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POSITIONAL ERROR ANALYSIS, A-10 AIRCRAFT ON THREE-AXIS GROUND M--ETC(U)

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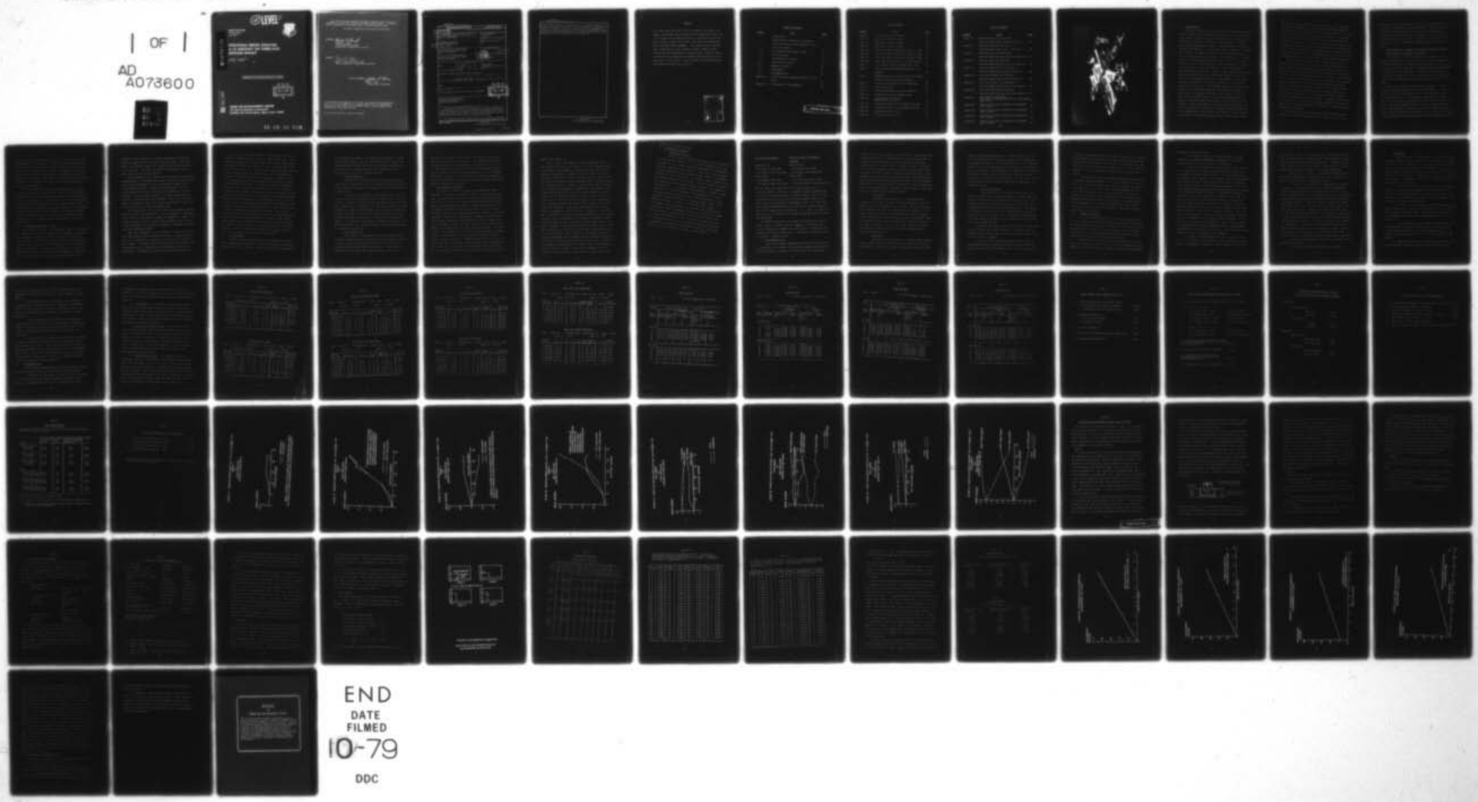

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In-House Report
July 1979

POSITIONAL ERROR ANALYSIS, A-10 AIRCRAFT ON THREE-AXIS GROUND MOUNT

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This report describes a test effort that was performed to determine the truth orientation of an A-10 aircraft mounted on a Scientific Atlanta Inc., Model PAEA-85 three-axis positioner at the Rome Air Development Center Newport Antenna Test Annex, and to estimate the errors inherent in using the aircraft positioning system in the process of antenna pattern testing.

The report describes the following aspects of this effort: (1) Establishment of a reference coordinate system for the aircraft, and alignment of the

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aircraft on the positioner, (2) Description of the inclinometer system used for determining the aircraft orientation, (3) Test procedures, (4) Discussion of results, (5) Summary of errors, and (6) Conclusions and recommendations for the guidance of personnel using the system for aircraft antenna pattern testing. The total system error was determined to be less than 0.683 degrees for a pitch maneuver, and less than 0.533 degrees for a roll maneuver.

