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ARID RELATIVE CALIBRATION EXPERIMENTAL DATA AND ANALYSIS

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ABSTRACT

Several experiments measure the orientation error of the ARID end-frame as well as linear displacements in the Orbiter's *y-* and *z-axes*. In each experiment the position of the ARID on the trolley is fixed and the manipulator extends and retracts along the Orbiter's *y-axis*. A sensor platform consisting of four sonars arranged in a "+" pattern measures the platform pitch about the Orbiter's *y-axis* (angle β) and yaw about the Orbiter's *x-axis* (angle α). Corroborating measurements of the yaw error were performed using a carpenter's level to keep the platform perpendicular to the gravity vector at each ARID pose being measured.

SUMMARY AND CONCLUSIONS

The preliminary experimental work performed here suggests that the ARID manipulator will admit efficient, reliable calibration. The pitch β of the tool-frame averages around 0.6 ± 0.02 degrees while the error in yaw α is as large as 4.65 ± 0.04 degrees when the ARID is stretched out to 4.45 ± 0.04 degrees when the ARID end-frame is close to the trolley. A commanded translation in four inch increments along the Orbiter's *y-axis* produced a consistent 3 15/16 $\pm$ 1/32 inch motion, with the exception of two points. The two anomalous points could be due to experimental error or to a bug in the ARID software. Less likely, in the author's judgement, the anomalies might be due to some ARID structural problem. The measurements also demonstrated that the ARID sags about one-half inch over its range of reach. The further the arm extends, the greater the sag.

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1. INTRODUCTION

Figure 1 depicts the experimental setup for relative calibration of the ARID manipulator. We measured the deviation in the sensor platform from level as the ARID extended and retracted at a fixed location on the trolley. The four sonars measured the height of the sensor platform from the table at four points. The angle $\alpha = \theta_1 + \theta_2 + \theta_3 + \theta_4$ equals the total angle change about the *x-Orbiter* axis induced by the revolute joints and the fixed angle θ_1. The deviation of the angle α from 90° can be computed from the sonar values h_1 (Top Sonar) and h_3 (Bottom Sonar). The angle β, which the ARID cannot actively compensate for, is the angle about the *y-Orbiter* axis and can be computed from the sonar values h_4 (Right Sonar) and h_2 (Left Sonar).

The idea behind these experiments is to determine whether calibration of the ARID robot will require elaborate procedures or not. For example, will calibration adjustments to α significantly depend upon how far the arm is extended?

After a brief discussion of the experiments, the actual data and experimental procedures are presented for each experiment. Several graphs of the data help to visualize the behavior and sources of kinematic error in the ARID.

2. DISCUSSION OF THE EXPERIMENTS

In *Experiments 1,2 and 3* we recorded the manipulator joint angles, the tool-center-point Orbiter-cartesian-coordinates, the angle α, and the four sonar readings. In *Experiments 2 and 3*, the arm is first extended and then retracted while keeping the sensor platform perpendicular to the gravity vector. The table, which was approximately leveled, appeared to be flat enough to make meaningful deductions from the sonar data. The experimental data seem to justify this claim.

If the table were perfectly flat, the sensor platform perfectly parallel and the sonar sensors perfectly accurate, the four sonars would have identical readings. Of course these perfect conditions cannot be met. All four sonars gave different readings. However, each sonar consistently measured the distance to the table, and so, maintained a fairly consistent relationship to the others, a desirable feature which will permit further calibration of the sonars. At a nominal 24 inches, the sonar readings consistently provided 3 digits accuracy with an uncertainty in the fourth digit not exceeding 0.060 inch.

In *Experiment 3* the sensor platform was commanded to be at $\alpha = 90°$, which, as seen in the earlier experiments, corresponds to about $\alpha = 94.6°$. This means the sensor platform was not parallel to the table during *Experiment 3*. The idea here was to test the total angular error in α from the Top and Bottom Sonar readings only and compare with the error in α measured in *Experiments 1 and 2*.

Experiment 4 attempted to quantify linear moves of the ARID. As the arm extends in 4 inch increments along *y-Orbiter* at constant elevation and trolley position, a plum bob hanging from the center of the sensor platform translates. The position of the bob tip is recorded on computer paper placed on the table surface.

3. CONCLUSIONS

While time has not permitted a thorough analysis of the data collected, it is hoped the data given in this paper will be of further use and analysis. Without absolute calibration, one is not able to quantify the ARID correction factors at this time. However, general comments about the ARID can be made from these preliminary experiments:

1. Effective calibration of the ARID should not pose any insurmountable difficulties. All errors appear to be correctable to produce the position tolerances required of the tool-center-point.

2. Separate calibration of the ARID revolute joints and the trolley should work quite well. This will reduce the number of data points.

3. A further reduction in calibration appears feasible using a calibration-model. This has yet to be shown however.

In sum, the experimental results obtained here are quite encouraging. The ARID position and orientation errors do not appear to be as large or as unpredictable as once thought.

