine the location of a machine's end effector (cutting tool, CMM probe, robot gripper, etc.) by trilateration, six lengths must be measured by the LBB. First the three base lengths are measured between the three base sockets which are affixed to the machine element that holds the effective workpiece (table on the M-60). From these three sockets a right handed coordinate system is defined for the LBB; Origin at the center of socket 1, X axis along the line joining the centers of sockets 1 and 2, Y axis perpendicular to X and in the plane of the centers of the three sockets, and Z axis perpendicular to X and Y. Next the remaining three lengths are measured between the three base sockets and the end effector socket. These six lengths form a tetrahedron from which the coordinates of the end effector socket is computed. The setup for this on the M-60 is shown in Figure 3 and Figure 4.

The test involved programming the M-60 to move through a series of 75 points shown in Table 2. These points were chosen to cover the LBB measurement range. The maximum X travel is 19 inches. The maximum Y travel is 21 inches. The maximum Z travel is 22 inches. Many of the points are visited several times from different directions. The M-60 was programmed to move in the LBB's coordinate system. This was accomplished by probing the location of three spheres held in the base sockets while the probe head was still on the M-60.

From the location of these sockets in the M-60's coordinate system, the coordinate transformation matrix between the two systems was determined and used to move the machine in the LBB's system. Following this, the probe head was removed and a magnetic socket was installed on the end of the M-60 ram. The LBB system measures the coordinates of the center of a sphere held in this socket in the LBB's coordinate system.

The initialized LBB was used to measure the three base lengths first, and then was fixtured between socket #1 and the ram socket. The M-60 then executed a CNC program which caused it to move to each of the 75 points. At each of these 75 points the M-60 paused for 10 seconds to insure the machine had settled at the point and the LBB measurement was taken. Then the LBB was placed between socket #2 and the ram socket and the machine restarted through the 75 points. Finally this was repeated for the LBB between socket #3 and the ram socket. With these six lengths recorded for all 75 points, the coordinates of the points were computed. This procedure has been termed sequential trilateration, due to the sequential nature of measuring the three variable lengths. This procedure of running the machine to the points three times for a complete measurement set could be replaced by a single run. However, this would require the operator to move the LBB to each of the three base sockets as the machine pauses at each measured point. The body heat from this additional human intervention would degrade the superb environmental control required for proper operation of the M-60. Sequential trilateration is appropriate for machines with demonstrated repeatability below the LBB's accuracy, which is true for the M-60. A setup showing the measurement of the lengths between socket #1 and the ram socket is shown in Figure 4. Figure 5 shows a photograph of this test in progress.

The complete test required approximately 3.5 hours due to the low traverse speed of the M-60. Each run through the 75 points required approximately 1.2 hours with IOR updated before each run. Three complete tests were taken over a two day period. Tables 3,4,5 show the three coordinate errors at each of the points for the three runs respectively. Also shown are the error multiples for each coordinate direction. The error multiples are purely a function of the geometry (aspect ratio) of the tetrahedron, and represent the ratio of the expected coordinate error to the LBB length error, assuming a unit LBB length error at each of the six legs of the tetrahedron. For example, if the LBB were to have a normally distributed length measurement error with standard deviation of $1.0\text{ }\mu\text{m}$ for each of the six leg lengths, and the error multiple were 2.0 for a particular coordinate direction, then the coordinate error would be normally distributed with a standard deviation of $2.0\text{ }\mu\text{m}$. These multiples give a good indication of when the geometry of the tetrahedron formed by the six lengths is going to give desired coordinate accuracy. The test points intentionally included points where the Z position of the ram approached the plane to the three base sockets. Obviously, when this is the case, the LBB cannot estimate the Z coordinate accurately. This is reflected in the high Z error multiples for points 1-5 and 71-75. For this reason, these points are not included in the results. The minimum height above the base plane which can be measured accurately (Z-coordinate) is approximately 7 inches.