PREFACE

This report describes the efforts performed to determine the angular positional error associated with supporting a full size A-10 aircraft on the PAEA-85 three-axis positioner located at RADC's Newport Antenna Test Annex. The work was accomplished under Job Order Number 21140001. The authors wish to extend their appreciation to Mr. Lawrence Crouth of RADC's Sensor Calibration and Instrumentation Branch and Mr. Edward Collucio of the 416th Field Maintenance Squadron Machine Shop for their assistance in this effort. This work was performed during the time period from Jun 77 to Dec 78.

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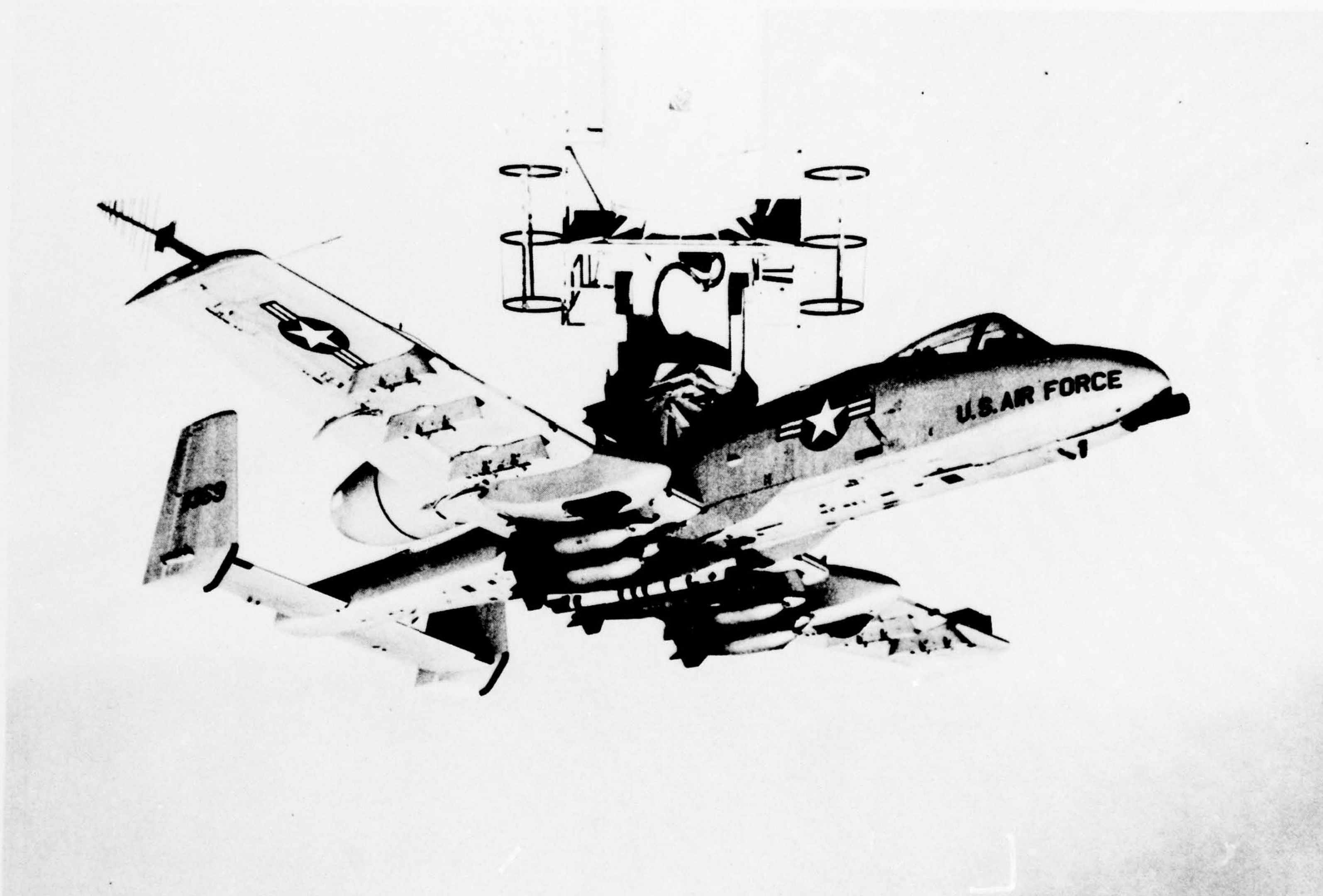
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I INTRODUCTION

In order to effectively and efficiently evaluate the multiple antenna systems of the A-10 aircraft under realistic flight conditions without actually flying it, the aircraft was attached to the turntable of a positioner which is located on top of a 30-foot tower at RADC's Newport Test Annex. The positioner, a Scientific-Atlanta Model PAEA-85, is a three-axis unit, azimuth over elevation over azimuth. It allows the aircraft to be tilted in pitch or roll and rotated about its yaw axis. See frontispiece. A digital readout of the instantaneous position of each axis is obtained through the use of synchro devices. This information is required to describe the aircraft orientation in space for purposes of evaluating antenna test data. However, since these devices measure only the motion which occurs between the turntable on which the aircraft is mounted and the points in the pedestal on which the synchros are mounted, an uncertainty remains as to the actual position of the aircraft. The inherent flexibility of the system caused by the foundation and tower, the pedestal structure and gear trains, the turntable bearings, the aircraft-to-pedestal mount and the aircraft itself, results in deformations due to gravity, wind, and thermal effects that are not detected by the synchros. Other contributions to the positional uncertainty are: errors in defining the reference coordinate system; inaccuracies in the manufacture, installation, and alignment of the components of the entire system; positioning of the aircraft on the mount;