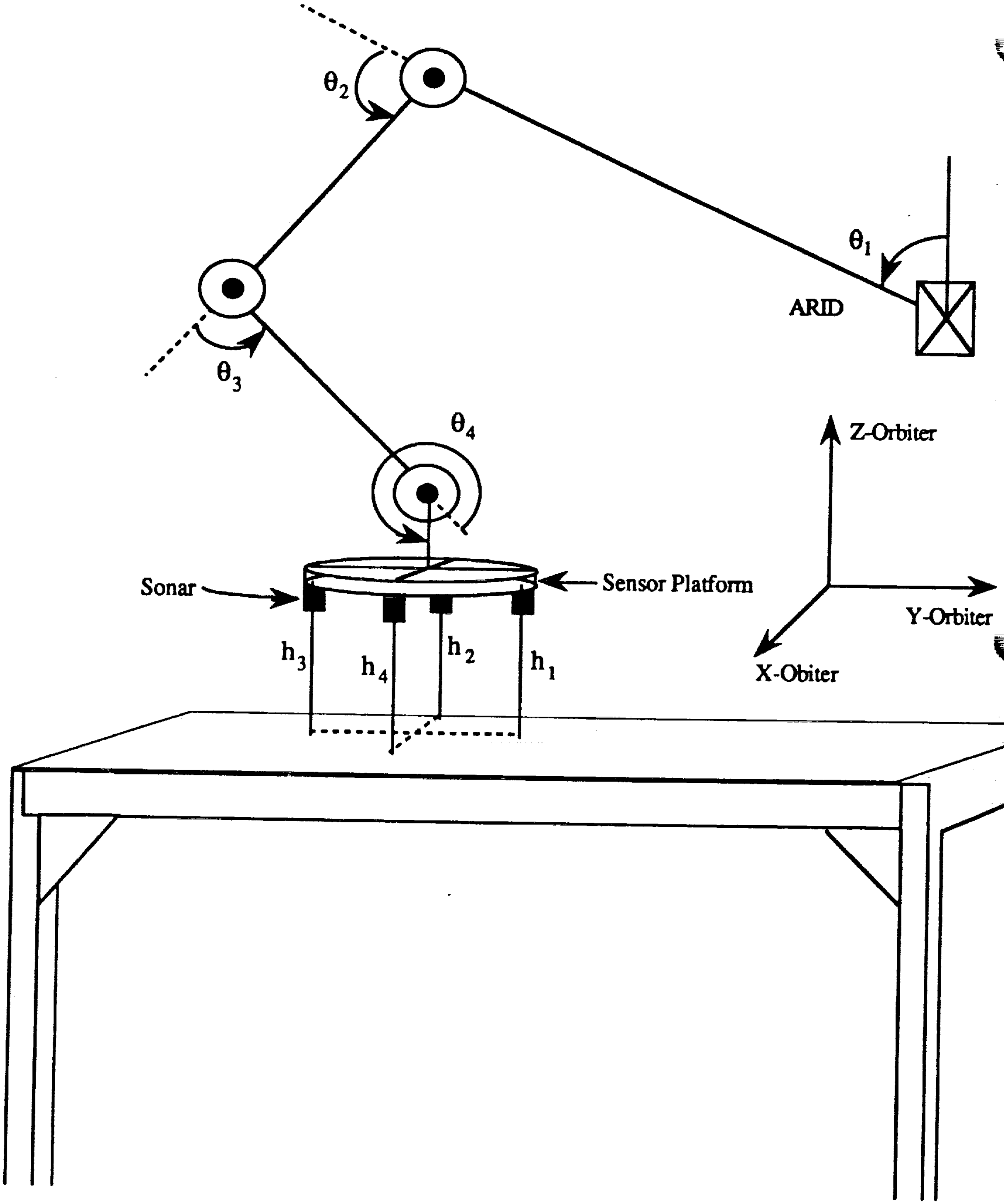


Figure 1 Experimental setup for the relative calibration experiments.

A1. EXPERIMENT 1: ANGLE ERRORS WHILE DECREASING Y

DATA FILE: EXP4.XCL

The sensor platform is kept parallel to X-Y plane of Orbiter. For each pose, the angle $\alpha = \theta_1 + \theta_2 + \theta_3 + \theta_4$ was adjusted to maintain the sensor platform orthogonal to the gravitational gradient. A carpenter's level resting on the platform indicated when the sensor platform was level. The repeatability of these measurements were within ± 0.04 degrees.The value of x-Orbiter and z-Orbiter were fixed at $x = 1018$ inches and $z = 366$ inches during the experiment.

Sonar measurements were taken in 4 inch increments for decreasing y-Orbiter, starting at $y = 220$ inches and ending at $y = 156$ inches (*Graph 1*, Graphs start on page 17.). A flat workbench beneath the sensor platform extended from $y = 204$ inches down to $y = 160$ inches. Thus, the sonars measured the distance from the sensor platform to the workbench and provided the necessary information for calculating the delta error in angle $\delta\alpha$ (Delta Alpha in the tables) and the total error in β (Beta in the tables). Since the greater part of the error in α is accounted for by keeping the sensor platform level, the Delta Alpha term corresponds to an additional angular error according to the sonar sensor readings. *Graph 4* plots $\delta\alpha$ and β.

EXPERIMENT 1: MANIPULATOR CONFIGURATION DATA

Joint 1 inches	Joint 2 degrees	Joint 3 degrees	Joint 4 degrees	X-Obiter inches	Y-Orbiter inches	Z-Orbiter inches
1022	66.0354	74.6549	-20.025	1018	156	366
1022	67.6619	78.7086	-25.6452	1018	160	366
1022	69.7574	82.1524	-31.1845	1018	164	366
1022	72.2576	84.9751	-36.4773	1018	168	366
1022	75.1458	87.2103	-41.5808	1018	172	366
1022	78.3716	88.8606	-46.417	1018	176	366
1022	81.9323	89.936	-51.053	1018	180	366
1022	85.7404	90.4319	-55.3171	1018	184	366
1022	89.7997	90.3483	-59.2827	1018	188	366
1022	94.0593	89.682	-62.8761	1018	192	366
1022	98.4625	88.4402	-66.0174	1018	196	366
1022	103.0012	86.6138	-68.7197	1018	200	366
1022	107.6145	84.2222	-70.8914	1018	204	366
1022	112.3593	81.2103	-72.6243	1018	208	366
1022	117.1814	77.5925	-73.8086	1018	212	366
1022	122.0921	73.3373	-74.4241	1018	216	366
1022	127.1358	68.3678	-74.4583	1018	220	366

EXPERIMENT 1: ALPHA ANGLE AND SONAR DATA

Alpha degrees	Top Sonar inches	Bottom Sonar inches	Left Sonar inches	Right Sonar Inches
85.46	23.2902	58.637	23.1988	23.3611
85.52	23.4018	23.299	23.2974	23.4689
85.52	23.4577	23.3739	23.363	23.5387
85.55	23.5412	23.4499	23.4446	23.6143
85.57	23.6018	23.5133	23.4985	23.6682
85.61	23.6762	23.5882	23.5807	23.7458
85.61	23.7165	23.6265	23.62	23.7922
85.65	23.7693	23.6896	23.6701	23.8492
85.66	23.8224	23.7344	23.7138	23.8888
85.66	23.8579	23.7632	23.7446	23.9227
85.68	23.885	23.794	23.775	23.9529
85.69	23.91	23.83	23.8102	23.981
85.74	23.9087	23.831	23.8072	23.9759
85.74	*59.0233	23.8245	23.8035	23.9593
85.76	*59.007	23.8435	23.8163	23.9678
85.8	*58.9945	23.8551	24.5672	25.0558
85.84	*58.9569	23.8378	*58.9563	59.1856

* These sonar measurements cannot be used since the associated sonar sensor is no longer above the table surface.

A2. EXPERIMENT 2: ANGLE ERRORS WHILE INCREASING Y
DATA FILE: EXP4.XCL

Experiment 2 possesses the same setup as *Experiment 1*. The only difference between the experiments is the direction of motion of the manipulator. The manipulator is moved from $y = 156$ inches to $y = 220$ inches in 4 inch increments during this experiment. *Graph 2* indicates the sonar readings for this experiment and *Graph 3* the difference in the respective sonar readings of *Experiments 1 and 2*. Ideally, the readings should be the same. The plots indicate the errors tend to be about ±0.010 inches about an average.

EXPERIMENT 2: MANIPULATOR CONFIGURATION DATA

Joint 1 inches	Joint 2 degrees	Joint 3 degrees	Joint 4 degrees	X-Obiter inches	Y-Orbiter inches	Z-Orbiter inches
1022	66.0354	74.6549	-20.025	1018	156	366
1022	67.683	78.7373	-25.7551	1018	160	366
1022	69.7824	82.1754	-31.2924	1018	164	366
1022	72.2909	84.9954	-36.601	1018	168	366
1022	75.1775	87.2224	-41.6846	1018	172	366
1022	78.4293	88.8717	-46.5857	1018	176	366
1022	81.9818	89.9376	-51.1841	1018	180	366
1022	85.7928	90.4264	-55.4439	1018	184	366
1022	89.8476	90.3372	-59.3895	1018	188	366
1022	94.0948	89.6695	-62.949	1018	192	366
1022	98.5061	88.4198	-66.1006	1018	196	366
1022	103.0303	86.5969	-68.7718	1018	200	366
1022	107.6522	84.1963	-70.9532	1018	204	366
1022	112.367	81.2041	-72.6358	1018	208	366
1022	117.1736	77.5997	-73.798	1018	212	366
1022	122.0921	73.3373	-74.4241	1018	216	366
1022	127.1358	68.3678	-74.4583	1018	220	366

EXPERIMENT 2: ALPHA AND SONAR DATA

Alpha degrees	Top Sonar inches	Bottom Sonar inches	Left Sonar inches	Right Sonar inches
85.46	23.2902	58.637	23.1988	23.3611
85.46	23.3839	23.301	23.2906	23.4533
85.46	23.4408	23.3644	23.3485	23.5184
85.48	23.5196	23.4451	23.4284	23.6014
85.51	23.5903	23.5204	23.5015	23.6672
85.51	23.6522	23.5784	23.5614	23.7275
85.53	23.6925	23.617	23.6058	23.7736
85.57	23.753	23.6842	23.661	23.8326
85.59	23.7997	23.7262	23.6995	23.8726
85.61	23.8383	23.7638	23.7388	23.9136
85.62	23.867	23.7896	23.7679	23.9417
85.65	23.8955	23.8218	23.8001	23.9698
85.69	23.9103	23.8486	23.8157	23.9837
85.73	*59.0375	23.8503	23.8184	23.9817
85.77	*58.9915	23.832	23.8038	23.9637
85.8	*58.9952	23.8618	24.5747	24.9497
85.84	*58.9569	23.8378	*58.9563	59.1856

* These sonar measurements cannot be used since the associated sonar sensor is no longer above the table surface.