For the three runs, the largest error spread in any coordinate direction is $80\text{ }\mu\text{in}$ ($2.0\text{ }\mu\text{m}$), neglecting the Z points where the error ratio is larger than 4.0. Note that the errors have been normalized to measurement point #33 since it is a central point of measurement returned to several times. This is equivalent to assuming that the M-60 coordinate system and the LBB coordinate system are coincident at this point. The errors had to be normalized since the

coordinates of the base sockets were determined using the probe. When the probe was replaced with a socket, the exact position of this socket relative to the now-absent probe tip could not be determined. Therefore, there was no way to determine the spatial relationship between the M-60 coordinate system and the LBB coordinate system. However, the relative motions are exact to within the uncertainty of the M-60. The choice of point for normalization affects the magnitude of the error at each point but does not affect the error range over a test.

Figure 6 shows a graphical representation of a subset of the measured points in the XY plane. The ideal points are represented by dots and the LBB's estimates are represented by "X". The Z component of error at these points are not visible on this graph. Figures 7 and 8 show similar graphs for points in the X-Z and Y-Z planes. The errors have been multiplied by 10,000 to make them discernible on the graphs. The LBB coordinates used for these graphs are the mean values over the three test runs. For test run #2, no data was collected for points 53, 54, and 55 due to a trigger malfunction. Therefore, for these points the figures show the mean of the values for runs 1 and 3. Multiple X's clustered around a single measurement point means that this point was visited several times from different directions. The variability of these points represents a combination of hysteresis and repeatability errors in the LBB.

A rectangle has been placed around each measurement point. The dimensions of this rectangle represent the expected coordinate error at the 1-sigma level for this point assuming a length error of $\pm 20 \mu\text{in.}$ ($\pm 0.5 \mu\text{m}$) in the measurement of each of the six legs of the tetrahedron. The fact that all of the LBB estimates are within these rectangles is evidence of the "averaging" properties of the trilateration process. In a cartesian measurement chain such as is found in most CMM's, a one unit error in an axis scale measurement will always create a one unit error in the coordinate estimate of the point being measured. In contrast, with trilateration, an error in the measurement of the length of a single leg, will cause an error in the estimate of the coordinate being measured in proportion to the magnitude of the partial derivative of the coordinate equation with respect to that leg length. This magnitude is less than one for many tetrahedron geometries.

Repeatability of LBB

The short period of time available for these tests on the M-60 allowed only three complete sets of data to be taken. Over the three tests, the largest spread of X coordinates at any point was $45 \mu\text{in.}$ ($1.13 \mu\text{m}$) with a standard deviation of $18 \mu\text{in.}$ ($0.45 \mu\text{m}$). The largest spread of Y coordinates was $27 \mu\text{in.}$ ($0.68 \mu\text{m}$) with a standard deviation of $14 \mu\text{in.}$ ($0.35 \mu\text{m}$). The largest spread of Z coordinates was $32 \mu\text{in.}$ ($0.8 \mu\text{m}$) with a standard deviation of $18 \mu\text{in.}$ ($0.45 \mu\text{m}$).

The LBB coordinates are expressed with respect to the LBB coordinate system, which is determined by the locations of the centers of the base sockets. This computation of the LBB repeatability assumes that the location of the base sockets relative to the M-60 coordinate system does not change between tests (i.e. no relative motion of LBB and M-60 coordinate systems). However, it was necessary to mount the base sockets on 20 inch high pillars in order to reach the ram in its lowest position, as shown in Figs. 3,4,5. It is suspected that local thermal gradients may have caused these pillars to bend slightly during the tests, thus moving the sockets relative to the M-60 coordinate system. These thermal gradients may possibly have been due to radiated heat from the laser system and/or human operators when they went in the room to move the LBB to another socket. It was not possible to quantify this effect. However, it would affect the repeatability of the LBB measurements.