mechanical synchro readout error; and human error in conducting the tests and taking data. Error analyses have been conducted in conjunction with previous tests of aircraft mounted in a similar manner on the same tower and positioner at Newport. A detailed discussion of the specific sources of error mentioned above is contained in RADC-TR-77-299, "F-111 Positional Error Analysis When Mounted on Three-Axis Positioner at RADC Newport Test Annex", and values of the expected errors are determined or estimated for each of the significant sources. Where appropriate, these error values are tabulated and used in this report without further discussion.

The purpose of this effort was to investigate the total angular positional error in elevation, hereafter referred to as total system error, associated with mounting the A-10 aircraft to the positioner, and maneuvering the aircraft about its pitch and roll axes. This was accomplished by the following: (1) Establishing a coordinate system for the aircraft and aligning the aircraft on the positioner, (2) Installing an inclinometer measurement system for determining aircraft orientation with respect to the gravity axis and for estimating errors associated with the aircraft positioning system, and (3) Testing to evaluate probable errors in the aircraft positioner system. Included in this report is a discussion of the results of the measurements, evaluation of system errors, and recommendation of procedures to be followed for estimating system errors.

The results of the test program show that in performing an aircraft rotation about the positioner elevation axis, the total system error is less than 0.683 degrees for a pitch manuever, and less than 0.533 degrees for a roll maneuver. Total system error is defined as the difference between the aircraft position as determined from the positioner instrumentation and the true aircraft position as indicated by inclinometers mounted in the aircraft, corrected for additional estimated errors as discussed herein.

II ESTABLISHMENT OF REFERENCE COORDINATE SYSTEM FOR AIRCRAFT AND ALIGNMENT OF AIRCRAFT ON PEDESTAL

After the aircraft was assembled in the hangar, it was leveled following the leveling procedure described in Appendix A. A reference platform was manufactured and installed in the interior of the aircraft near frame 540 in accordance with procedures which are also described in Appendix A. The platform was designed to be used with a bubble-type level or with electrical inclinometers such as those manufactured by Schaevitz which were used in this study.

After the aircraft was leveled in the hangar, various reference marks were placed on the aircraft fuselage. A set of marks was placed on both sides of the aircraft with the help of an engineer's level. This established a horizontal reference plane. The horizontal plane reference marks were not used in this test. They were intended primarily for use in determining aircraft fuselage droop. However, since the inclinometer measurement system transducers were mounted close to the points of support of the aircraft, fuselage droop became of minor significance, and the value previously measured in the F-111 tests was used in the determination of system error. Another set of marks was placed on the top and bottom of the fuselage to define a vertical reference plane. Fore-to-aft position can be adequately specified in terms of the fuselage station numbers as provided by the aircraft manufacturer's drawings. The details of the procedures which were followed to determine the locations of the reference marks are described in Appendix A.

Prior to mounting the aircraft on the pedestal, a test was performed to check the elevation axis readout of the positioner. A machinists level was placed on the pedestal platform perpendicular to the elevation axis. The elevation axis drive was operated to bring the level within one division (0.0005 in/ft) of zero. At this position, the elevation axis readout indicated +0.23 degrees. This means that with the lower azimuth set at 0 degrees and the elevation axis readout set at 0 degrees, the pedestal platform would be tilted 0.23 degrees upward with respect to the site on Tanner Hill.

III INCLINOMETER MEASUREMENT SYSTEM

The turntable position is determined by synchros that measure the elevation and azimuth movements of the turntable and display these movements on digital readouts located at the positioner control console. In order to provide some means for checking the synchro readout system and for estimating the errors associated with aircraft, mount, and pedestal deflection, the aircraft was instrumented with two Schaevitz servo inclinometers. Both inclinometers were mounted on a specially made platform which was attached to the aircraft at a location selected to be near the points of support of the aircraft on the positioner. One inclinometer was mounted so that its inclination would sense the pitch of the aircraft. The other inclinometer was mounted so that it would sense the roll of the aircraft.

The inclinometers are closed-loop, force-balance type sensors. A pendulum mass is suspended which tends to rotate relative to the frame of the inclinometer as the inclinometer is made to tilt. As the pendulum rotates, a signal is generated which drives a torque motor which in turn repositions the pendulum in its null position. The torque motor current is directly proportional to the gravity force acting on the pendulum. Thus, the torque motor and the inclinometer output are directly proportional to the sine of the angle of tilt of the inclinometer base.

The inclinometers used in this study were designed to operate between 0 degrees and ± 50 degrees. Each instrument was calibrated at the factory at one degree increments throughout its range. The calibration data as well as other data pertaining to the accuracy of the inclinometer are provided in Appendix B including a calibration check performed at RADC.