A3. EXPERIMENTS 1 & 2: ALPHA AND BETA ANGLE ERRORS

The errors $\delta\alpha$ and β are computed from

Delta Alpha = atan[Bottom_Sonar - Top_Sonar)/16],

Beta = atan[Left_Sonar - Right_Sonar)/16],

respectively. *Graph 4* plots the $\delta\alpha$ and β angle errors together and*Graph 5* plots the total angle error $\varepsilon_\alpha := 90° - \alpha$ for *Experiment 1 and 2* combined.

EXPERIMENT 1

Alpha Error =90 -Alpha degrees	Delta Alpha degrees	Beta degrees
4.54	*65.645750	-0.5811741
4.48	-0.3681203	-0.6141156
4.48	-0.3000839	-0.629154
4.45	-0.3269405	-0.6076706
4.43	-0.316914	-0.6076706
4.39	-0.3151236	-0.5911998
4.39	-0.3222854	-0.616622
4.35	-0.2854022	-0.6413278
4.34	-0.3151236	-0.6266476
4.34	-0.3391154	-0.6377473
4.32	-0.3258662	-0.6370312
4.31	-0.2864765	-0.6116092
4.26	-0.2782404	-0.60409
4.26	*-65.55531	-0.5579
4.24	*-65.53364	-0.5425032
4.2	*-65.51883	-1.7491263
4.16	*-65.50634	*-0.821064

EXPERIMENT 2

Alpha Error =90 -Alpha degrees	Delta Alpha degrees	Beta degrees
4.54	*65.645750	-0.5811741
4.54	-0.2968611	-0.5826064
4.54	-0.2735853	-0.6083867
4.52	-0.2667815	-0.6194865
4.49	-0.2503093	-0.59334[illegible]
4.49	-0.2642749	-0.5947804
4.47	-0.2703625	-0.6008675
4.43	-0.2463703	-0.6144737
4.41	-0.2632006	-0.6198445
4.39	-0.2667815	-0.6259315
4.38	-0.2771662	-0.6223509
4.35	-0.2639168	-0.6076706
4.31	-0.2209458	-0.6015836
4.27	*-65.54819	-0.5847547
4.23	*-65.53119	-0.5725806
4.2	*-65.51514	-1.342624
4.16	*-65.50634	*-0.821064

* These computations cannot be used since the associated sonar sensor is no longer above the table surface.

Some statistics computed for these angles, in degrees, are given below. Subscript 1 refers to *Experiment 1* and subscript *2* to *Experiment 2*.

Angle $\delta\alpha$: $\delta\alpha_{1av} = -0.3149743$, $\delta\alpha_{2av} = -0.2633797$

Angle α: $\alpha_{1av} = 4.34941176$, $\alpha_{2av} = 4.39529412$

Standard Deviation angle α: $\sigma_1 = 0.10579878$, $\sigma_2 = 0.1248558$

Angle β: $\beta_{1av} = -0.6187405$, $\beta_{2av} = -0.6076109$

A4. ARID SAG

As the ARID arm extends the sensor platform came closer to the flat table surface, even though the *z*- coordinate was supposedly fixed at *366* inches. This effect, called *sag* , appears to follow a quadratic curve, although this has not been verified. The total sag from $y = 204$ inches to $y = 160$ inches as measured by the different sonars at $x = 1018$ inches is tabulated below. Over the 44 inch span involved in the experiments, the tool-center-point drops a little over one-half an inch.

SAG COMPUTATIONS

	Top Sonar	Bottom Sonar	Left Sonar	Right Sonar
Sag Exp1	0.5069	0.532	0.5098	0.507
Sag Exp2	0.5264	0.5476	0.5251	0.5304

A5. EXPERIMENT 3: SONAR MEASUREMENT OF ALPHA ERROR

DATA FILE: EXP5.XCL

The total angle $\alpha = \theta_2 + \theta_3 + \theta_4$ was set equal to 90° through the ARID user interface. The actual angle α is less than the set-point established by the ARID control program, as *Experiments 1 and 2* demonstrated. Consequently, the sensor platform was not parallel to X-Y plane of the Orbiter during *Experiment 3*. The value of x-Orbiter and z-Orbiter were fixed at $x = 1018$ inches and $z = 366$ inches during the experiment.

Sonar measurements were taken in 4 inch increments for decreasing y-Orbiter, starting at $y = 220$ inches and ending at $y = 156$ inches. A flat workbench beneath the sensor platform extended from $y = 204$ inches down to $y = 160$ inches. Thus, the sonars measured the distance from the sensor platform to the workbench and provided the necessary information for calculating the errors in angle α (Alpha in the tables) and β (Beta in the tables).

EXPERIMENT 3: MANIPULATOR CONFIGURATION DATA

Joint 1 degrees	Joint 2 degrees	Joint 3 degrees	Joint 4 degrees	X Orbiter inches	Y Orbiter inches	Z Orbiter inches	Alpha degrees
1022	66.328	76.1573	-17.2802	1018	160	366	89.9999
1022	68.1183	80.0433	-22.9564	1018	164	366	89.9999
1022	70.3506	83.2977	-28.4431	1018	168	366	89.9999
1022	72.9923	85.9472	-33.7343	1018	172	366	89.9999
1022	76.01	88.0057	-38.8105	1018	176	366	89.9999
1022	79.3677	89.4797	-43.6421	1018	180	366	89.9999
1022	83.0268	90.3711	-48.1927	1018	184	366	89.9999
1022	86.9466	90.6805	-52.4219	1018	188	366	89.9999
1022	91.0865	90.4079	-56.2892	1018	192	366	89.9999
1022	95.4076	89.5532	-59.7556	1018	196	366	89.9999
1022	99.8757	88.1161	-62.7866	1018	200	366	89.9999
1022	104.463	86.0946	-65.3524	1018	204	366	89.9999
1022	109.1504	83.4827	-67.4279	1018	208	366	89.9999
1022	113.9287	80.2671	-68.9906	1018	212	366	89.9999
1022	118.8012	76.4221	-70.0181	1018	216	366	89.9999
1022	123.7853	71.9024	-70.4825	1018	220	366	89.9999

EXPERIMENT 3: SONAR DATA

Top Sonar Inches	Bottom Sonar Inches	Left Sonar Inches	Right Sonar Inches
24.1232	22.9023	23.4291	23.5767
24.203	22.901	23.4934	23.6577
24.2652	22.9769	23.5756	23.7319
24.315	23.0169	23.6264	23.7827
24.383	23.0881	23.6857	23.8387
24.4236	23.1417	23.7392	23.8973
24.4676	23.1936	23.7845	23.9431
24.5159	23.2444	23.8299	23.9864
24.5505	23.2892	23.861	24.0244
24.5691	23.3105	23.8854	24.0512
24.5917	23.3282	23.9125	24.0681
24.608	23.3638	23.9308	24.0841
25.378	23.379	23.9369	24.0922
59.752	23.378	23.9426	24.0918
59.7324	23.3916	24.3526	24.5982
59.7094	23.3885	59.1076	59.3513

A6. EXPERIMENT 3: ALPHA AND BETA ANGLE ERRORS

The angle error in α and β were compute from

Alpha Error= atan[Bottom_Sonar - Top_Sonar)/16]

Beta Error= atan[Left_Sonar - Right_Sonar)/16] .