Hysteresis in the LBB

Numerous points were approached from multiple directions to evaluate any hysteresis in the LBB measurement system. Unlike cartesian machines, where a single axis can be actuated while the others are held stationary, all three variable legs of the tetrahedron change length for any straight line motion. Therefore, if a point is approached from one linear direction, and then from the opposite direction, the individual leg lengths will change from increasing to decreasing or vice-versa. Since all three coordinates depend on the length of all of the legs, one might expect the direction of any hysteresis errors to be independent of the direction of motion. However, examination of the data and the error plots shows that the primary hysteresis error appears to be in the direction of motion for X and Y motions. This tendency is less strong in the Z direction. The average hysteresis value for the X-direction was $34\mu\text{in.}$ ($0.85\mu\text{m}$) with a standard deviation of $12.8\mu\text{in.}$ ($0.32\mu\text{m}$). For the Y-direction the average hysteresis error was $42\mu\text{in.}$ ($1.05\mu\text{m}$) with a standard deviation of $12.2\mu\text{in.}$ ($0.31\mu\text{m}$). For the Z-direction the average hysteresis error was $20\mu\text{in.}$ ($0.5\mu\text{m}$) with a standard deviation of $14.8\mu\text{in.}$ ($0.37\mu\text{m}$).

Uncertainty of M-60 Positioning

The results shown assume that the M-60 possesses "perfect" volumetric positioning accuracy and therefore any deviation between the commanded coordinates and the LBB measured coordinates is due solely to errors in the LBB system. In reality, although the M-60 possesses outstanding accuracy for a machine of its size, it is not perfect.

The positioning repeatability of the X-axis of the M-60 is $\pm 1\mu\text{in.}$ ($\pm 0.03\mu\text{m}$). The hysteresis (reversal error) of the X-axis is $\pm 2\mu\text{in.}$ ($\pm 0.05\mu\text{m}$). The M-60's quoted uncertainty for measurement of length standards is $12 + 0.4xL[\text{in}] \mu\text{in}$ ($0.3 + 0.4xL[\text{m}] \mu\text{m}$). This data was obtained in accordance with NIST Technical Note 1297 using a coverage factor of 2 (approximately 2σ). The M-60 has been qualified by NIST for calibration of primary length standards. The quoted 1-D measurement uncertainty includes the errors in the probe. If we assume that the probing errors are independent of location, then the best possible volumetric positioning uncertainty for the M-60 is equal to the 1-D positioning uncertainty, $0.4xL[\text{in}] \mu\text{in}$ ($0.4xL[\text{m}] \mu\text{m}$). In reality, the volumetric positioning uncertainty will be greater than this due to errors in the other axes and imperfect alignment of the axes.

Prior to the start of these tests, the M-60 was checked with the Renishaw Machine Checking Gage. The total variation (Max - Min) in measured radii using a 6" arm was $18\mu\text{in.}$ Using a 15 inch arm, the total variation was $16\mu\text{in.}$ Using a 21 inch arm, the total variation was $22\mu\text{in.}$ Again, these numbers include probe variability.

For the purposes of these tests, the measurement uncertainty is less important than the positioning uncertainty. The volumetric positioning error map of the M-60 is not known at this time. However, from the data shown above, it seems likely that the maximum positioning error of the M-60 over the data points used in these tests is less than $10\mu\text{in.}$ This amounts to approximately 25% of the apparent LBB uncertainty. Therefore, the assumption used in these tests of "perfect" M-60 positioning is not strictly true. A complete evaluation of the volumetric error map of the M-60 would be required to obtain a better estimate of the LBB accuracy.

Conclusions

A series of tests were performed to evaluate the spatial and length measurement accuracy of the LBB. The length measurement accuracy tests consisted of using the initialized LBB to measure the distance between two magnetic sockets. While the LBB was installed in the sockets, the M-60 probed the spheres at the LBB ends and computed their coordinates. The deviations between the LBB predicted length and the M-60 predicted length ranged from +56 to -21 μ in. The mean value of the length measurement errors was 21.5 μ in. with a standard deviation of 10.5 μ in.

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No meaningful statement about the repeatability of the LBB measurements can be made due to the low number of tests conducted(three). However, the maximum spread over the three tests between the measured X coordinates at any test point was 45 μ in. with a standard deviation of 25 μ in. The maximum spread in Y coordinates was 27 μ in. with a standard deviation of 14 μ in. The maximum spread in Z coordinates was 32 μ in. with a standard deviation of 18 μ in.

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Based on these results, it appears that the length measurement uncertainty of the LBB is approximately $\pm 21\mu$ in. at the 2σ level. The error of any coordinate measurement over distances of 19 X 21 X 15 inches was found to be within $\pm 40\mu$ in.