When the inclinometer is tilted about its nonsensitive axis, no output voltage would be observed in theory. In practice, however, it is impossible to construct a device which is perfect in this respect. The output which is observed for rotation about the nonsensitive axis is indicated by the instrument's cross-axis sensitivity. The numerical value of the cross-axis sensitivity is the measured voltage output which is observed when the inclinometer is tilted 90 degrees about its nonsensitive axis. Like the primary output of the inclinometer, the voltage output associated with tilt about the nonsensitive axis is proportional to the sine of the angle of tilt. However, the calibration check referred to above indicated that the nonsensitive axis data departs substantially from the manufacturer's prediction. Figures B2 thru B5 of Appendix B provide calibration curves which can be used to estimate actual nonsensitive axis motions from the inclinometer output voltage. In these tests they were also used to predict the amount of the output voltage which was due to a known rotation about the nonsensitive axis. For example, if a pitch maneuver was performed, the inclinometer which was mounted to sense pitch rotation, provided a voltage output proportional to the amount of that rotation. The other inclinometer, mounted to sense roll rotation, provided a voltage which included not only any roll rotation occurring during the pitch maneuver, but also a voltage generated by rotation about the nonsensitive axis produced by the primary pitch maneuver. The above mentioned curves were used to estimate the amount of the inclinometer voltage which was due to the pitch rotation. This was subtracted from the total voltage, the difference being the amount due to the roll rotation.

IV TEST PROCEDURES

A number of pedestal maneuvers were performed, during which time simultaneous measurements of synchro readout and inclinometer voltage were made. Essentially eight test maneuvers were performed:

(1) Nosedown Pitch Change, (2) Taildown Pitch Change, (3) Right Wing Down Roll Change, and (4) Left Wing Down Roll Change, each being performed for both right side up and upside down positions of the aircraft. Measurement data was collected on 28 Oct 77 (Upside Down) and 31 Mar 78 (Right Side Up).

A. Pitch Change Tests

These tests were performed by rotating the upper and lower tables to the desired synchro readouts such that a rotation of the positioner elevation axis would result in a pitch rotation of the aircraft.

One test was performed by lowering the nose of the aircraft, the other by lowering the tail of the aircraft. The aircraft was oriented so that the pitch inclinometer registered 0.001 Volt, equivalent to 0.00 degrees after the upper and lower azimuth settings were made, and subsequently, the aircraft was rotated to provide pitch angles of 10, 20, 30, 40 and 45 degrees for both nosedown and noseup orientation, as indicated by the pitch inclinometer. For each pitch orientation, including 0.00 degrees, the pitch inclinometer, the elevation synchro, and the roll inclinometer readings were recorded.

B. Roll Change Tests

These tests were performed by again rotating the upper and lower azimuth tables to the desired synchro readout, such that a rotation of the positioner elevation axis would result in a rotation of the aircraft about its roll axis. Tests were performed for both clockwise and counterclockwise rolls. The aircraft was oriented so that the roll inclinometer registered 0.001 Volt, equivalent to 0.00 degrees after the upper and lower settings were made, and subsequently, for angles of 10, 20, 30, 40, and 45 degrees as indicated by the roll inclinometer except that for the upside down, right wing down roll test, a 35 degree reading was taken also. For each angle, including 0.00 degrees, the roll inclinometer, the elevation synchro, and the pitch inclinometer readings were recorded.

V PRESENTATION OF RESULTS

The results of the test program are presented in Tables 1 through 4 and Figures 1 through 4. Tables 1 and 2 present basic data for pitch and roll tests for right side up and upside down positions of the aircraft. Data includes nominal pitch or roll angle as determined by inclinometer reading, along with the corresponding elevation synchro reading in the first two columns. The next column is the difference between inclinometer and synchro readings. The next two columns, Δ inc. and Δ syn., represent the total change, obtained by subtracting the initial reading from each succeeding reading. The next column is error, defined as the Δ synchro reading minus the Δ inclinometer reading. The final column is the voltage read from the inclinometer which is rotated about its nonsensitive axis by the primary rotation of the aircraft. Figures 1 and 2 are a graphical presentation of the error versus the angle of rotation. This data represents the final output of the test - the difference between the actual orientation of the aircraft as defined by the inclinometers, and the position shown by the synchros.

Tables 3 and 4 and Figures 3 and 4 present the results of the evaluation of cross-axis effects, i.e., roll rotations which occur during a pitch maneuver and pitch rotations which occur during a roll maneuver. Column 1 lists the angles of primary rotation, either pitch or roll. Column 2 lists the voltage output of the inclinometer experiencing the primary rotation about its nonsensitive axis. Column 3 is the voltage taken from Appendix B, Figures B2 through B5 as appropriate, and represents the voltage which should exist due solely to the primary rotation. Column 4 is the difference between columns 2 and 3 and is the voltage due to rotation of this inclinometer about its sensitive axis, and which includes the effect of any initial out-of-level condition. Column 5 is the angle represented by this voltage, taken from Appendix B, Tables B3 or B4. Column 6 is the voltage due to initial out-of-level occurring perpendicular to the primary rotation, and is calculated for each angle of rotation by multiplying the total initial out-of-level value by the cosine of the angle. Column 7 is the difference between columns 4 and 6, and is the voltage due to cross-axis rotations due to unknown effects, such as deflections of the aircraft or the support structure, or minor misalignments such as nonparallelism or nonperpendicularity of aircraft centerline and positioner elevation axis. Column 8 is the angle represented by this voltage, taken from Appendix B, Tables B3 or B4. Columns 5 and 8 are the angular cross-axis motions, 5 being the total motion, while 8 is the part of the motion whose cause is unknown.