The results of these computations are tabulated below and appear in *Graphs 6 and 7*, respectively. According to this experiment the error in α decreases with increasing *y-Orbiter* just as in *Experiments 1 and 2* (*Graph 5*). The numerical values correspond within 3% to 6% of each other. *Graph 8* compares the value of β measured in *Experiments 1,2 and 3*. The values of β differ by no more than 0.1 degree. While 0.1 degree corresponds to about an 17% error, the absolute magnitude of the error will not cause the too-center-point to deviate more than *displacement* $\approx 24" \times 0.1\,\pi/180° < 0.020$ inch. Thus, using the average value of β for all manipulator configurations will probably be sufficient.

EXPERIMENT 3: ANGLE ERROR FROM SONAR READINGS

Alpha Error	Beta Error
-4.36357	-0.5285386
-4.6521934	-0.5883354
-4.6034532	-0.5596903
-4.6383191	-0.5596903
-4.6269347	-0.5478742
-4.5806818	-0.5661355
-4.5525713	-0.5679258
-4.5436752	-0.5604065
-4.5073765	-0.5851128
-4.4977674	-0.5937063
-4.5152059	-0.5571839
-4.4465148	-0.5489484
*-7.1214904	-0.5561097
*-66.256524	-0.5342677
*-66.237234	*-0.879421
*-66.225658	*-0.872619

* These computations cannot be used since the associated sonar sensor is no longer above the table surface.

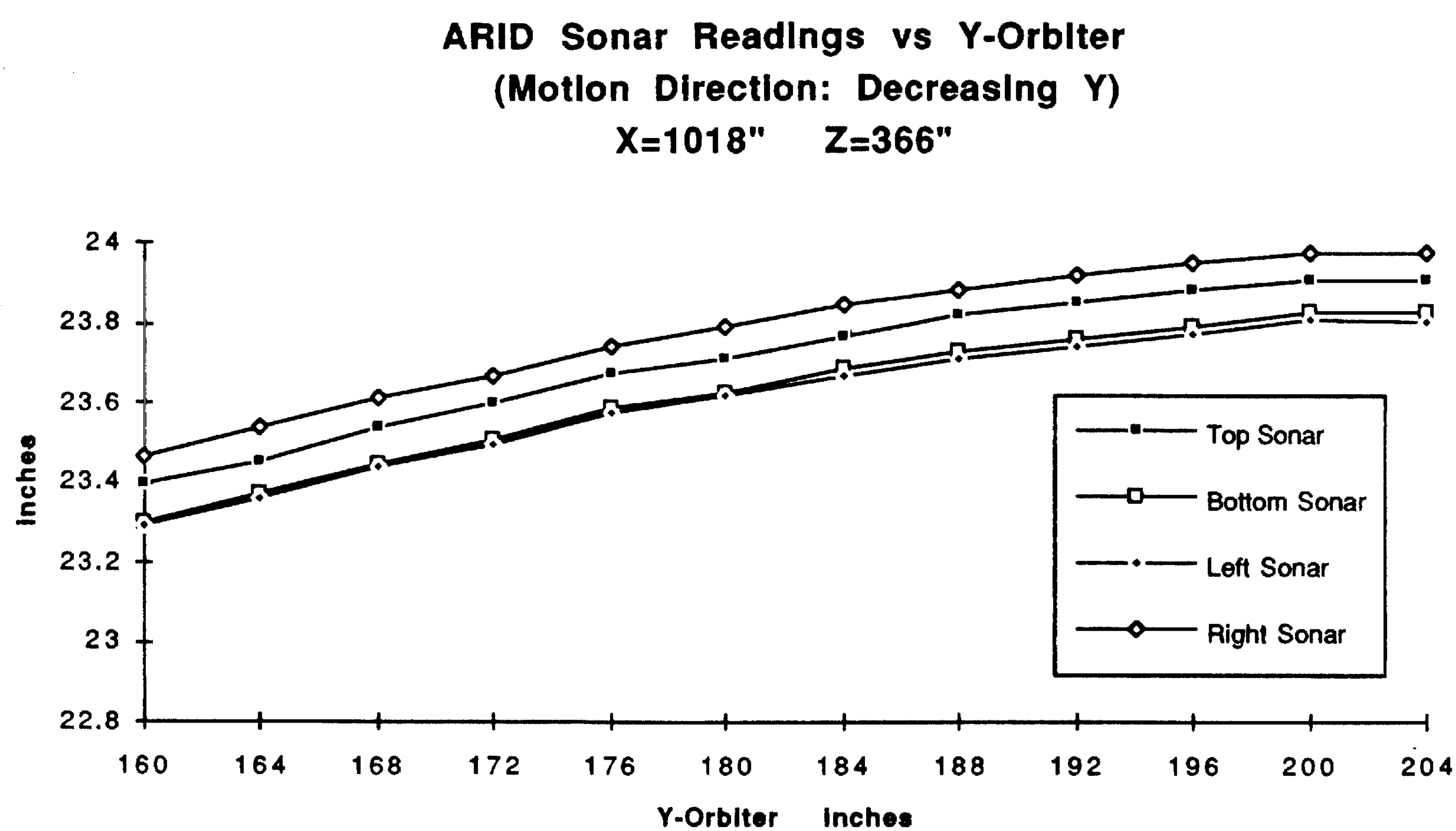
A7. EXPERIMENT 4: LINEAR DISPLACEMENT ALONG Y
DATA FILE: EXP4.XCL

The user commands the ARID robot to go to poses $P = (x_0, y, z_0, \alpha)$. The value of y was commanded to range from *180* inches to *220* inches in *4* inch increments while $x_0 = 1018$ inches and $z_0 = 366$ inches. For each pose, the angle $\alpha = \theta_2 + \theta_3 + \theta_4$ was adjusted so that the sensor platform remained perpendicular to the gravity vector. A plum bob hanging from the sensor platform was used to mark off the linear moves on a piece of computer paper placed on a flat table underneath the sensor platform. The accuracy of the technique was estimated to be $\pm \frac{1}{32}$ inch. *Graph 9* depicts the data tabulated below.