Figure 1 The LBB at minimum and maximum length.

Figure 2 Initialization procedure for LBB.

Figure 3 Measurement setup on M60 CMM.

Figure 4 Base length measurement for length comparison to M60.

Figure 5. Photo of spatial measurement accuracy test in progress.

TABLE 1
MEASUREMENT POINTS AND ERROR MULTIPLES

<u>POINT</u>	<u>X</u>	<u>Y</u>	<u>Z</u>	<u>SX</u>	<u>SY</u>	<u>SZ</u>
1	11.1	6.41	0	0.9	1.8	∞
2	11.1	6.41	1	0.9	1.8	20.1
3	11.1	6.41	2	0.9	1.8	10.1
4	11.1	6.41	3	0.9	1.8	6.8
5	11.1	6.41	5	1.0	1.8	4.2
6	11.1	6.41	7	1.0	1.8	3.1
7	11.1	6.41	9	1.1	1.8	2.6
8	11.1	6.41	11	1.1	1.9	2.2
9	11.1	6.41	13	1.2	2.0	2.0
10	15	6.41	13	1.2	2.1	2.3
11	19	6.41	13	1.2	2.5	2.8
12	20.5	6.41	13	1.2	2.6	3.0
13	19	6.41	13	1.2	2.5	2.8
14	15	6.41	13	1.2	2.2	2.3
15	11.1	6.41	13	1.2	2.0	2.0
16	7	6.41	13	1.3	1.9	1.7
17	3	6.41	13	1.5	2.0	1.5
18	1.5	6.41	13	1.5	2.1	1.5
19	3	6.41	13	1.5	2.0	1.5
20	7	6.41	13	1.3	1.9	1.7
21	11.1	6.41	13	1.2	2.0	2.0
22	11.1	10	13	1.3	1.9	2.4
23	11.1	14	13	1.4	1.9	2.9
24	11.1	18.5	13	1.6	2.0	3.7
25	11.1	14	13	1.4	1.9	2.9
26	11.1	10	13	1.3	1.9	2.4
27	11.1	6.41	13	1.2	2.0	2.0
28	11.1	2	13	1.2	2.1	1.7
29	11.1	-2	13	1.2	2.3	1.7
30	11.1	-2.5	13	1.2	2.3	1.7
31	11.1	-2	13	1.2	2.3	1.7
32	11.1	2	13	1.2	2.1	1.7
33	11.1	6.41	13	1.2	2.0	2.0
34	11.1	6.41	16	1.3	2.1	1.8
35	15	6.41	16	1.3	2.3	2.1
36	18.5	6.41	16	1.3	2.5	2.4
37	15	6.41	16	1.3	2.3	2.1
38	11.1	6.41	16	1.3	2.1	1.8
39	7	6.41	16	1.4	2.0	1.5

40	3.5	6.41	16	1.6	2.0	1.4
41	7	6.41	16	1.4	2.0	1.5
42	11.1	6.41	16	1.3	2.1	1.8
43	11.1	10	16	1.4	2.0	2.1
44	11.1	14	16	1.5	2.0	2.5
45	11.1	16	16	1.6	2.0	2.8
46	11.1	14	16	1.5	2.0	2.5
47	11.1	10	16	1.4	2.0	2.1
48	11.1	6.41	16	1.3	2.1	1.8
49	11.1	2	16	1.3	2.2	1.5
50	11.1	-0.5	16	1.3	2.3	1.5
51	11.1	2	16	1.3	2.2	1.5
52	11.1	6.41	16	1.3	2.1	1.8
53	11.1	6.41	19	1.5	2.2	1.6
54	15.5	6.41	19	1.4	2.4	2.0
55	11.1	6.41	19	1.5	2.2	1.6
56	6	6.41	19	1.6	2.1	1.4
57	11.1	6.41	19	1.5	2.2	1.6
58	11.1	10	19	1.5	2.1	1.9
59	11.1	12.5	19	1.6	2.1	2.1
60	11.1	10	19	1.5	2.1	1.9
61	11.1	6.41	19	1.5	2.2	1.6
62	11.1	2.5	19	1.4	2.3	1.5
63	11.1	6.41	19	1.5	2.2	1.6
64	11.1	6.41	22	1.6	2.3	1.6
65	11.1	6.41	19	1.5	2.2	1.6
66	11.1	6.41	16	1.3	2.1	1.8
67	11.1	6.41	13	1.2	2.0	2.0
68	11.1	6.41	11	1.1	1.9	2.2
69	11.1	6.41	9	1.1	1.9	2.6
70	11.1	6.41	7	1.0	1.9	3.1
71	11.1	6.41	5	1.0	1.8	4.2
72	11.1	6.41	3	0.9	1.8	6.8
73	11.1	6.41	2	0.9	1.8	10.1
74	11.1	6.41	1	0.9	1.8	20.1
75	11.1	6.41	0	0.9	1.8	∞