VI DISCUSSION OF RESULTS

A. Initial Out-of-Level

An out-of-level condition was found to exist between the aircraft and the turntable, i.e., with the turntable level, the aircraft was out of level in planes perpendicular to and parallel with the centerline of the aircraft. This can be seen by examining the elevation synchro readings for the 0 degree inclinometer settings for all of the tests. For example, refer to Table 1 for the upside down tests of 28 October. For the 0 degrees inclinometer readings we find elevation synchro readings of 0.41 degrees, nosedown pitch, -0.12 degrees taildown pitch, 0.37 degrees, right wing down roll, and 0.00 degrees, left wing down roll. By subtracting one pitch reading from the other and dividing by 2, we obtain the actual out-of-level, or $\frac{+0.41 - (-0.12)}{2} = \frac{0.53}{2} = 0.26$ degrees nose high. Similarly, in the other plane, $\frac{0.37 - 0}{2} =$ 0.18 degrees right wing high. For the right side up position of the aircraft, the corresponding values are 0.49 degrees nose high and 0.15 degrees left wing high. These values all apply to the case where the turntable is level. They can be further verified by referring to the cross-axis inclinometer reading in each case. A comparison of nonlevelness obtained from synchro readings and from cross-axis inclinometer readings is shown below:

From synchro readings	From cross-axis inclinometer readings
Right Side Up:	Right Side Up:
0.49 degrees nose high	0.495 degrees nose high
0.15 degrees left wing high	0.123 degrees left wing high
Upside Down:	Upside Down:
0.26 degrees nose high	0.265/0.30 degrees nose high
0.18 degrees right wing high	0.263/0.089 degrees right wing high

The two values for both cases of the upside down test, i.e., 0.265/0.30 degrees, indicate a discrepancy between readings taken for aircraft azimuth positions 180 degrees apart. Since the turntable was level in all cases, no such discrepancy should exist, and it must be attributed to experimental error. On 2 Nov 1978, shims were placed between the aircraft and the support mounting pads in the upside down configuration. As a result, the amount of out-of-level was reduced to 0.02 degrees nose high and 0.05 degrees left wing high.

It should be noted that the method of obtaining the error in Tables 1 and 2, in which only the changes in inclinometer and synchro readings are compared, has the effect of eliminating the error due to initial nonlevelness. Nonlevelness, therefore, will be listed as a separate error.

B. Inclinometer Tests

These tests compare the angular position of the aircraft as described by the synchro system with the angular position with respect to gravity (vertical) as described by the inclinometer system. Since the inclinometer system takes its measurement with respect to gravity, it includes deformations occuring in the system between the inclinometer system platform and the ground whether caused by gravity, wind, or thermal effects. The difference, or error measured, therefore, tends to be the total error occurring in vertical planes, except for the initial out-of-level condition of the aircraft as discussed herein, and distortions of the aircraft beyond the inclinometer platform. The inclinometer data itself is in error because of inaccuracy of the inclinometers, error in establishing the inclinometer level reference plane, and errors in reading the inclinometer output.

1. Pitch Test

Maximum error measured was -0.04 degrees which occurred for the right side up, tail down position at 40 to 45 degrees pitch. The negative error indicates that the rotation of the aircraft was greater than indicated by the synchro. In all cases, the error tended to increase uniformly with increasing pitch, except that for the upside down, tail down position, there was virtually no error until 45 degrees was reached and then it was only 0.01 degree. For one case, right side up, nose down, the rotation of the aircraft was less than indicated by the synchro (positive error).

2. Roll Test

Maximum error measured was 0.21 degrees which occurred for the right side up, right wing down position of the aircraft. A maximum of 0.20 degrees occurred for the upside down left wing down and right wing down positions. In these three cases, the error increased with increasing roll angle, the maximum values occurring at 45 degrees. For the right side up, left wing down position, the error increased up to 40 degrees, at which point, it was 0.09 degrees, then decreased to 0.08 degrees at 45 degrees. Note that for both aircraft upside down conditions, aircraft rotation as indicated by the inclinometers was less then indicated by the synchros, while for both right side up conditions, the opposite was true.

3. Cross-Axis Effects

The maximum cross-axis motion observed was 0.614 degrees of pitch motion occurring during a 40 degree right wing down roll motion with the aircraft right side up. This value includes the effect of initial out-of-level. With this effect eliminated from the data, the remaining motion is 0.230 degrees. The maximum cross-axis pitch error remaining after removal of initial out-of-level effects was 0.257 degrees of pitch motion occurring during a 45 degree left wing down roll rotation with the aircraft right side up.