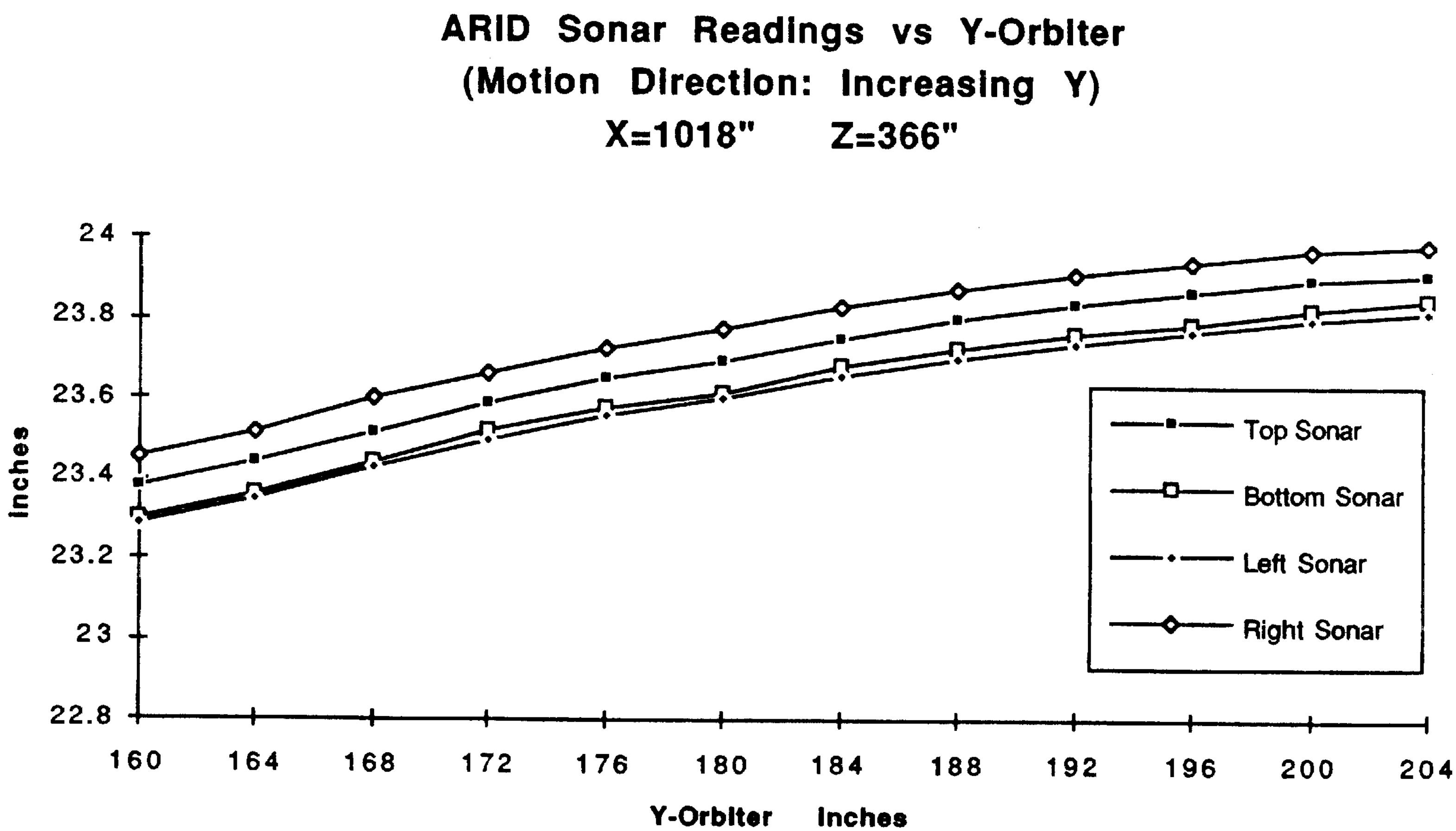
EXPERIMENT 4: DATA

Y-Orbiter inches	Y Increment inches
180	3.9375
184	3.9375
188	3.9375
192	3.9375
196	3.875
200	3.9375
204	3.9375
208	3.96875
212	3.9375
216	3.984375
220	-------
Total Increment Y-Orbiter	39.390625
Tape Measure	39.4375
Commanded	40

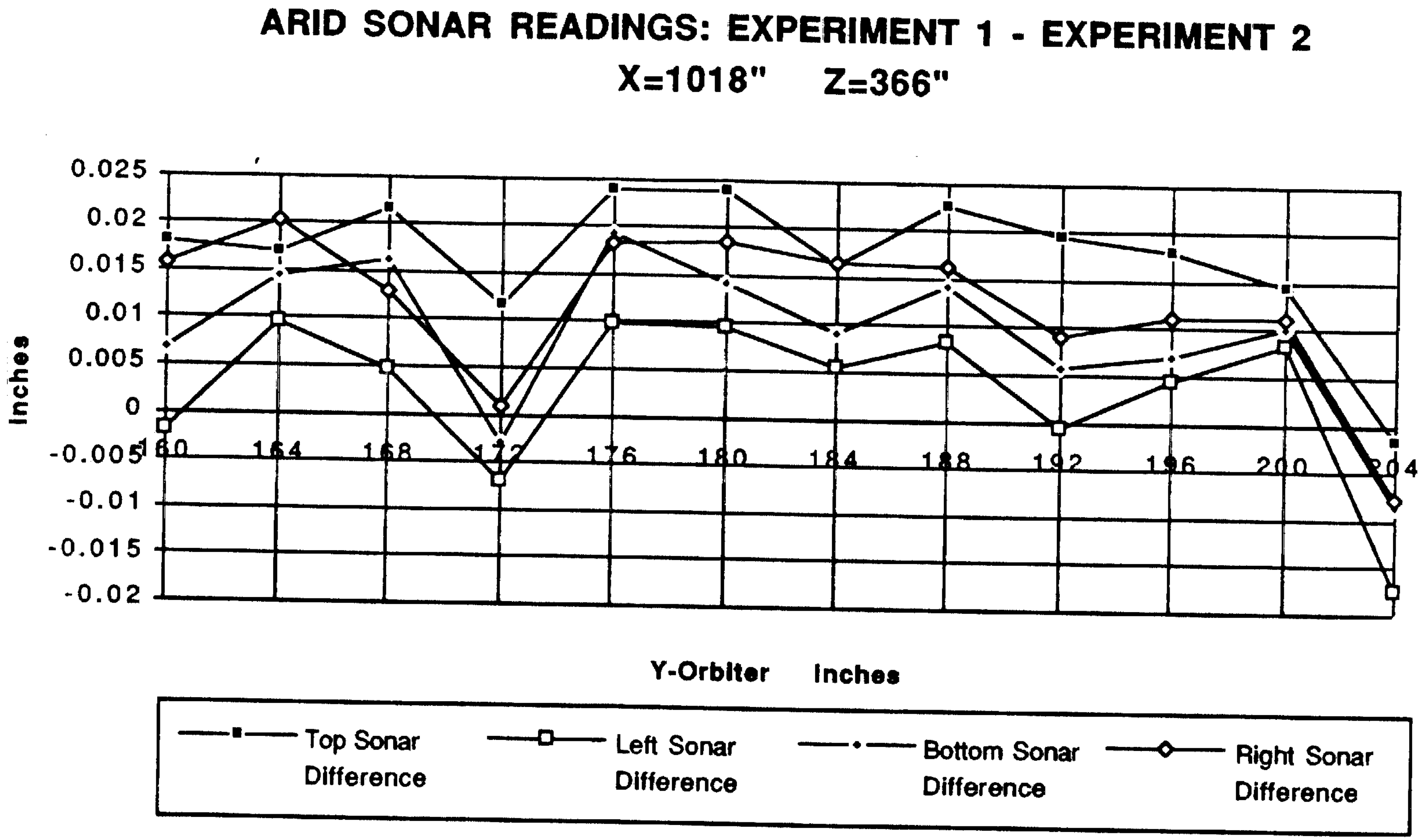
A8. GRAPHS OF ARID EXPERIMENTS



Graph 1 Sonar Readings, Experiment 1.