TABLE 2
LBB LENGTH ACCURACY

	<u>M-60'S ESTIMATE</u>	<u>LBB'S ESTIMATE</u>	<u>LBB ERROR (μin)</u>
LB1	21.192007	22.192032	+ 25
LB2	22.183773	22.183829	+ 56
LB3	22.171218	22.171216	- 2
LB1	22.192011	22.192044	+ 33
LB2	22.183771	22.183809	+ 38
LB3	22.171218	22.171197	- 21

TABLE 3
COORDINATE ERRORS 1ST RUN

<u>POINT</u>	<u>X ERROR</u>	<u>Y ERROR</u>	<u>Z ERROR</u>
1	0.000016	-0.000016	0.025943
2	0.000011	-0.000008	0.000367
3	0.000008	-0.000008	0.000164
4	0.000004	0.000000	0.000111
5	-0.000002	0.000001	0.000061
6	-0.000008	-0.000002	0.000038
7	-0.000005	0.000006	0.000023
8	-0.000008	0.000005	0.000015
9	-0.000007	0.000004	0.000003
10	-0.000034	-0.000002	-0.000010
11	-0.000019	-0.000004	-0.000011
12	-0.000017	-0.000005	-0.000012
13	0.000016	0.000002	-0.000014
14	0.000004	0.000006	-0.000008
15	0.000006	0.000012	-0.000006
16	0.000016	0.000034	-0.000027
17	0.000011	0.000049	-0.000038
18	0.000010	0.000050	-0.000042
19	-0.000037	0.000054	-0.000038
20	-0.000029	0.000020	-0.000015
21	-0.000023	0.000010	-0.000002
22	0.000001	-0.000009	-0.000013
23	-0.000011	0.000009	-0.000021
24	-0.000040	0.000039	-0.000035
25	-0.000011	0.000057	-0.000019
26	-0.000009	0.000033	-0.000012

27	0.000000	0.000034	-0.000006
28	-0.000004	0.000036	-0.000011
29	0.000002	0.000015	-0.000015
30	0.000006	0.000016	-0.000021
31	0.000002	-0.000004	-0.000008
32	-0.000001	0.000008	-0.000009
33	0.000000	0.000000	0.000000
34	-0.000002	0.000015	-0.000013
35	-0.000022	0.000015	-0.000016
36	-0.000019	-0.000006	-0.000016
37	0.000017	0.000021	-0.000010
38	0.000013	0.000024	-0.000017
39	0.000005	0.000041	-0.000025
40	-0.000005	0.000056	-0.000038
41	-0.000030	0.000041	-0.000019
42	-0.000024	0.000015	-0.000013
43	-0.000004	-0.000012	-0.000017
44	-0.000017	0.000005	-0.000023
45	-0.000019	0.000018	-0.000027
46	-0.000013	0.000046	-0.000026
47	-0.000008	0.000040	-0.000014
48	-0.000009	0.000036	-0.000017
49	-0.000008	0.000021	-0.000024
50	-0.000006	0.000014	-0.000027
51	-0.000001	-0.000008	-0.000020
52	-0.000002	-0.000010	-0.000018
53	-0.000002	0.000010	-0.000014
54	-0.000021	0.000016	-0.000017
55	0.000014	0.000014	-0.000020
56	-0.000005	0.000035	-0.000035
57	-0.000023	0.000012	-0.000017
58	-0.000006	-0.000004	-0.000019
59	-0.000011	0.000000	-0.000024
60	-0.000006	0.000052	-0.000019
61	-0.000010	0.000042	-0.000016
62	-0.000015	0.000037	-0.000014
63	-0.000006	-0.000012	-0.000019
64	-0.000012	0.000011	-0.000013
65	-0.000002	0.000024	-0.000028
66	-0.000009	0.000015	-0.000028
67	-0.000013	0.000015	-0.000013
68	-0.000023	0.000017	0.000005
69	-0.000035	0.000033	0.000035
70	0.000000	0.000003	0.000006