The major contributor to cross-axis errors in these tests was the initial out-of-level condition. The curves show substantially lower error values in all cases when the initial out-of-level effect is removed.

Cross-axis errors occurring during the roll tests are substantially greater than during pitch tests, for both total errors, and errors due to unknown causes. Cross-axis errors due to unknown causes during roll tests tend to increase in a somewhat linear manner with increasing roll angle, and are larger for the right side up orientation of the aircraft. For pitch tests, the errors are very small for the nose down case, i.e., less than 0.02 degrees. For the tail down case, they increase to almost 0.1 degree.

An attempt was made to determine the error introduced into the primary motion measurement - for instance pitch - by a cross-axis roll rotation by going to the curves of Appendix B, Figures B2 through B5 with the sine of the cross-axis angles, but the values were too small to be of any significance. From this it can be seen that while cross-axis motions up to the order of 0.6 degree do occur, their effect on the accuracy of primary motion data is negligible. Note that the mathematical signs of the errors in the cross-axis data do not have a consistent physical significance in this data.

VII SUMMARY OF ERRORS

A. As mentioned previously in the introduction, RADC-TR-77-299 contains a detailed discussion of anticipated error sources for test programs such as this. See Section V for the discussion, and Section VI for specific values assigned. The error sources and values shown in Table 5 were taken from the report and are considered to be directly applicable to this test.

Additional error sources and values identified as part of this test program are shown in Table 6, and the maximum differences found to exist between elevation synchro readings and inclinometer readings are shown in Table 7.

B. In order to arrive at a probable value for total system error, a logical combination (summation) of the items listed in Tables 5, 6, and 7 must be accomplished.

It must first be noted that certain items listed in Table 5 are included in the observed difference between synchro and inclinometer readings listed in Table 7 and should therefore not be included in the summation. For example, since the inclinometers measure the position of the platform on which they are mounted with respect to gravity, all deformations and other errors occurring between the ground and the inclinometer platform are included in the difference between readings. In addition to pedestal deformation and synchro readout error shown as Items 2 and 4 of Table 5, this would include foundation and tower deflections, aircraft support structure deflections, and aircraft structure deflections between the points of aircraft support and the inclinometer platform. The aircraft deformation shown as Item 3 in Table 5 is considered to occur beyond the inclinometer platform and is not included in the difference between readings. It will therefore be included in the summation. Table 5, Item 1, "Establishing Reference Coordinate System," and Item 5, "Inclinometer Readout Error," are likewise not included in the difference between readings and will be included in the summation.

It should be further noted that Items 2 and 4 of Table 6 will not be included in the summation. Both items define an error which is an unwanted yaw rotation. Item 2 defines a yaw of the aircraft with respect to a perpendicular to the positioner elevation axis, while Item 4 defines a yaw of the inclinometer principal axis with respect to the same reference. In both cases the error in pitch or roll angles caused by these items is a second order effect which is so small as to be truly negligible.

Finally, Item 5, Table 5, "Inclinometer Readout Error", will not be included as a separate error as it is included as part of Item 5, Table 6, "Inclinometer Error".

C. Items to be included in the summation are as shown in Table 8. Note that the first five items are random in the sense that their direction is unknown, and in the case of aircraft deformation, both value and direction vary with the location of the particular antenna being considered with respect to the inclinometer system. It therefore seems reasonable to combine them by the root of the sum of the squares method (RSS), i.e., by squaring each value, summing, and taking the square root of the sum. The value thus obtained is 0.153 degrees. Items 6 and 7, the initial out-of-level , and the difference between synchro and inclinometer readings, are measured quantities which should be either added or subtracted from each other, and the result added to the RSS value of Items 1 through 5 to obtain the Total System Error. The determination as to whether Items 6 and 7 should be added or subtracted was made by inspection of the data.

Results of the summation for twelve test conditions are presented in Table 9.

D. Cross-Axis Effects are summarized in Table 10.

VII CONCLUSIONS

1. When the table of the positioner is level, the elevation axis readout indicates an angle of +0.23 degrees. This means that with the lower azimuth set at zero degrees and the elevation axis set at zero degrees, the positioner table is tilted 0.23 degrees upward with respect to the site on Tanner Hill. Reduction of the data in this report is such that this factor is not included in the results. It should be treated as an additional bias error and corrected for accordingly.

2. Prior to 2 Nov 78, an initial out-of-level condition existed such that with the turntable level, the right side up aircraft was tilted 0.49 degrees nose high and 0.15 degrees left wing high. The upside down aircraft was tilted 0.26 degrees nose high and 0.18 degrees right wing high.

3. On 2 Nov 78, the initial out-of-level was reduced such that the upside down aircraft was titled 0.02 degrees nose high and 0.05 degrees left wing high. This amount of out-of-level can be considered to be zero as far as Conclusions 6 and 7 are concerned.

4. When conducting tests requiring a pitch maneuver, the maximum probable difference between synchro readings and true aircraft position when the out-of-level condition of Para 2 is included but the difference of Para 1 is not included, is 0.683 degrees.

5. When conducting tests requiring a roll maneuver, the maximum probable difference between synchro readings and true

aircraft position when the out-of-level condition of Para 2 is included but the difference of Para 1 is not included, is 0.533 degrees.