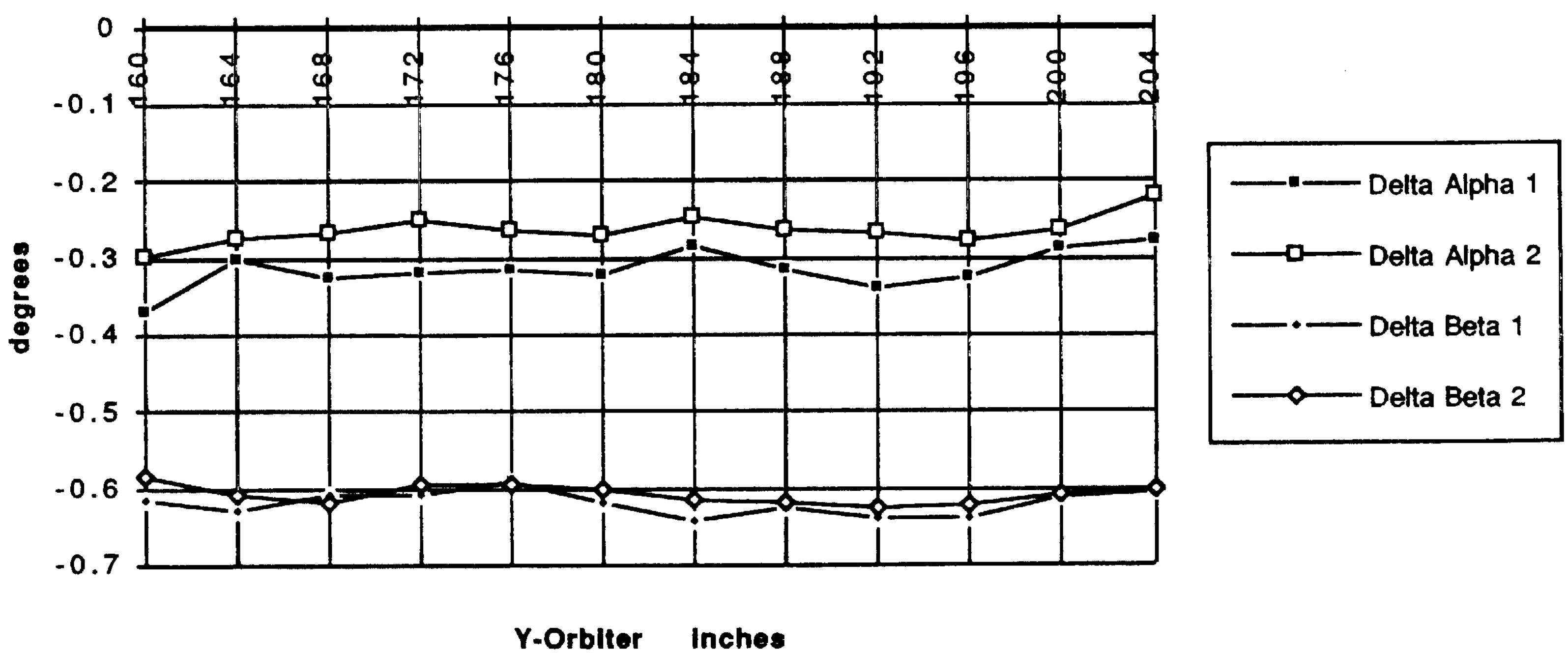


Graph 2 Sonar Readings, Experiment 2.

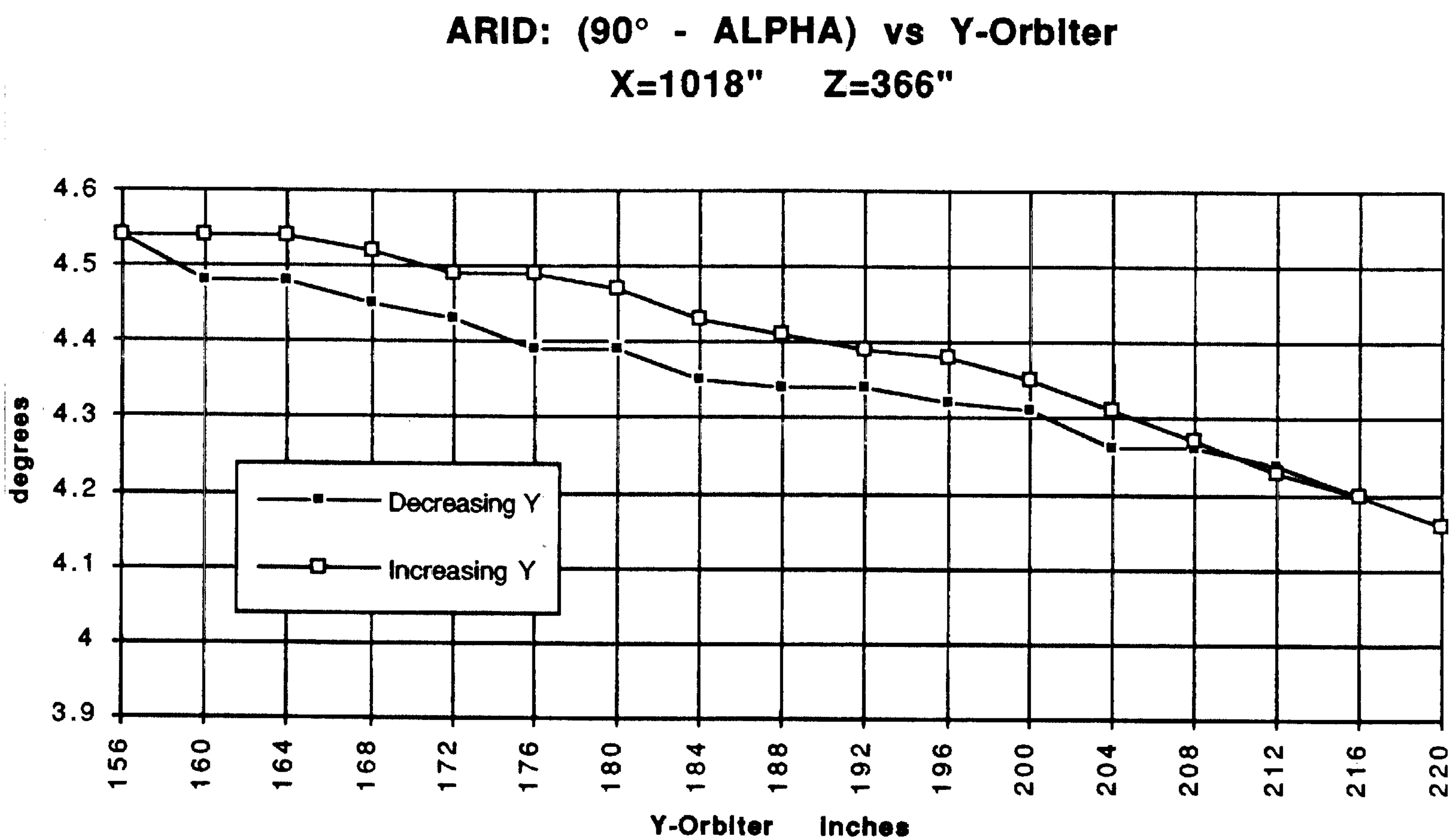


Graph 3 Difference in Sonar Readings, Experiments 1 and 2.