71	0.000003	0.000003	0.000025
72	0.000006	-0.000001	0.000070
73	0.000013	-0.000008	0.000087
74	0.000013	-0.000012	0.000266
75	0.000014	-0.000012	0.023980

TABLE 4
COORDINATE ERRORS FOR 2ND RUN

<u>POINT</u>	<u>X ERROR</u>	<u>Y ERROR</u>	<u>Z ERROR</u>
--------------	----------------	----------------	----------------

1	0.000033	0.000001	0.021202
2	0.000019	0.000014	0.000317
3	0.000009	0.000016	0.000147
4	0.000016	0.000011	0.000082
5	0.000005	0.000031	0.000040
6	-0.000004	0.000021	0.000034
7	-0.000004	0.000021	0.000016
8	-0.000013	0.000017	0.000008
9	-0.000016	0.000020	0.000003
10	-0.000041	0.000010	-0.000010
11	-0.000026	0.000010	-0.000013
12	-0.000018	0.000018	-0.000012
13	0.000016	0.000025	-0.000024
14	-0.000004	0.000018	-0.000013
15	0.000003	0.000024	-0.000010
16	0.000009	0.000019	-0.000020
17	0.000001	0.000031	-0.000042
18	0.000001	0.000028	-0.000043
19	-0.000046	0.000042	-0.000036
20	-0.000019	0.000013	-0.000012
21	-0.000016	0.000017	0.000000
22	-0.000007	-0.000010	-0.000011
23	-0.000015	0.000005	-0.000021
24	-0.000022	0.000020	-0.000026
25	-0.000011	0.000058	-0.000021
26	-0.000007	0.000037	-0.000011
27	-0.000007	0.000037	-0.000002
28	-0.000002	0.000055	-0.000005
29	0.000000	0.000040	-0.000001
30	0.000001	0.000043	-0.000003
31	0.000003	0.000015	0.000003
32	0.000004	0.000025	-0.000005

33	0.000000	0.000000	0.000000
34	0.000003	0.000019	-0.000010
35	-0.000024	0.000037	-0.000015
36	-0.000014	0.000024	-0.000015
37	0.000025	0.000037	-0.000016
38	0.000021	0.000021	-0.000018
39	0.000021	0.000031	-0.000020
40	0.000013	0.000034	-0.000030
41	-0.000029	0.000036	-0.000019
42	-0.000004	0.000019	-0.000025
43	0.000007	-0.000009	-0.000017
44	-0.000002	0.000008	-0.000020
45	0.000000	0.000012	-0.000024
46	0.000002	0.000057	-0.000025
47	0.000003	0.000042	-0.000015
48	0.000003	0.000049	-0.000022
49	0.000004	0.000043	-0.000023
50	0.000007	0.000037	-0.000023
51	0.000004	0.000001	-0.000022
52	0.000003	-0.000002	-0.000027
53	#####	#####	#####
54	#####	#####	#####
55	#####	#####	#####
56	0.000015	0.000025	-0.000032
57	-0.000020	0.000027	-0.000022
58	0.000005	0.000000	-0.000025
59	0.000003	0.000000	-0.000024
60	0.000000	0.000053	-0.000025
61	-0.000003	0.000046	-0.000028
62	-0.000012	0.000044	-0.000024
63	-0.000008	-0.000013	-0.000029
64	-0.000012	0.000013	-0.000021
65	0.000013	0.000022	-0.000039
66	0.000007	0.000021	-0.000038
67	0.000016	0.000024	-0.000021
68	0.000014	0.000022	-0.000016
69	0.000012	0.000020	-0.000011
70	0.000017	0.000018	-0.000004
71	0.000020	0.000019	0.000011
72	0.000018	0.000015	0.000047
73	0.000021	0.000012	0.000070
74	0.000026	0.000005	0.000149
75	0.000029	0.000001	0.018777