6. When conducting tests requiring a pitch maneuver, a simultaneous roll rotation of up to 0.23 degrees, including the effect of initial out-of-level, can be expected to exist. This reduces to approximately 0.10 degrees if out-of-level is not considered.

7. When conducting tests requiring a roll maneuver, a simultaneous pitch rotation of up to 0.61 degrees, including the effects of initial out-of-level, can be expected to exist. This reduces to approximately 0.26 degrees if out-of-level is not considered.

8. Above values are extremes which cover the full range of angles of rotation for both right side up and upside down positions of the aircraft. Data contained herein can be used to determine probable errors for more specific cases of orientation and rotation. The effect of initial out-of-level can be eliminated from the errors listed in Table 9 by simply deleting the out-of-level values from the summation.

IX RECOMMENDATIONS

The following recommendations are made concerning future aircraft antenna testing on the Scientific-Atlanta pedestal:

A. General. The procedure followed in this test program is satisfactory, provided that the degree of accuracy stated herein is acceptable for future tests. When more stringent requirements are imposed, such as inclusion of directional antennas, or location of antennas in areas where major deflections occur, test procedures will have to be refined to achieve greater accuracy.

B. Inclinometers. Inclinometers should be calibrated about both axes prior to the start of each major test program, and means should be developed to permit periodic rechecks between calibrations to insure that reinstallation of inclinometers after such things as changes in aircraft orientation does not result in inclinometer performance degradation.

C. Reference Coordinate System. Both horizontal and vertical plane reference marks should be placed on the aircraft when it is precisely levelled in the hangar as in the past, even though, as in the present case, an immediate need for the horizontal plane marks is not apparent. The possibility that they will be needed always exists and comparatively little additional effort is required to place them at that time, while a major effort would be required later.

D. Aircraft Installation. The aircraft should be installed to be level in both planes when mounted on the pedestal table, when the table itself is also level. The system of checking the level of the table using a machinists level as described herein is adequate. The aircraft level should be verified by the inclinometer system and modifications made to the mount as required prior to the start of testing. With the table and the aircraft level, the elevation synchro should be set to read zero.

TABLE 1A

PITCH TEST NOSE DOWN

Date: 28 Oct 77 Configuration: Upside Down Winds: 10 mph

Lower AZ: +0.06° Upper AZ: 0.00°

SN 1790 Pitch Inc.	Elev. Syn.	Difference	From Start ΔInc.	ΔSyn.	Error	SN 1791 Roll Inc.
+0.001V=0°	0.41	-0.41	0	0	0	+0.023V
+1.132=10°	10.41	-0.41	10	10	0	+0.010V
+2.229=20°	20.42	-0.42	20	20.01	-0.01	0
+3.258=30°	30.43	-0.43	30	30.02	-0.02	-0.013V
+4.188=40°	40.43	-0.43	40	40.02	-0.02	-0.025V
+4.607=45°	45.43	-0.43	45	45.02	-0.02	---

PITCH TEST TAIL DOWN

Date: 28 Oct 77 Configuration: Upside Down Winds: 15mph

Lower AZ: +0.06° Upper AZ: 180.00°

SN 1790 Pitch Inc.	Elev Syn.	Difference	From Start ΔInc.	ΔSyn.	Error	SN 1791 Roll Inc.
+0.001V=0°	-0.12	0.12	0	0	0	+0.010V
-1.130=10°	9.88	0.12	10	10	0	+0.030V
-2.227=20°	19.99	0.12	20	20	0	+0.040V
-3.256=30°	29.88	0.12	30	30	0	+0.050V
-4.186=40°	39.88	0.12	40	40	0	---
-4.604=45°	44.89	0.12	45	45.01	-0.01	+0.065V

TABLE 1B

ROLL TEST RIGHT WING DOWN

Date: 28 Oct 77 Configuration: Upside Down Winds: 18mph

Lower AZ: +0.06° Upper AZ: 90.00°

SN 1791 Roll Inc.	Elev. Syn.	Difference	From Start ΔInc.	ΔSyn.	Error	SN 1790 Pitch Inc.
-0.001V=0°	0.37	-0.37	0	0	0	-0.030V
-1.134V=10°	10.36	-0.36	10	9.99	0.01	-0.040V
-2.232=20°	20.32	-0.32	20	19.95	0.05	-0.055V
-3.262=30°	30.25	-0.25	30	29.88	0.12	-0.063V
-3.742=35°	35.20	-0.20	35	34.83	0.17	-0.068V
-4.193=40°	40.20	-0.20	40	39.83	0.17	-0.071V
-4.612=45°	45.17	-0.17	45	44.80	0.20	-0.075V

ROLL TEST LEFT WING DOWN

Date: 28 Oct 77 Configuration: Upside Down Winds: 15-18mph

Lower AZ: +-.06° Upper AZ: 270°

SN1791 Roll Inc.	Elev.Syn.	Difference	From Start ΔInc.	ΔSyn.	Error	SN 1790 Pitch Inc.
+0.001V=0°	0	0	0	0	0	-0.035V
+1.132=10°	9.98	+0.02	10	9.98	0.02	-0.020V
+2.231=20°	19.95	+0.05	20	19.95	0.05	0
+3.263=30°	29.88	+0.12	30	29.88	0.12	-0.010V
4.195=40°	39.82	+0.18	40	39.82	0.18	-0.035V
4.615=45°	44.80	+0.20	45	44.80	0.20	-0.040V