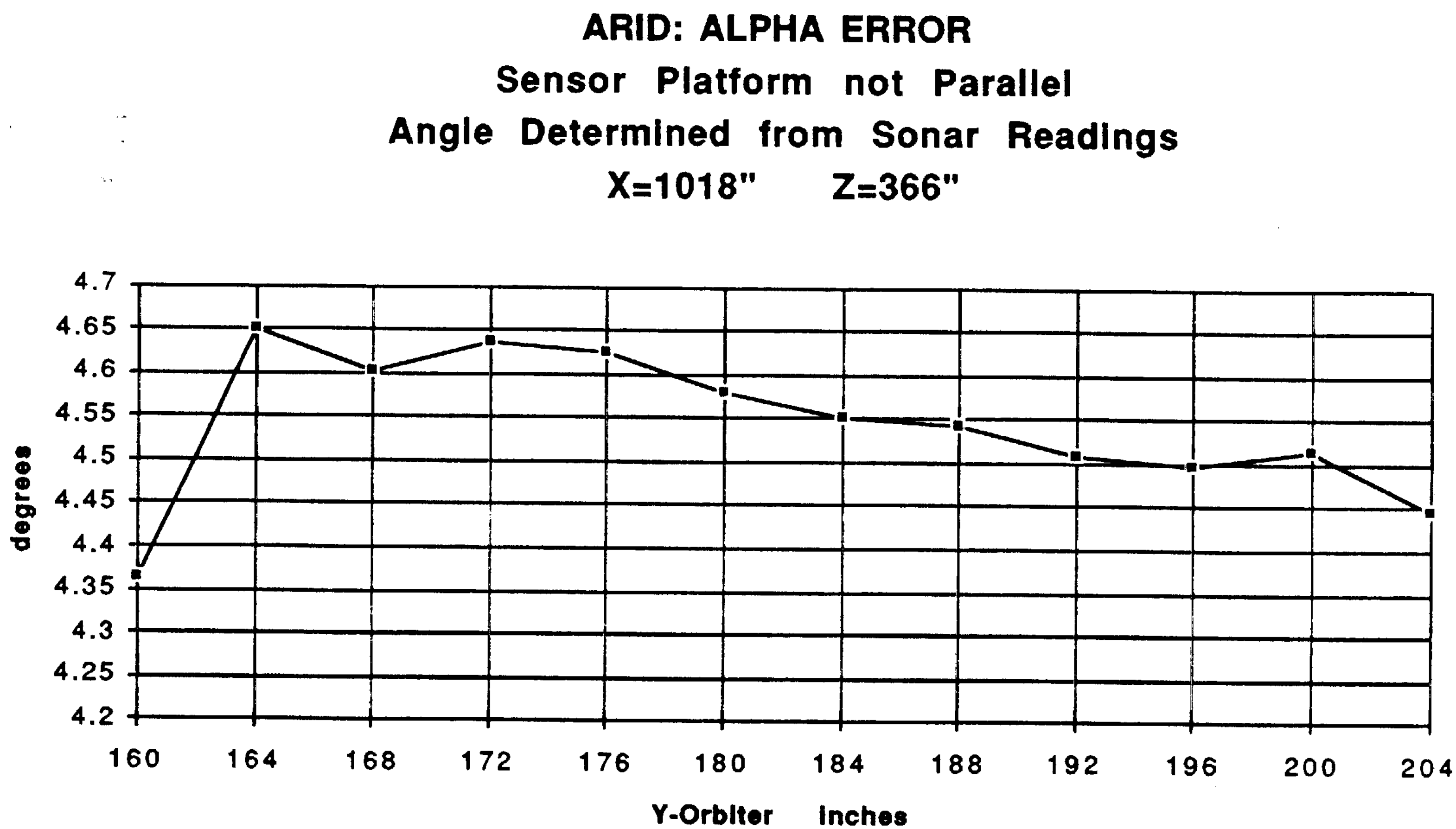
ARID ALPHA AND BETA ANGLE ERRORS
Sensor Platform Parallel to Table
X=1018" Z=366"



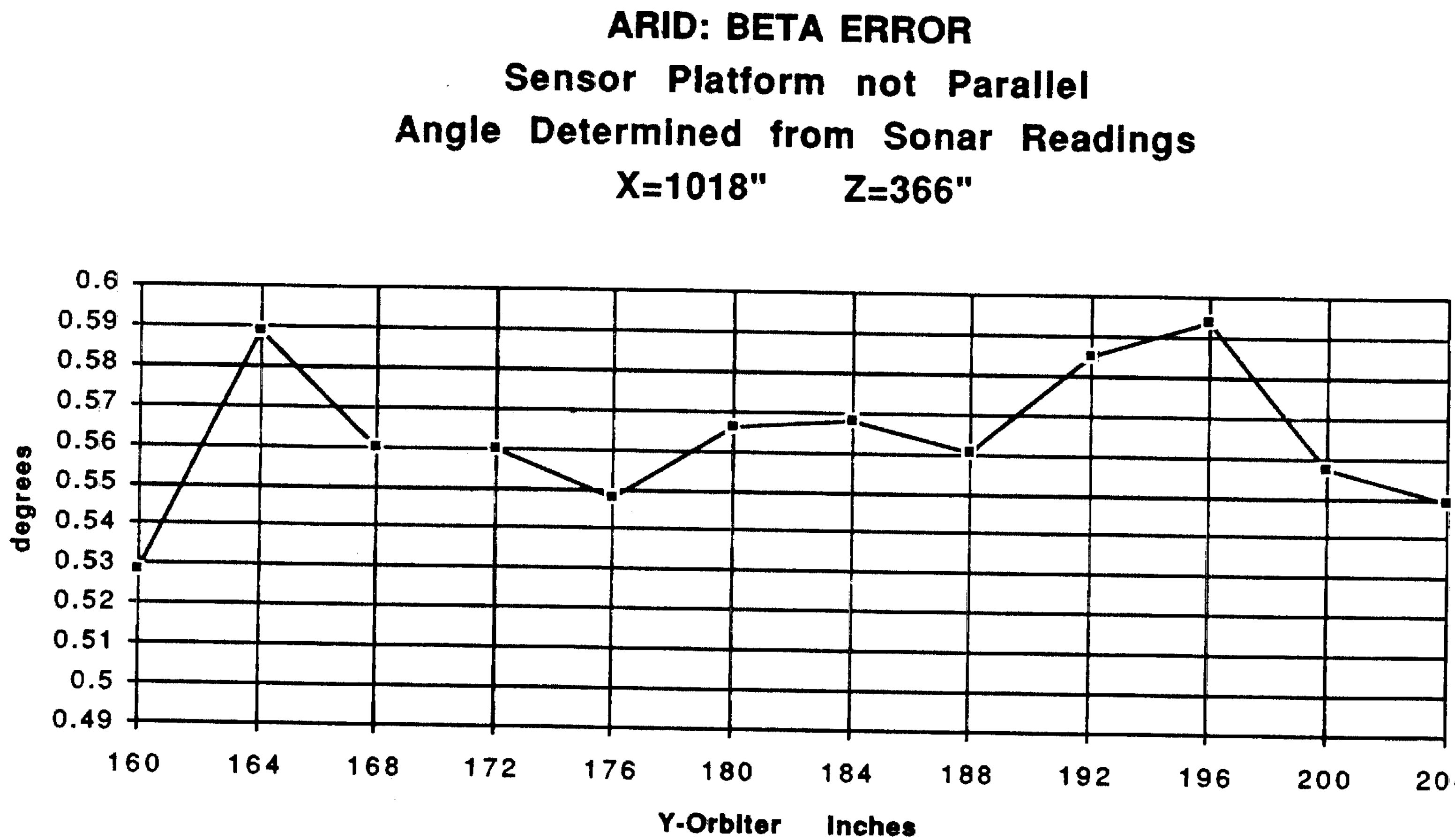
Graph 4 Delta error in α and total error in β based upon sonar readings, Experiments 1 and 2.