TABLE 5
COORDINATE ERRORS FOR 3RD RUN

<u>POINT</u>	<u>X ERROR</u>	<u>Y ERROR</u>	<u>Z ERROR</u>
1	0.000029	-0.000003	0.029336
2	0.000026	-0.000004	0.000538
3	0.000023	-0.000004	0.000245
4	0.000015	0.000006	0.000174
5	0.000012	0.000015	0.000091
6	0.000004	0.000019	0.000057
7	0.000001	0.000014	0.000036
8	0.000001	0.000013	0.000021
9	-0.000004	0.000017	0.000011
10	-0.000034	-0.000006	-0.000006
11	-0.000024	-0.000008	-0.000011
12	-0.000018	-0.000001	-0.000016
13	0.000028	0.000016	-0.000019
14	0.000004	0.000014	-0.000010
15	0.000009	0.000017	-0.000006
16	0.000013	0.000017	-0.000018
17	0.000003	0.000040	-0.000039
18	-0.000004	0.000047	-0.000047
19	-0.000044	0.000047	-0.000032
20	-0.000016	0.000015	-0.000007
21	-0.000023	0.000002	-0.000004
22	0.000005	-0.000014	-0.000010
23	0.000001	0.000006	-0.000017
24	0.000005	0.000031	-0.000032
25	0.000005	0.000069	-0.000022
26	-0.000002	0.000040	-0.000016
27	-0.000007	0.000041	-0.000004
28	-0.000016	0.000055	-0.000010
29	-0.000014	0.000042	-0.000002
30	-0.000013	0.000042	-0.000009
31	-0.000014	-0.000001	-0.000003
32	-0.000010	0.000011	-0.000009
33	0.000000	0.000000	0.000000
34	0.000002	0.000025	-0.000006
35	-0.000025	0.000029	-0.000013
36	-0.000014	0.000014	-0.000016
37	0.000032	0.000038	-0.000015
38	0.000013	0.000023	-0.000018
39	0.000002	0.000041	-0.000027

40	-0.000005	0.000051	-0.000040
41	-0.000034	0.000045	-0.000012
42	-0.000005	0.000021	-0.000015
43	0.000004	-0.000016	-0.000014
44	-0.000008	0.000003	-0.000020
45	-0.000013	0.000016	-0.000019
46	-0.000003	0.000057	-0.000023
47	-0.000004	0.000050	-0.000013
48	-0.000005	0.000054	-0.000018
49	-0.000008	0.000041	-0.000020
50	-0.000006	0.000032	-0.000026
51	-0.000001	-0.000006	-0.000023
52	0.000002	-0.000009	-0.000023
53	-0.000002	0.000019	-0.000010
54	-0.000012	0.000030	-0.000020
55	0.000027	0.000021	-0.000023
56	0.000000	0.000033	-0.000031
57	-0.000030	0.000026	-0.000015
58	0.000004	-0.000008	-0.000019
59	-0.000010	0.000002	-0.000020
60	-0.000001	0.000059	-0.000021
61	0.000003	0.000059	-0.000021
62	-0.000003	0.000053	-0.000017
63	-0.000006	-0.000021	-0.000023
64	-0.000002	0.000012	-0.000012
65	0.000011	0.000031	-0.000040
66	0.000002	0.000033	-0.000040
67	-0.000004	0.000020	-0.000019
68	-0.000008	0.000025	-0.000007
69	-0.000047	0.000044	0.000031
70	0.000002	0.000017	0.000005
71	0.000002	0.000009	0.000022
72	0.000008	0.000004	0.000065
73	0.000010	0.000001	0.000101
74	0.000019	0.000002	0.000268
75	0.000020	-0.000006	0.022406

Figure 5. Plot of LBB measured points in XY plane.

Figure 6. Plot of LBB measured points in XZ plane.

Figure 7. Plot of LBB measured points in YZ plane.

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