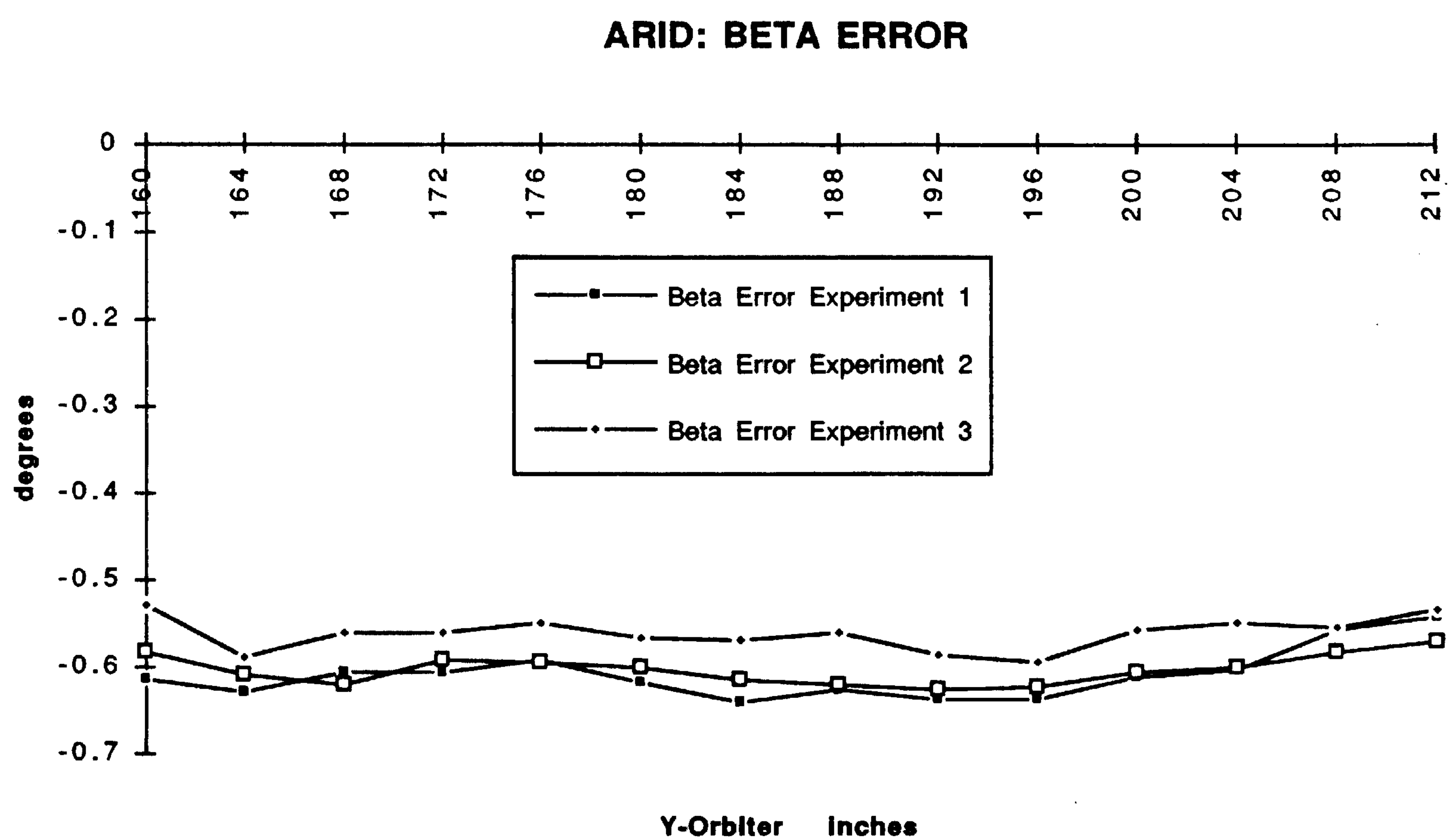
Graph 5 Total error in α, Experiments 1 and 2.



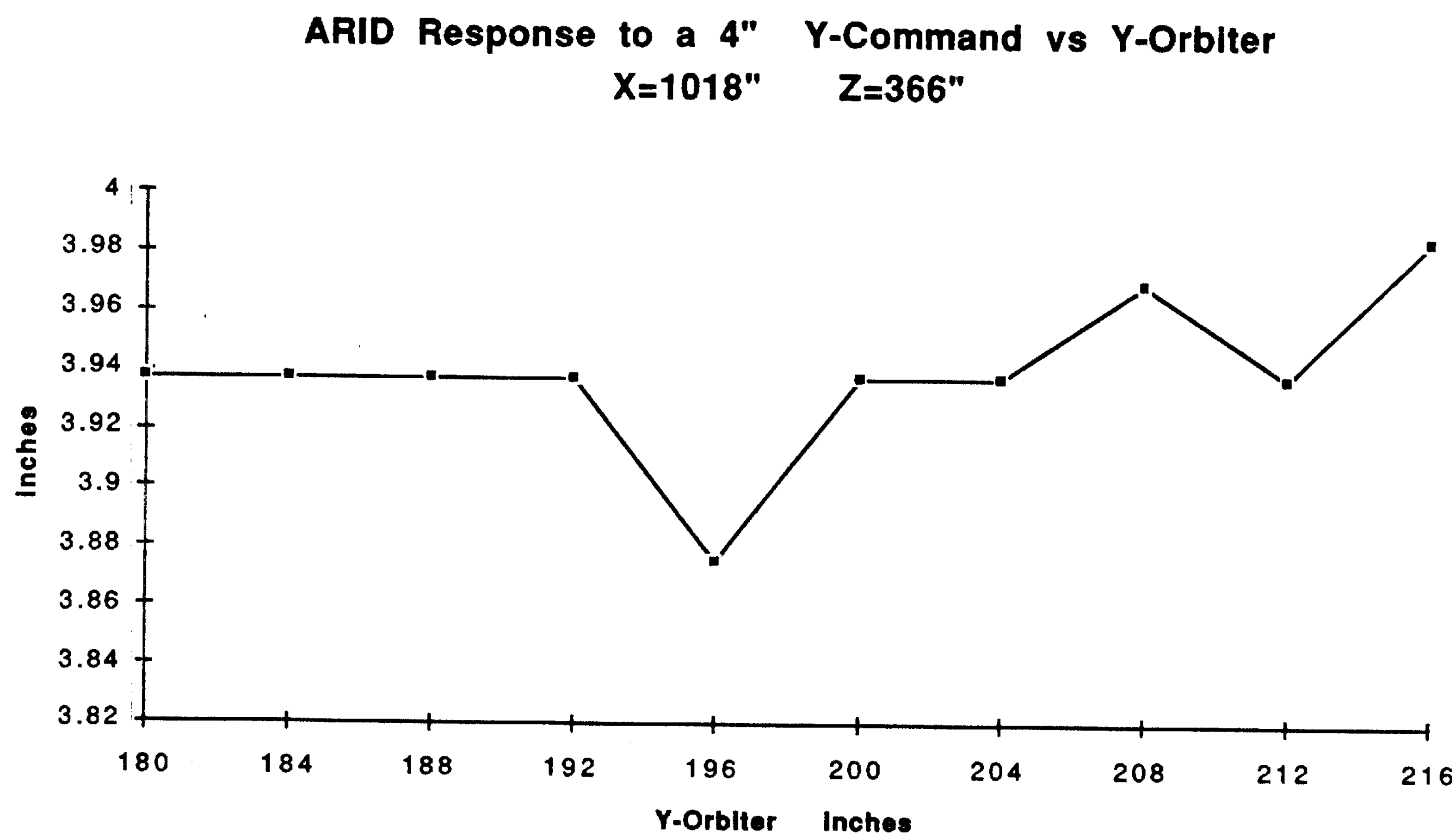
Graph 6 Total error in α based upon sonar readings, Experiment 3.



Graph 7 Total error in β based on sonar readings, Experiment 3.



Graph 8 Total error in β, Experiments 1, 2 and 3.



Graph 9 ARID response to successive 4 inch moves along *y-Orbiter*, Experiment 4.