TABLE 2A

PITCH TEST NOSE DOWN

Date: 31 Mar 78 Configuration: Right Side Up Winds: 0-8mph

Lower AZ: 0.00^{o} Upper AZ: 0.00^{o}

SN 1790 Pitch Inc.	Elev. Syn.	Difference	From Start Δ Inc.	Δ Syn.	Error	SN 1791 Roll Inc.
$+0.001V=0^{o}$	+0.64	+0.64	0	0	0	+0.013V
$-0.130=10^{o}$	10.65	+0.65	10	10.01	+0.01	+0.002V
$-2.227=10^{o}$	20.66	+0.66	20	20.02	+0.02	-0.008V
$-3.256=30^{o}$	30.67	+0.67	30	30.03	+0.03	-0.020V
$-4.186=40^{o}$	40.67	+0.67	40	40.03	+0.03	-0.029V
$-4.604=45^{o}$	45.67	+0.67	45	45.03	+0.03	-0.035V

PITCH TEST TAIL DOWN

Date: 31 Mar 78 Configuration: Right Side Up Winds: 0-8mph

Lower Az: $+0.01^{o}$ Upper AZ: 180.00^{o}

SN1790 Pitch Inc.	Elev. Syn.	Difference	From Start Δ Inc.	Δ Syn.	Error	SN 1791 Roll Inc.
$+0.001V=0^{o}$	-0.33	-0.33	0	0	0	+0.012V
$+1.132=10^{o}$	9.66	-0.34	10	9.99	-0.01	+0.025V
$+2.229=20^{o}$	19.65	-0.35	20	19.98	-0.02	+0.038V
$+3.258=30^{o}$	29.64	-0.36	30	29.97	-0.03	+0.050V
$+4.188=40^{o}$	39.63	-0.37	40	39.96	-0.04	+0.061V
$+4.607=45^{o}$	44.63	-0.37	45	44.96	-0.04	+0.066V

TABLE 2B

ROLL TEST LEFT WING DOWN

Date: 31 Mar 78 Configuration: Right Side Up Winds: 3-6mph

Lower AZ: 0.00^{o} Upper AZ: 270.00^{o}

SN1791 Roll Inc.	Elev.Syn.	Difference	From Start Δ Inc.	Δ Syn.	Error	SN1790 Pitch Inc.
$-0.001V=0^{o}$	0.31	+0.31	0	0	0	+0.056V
$-1.134=10^{o}$	10.30	+0.30	10	9.99	-0.01	+0.067V
$-2.232=20^{o}$	20.26	+0.26	20	19.95	-0.05	+0.075V
$-3.262=30^{o}$	30.23	+0.23	30	29.92	-0.08	+0.084V
$-4.193=40^{o}$	40.22	+0.22	40	39.91	-0.09	+0.089V
$-4.619=45^{o}$	45.23	+0.23	45	44.92	-0.08	+0.091

ROLL TEST RIGHT WING DOWN

Date: 31 Mar 78 Configuration: Right Side Up Winds: 3-6mph

Lower AZ: 0.01^{o} Upper AZ: 90^{o}

SN1791 Roll Inc.	Elev.Syn.	Difference	From Start Δ Inc.	Δ Syn.	Error	SN1790 Pitch Inc.
$-0.001V=0^{o}$	0.02	-0.02	0	0	0	+0.057V
$+1.132=10^{o}$	10.01	-0.01	10	9.99	-0.01	+0.047V
$+2.231=20^{o}$	19.99	+0.01	20	19.97	-0.03	+0.035V
$+3.263=30^{o}$	29.95	+0.05	30	29.93	-0.07	+0.023V
$+4.195=40^{o}$	29.97	+0.13	40	39.85	-0.15	+0.012V
$+4.615=45^{o}$	44.81	+0.19	45	44.79	-0.21	+0.004V

TABLE 3A

CROSS AXIS DATA

Date: 28 Oct 77 Aircraft Configuration: Upside Down

Pitch	Roll Inclinometer Data		Serial 1791				
			Difference			Difference	
1. Angle (Degrees)	2. Measured Voltage	3. Voltage due to Pitch	4. Voltage 2.-3	5. Angle (Degrees)	6. Voltage due to Initial out of Level	7. Voltage 4.-6	8. Angle (Degrees)
Nose Down:							
0	+0.023	-0.003	+0.026	+0.230	+0.026	0	0
10	+0.010	-0.014	+0.024	+0.212	+0.0256	-0.002	-0.017
20	0	-0.024	+0.024	+0.212	+0.0244	-0.0004	-0.003
30	-0.013	-0.034	+0.021	+0.186	+0.0225	-0.0015	-0.013
40	-0.025	-0.043	+0.018	+0.159	+0.0199	-0.0019	-0.017
50	--	--	--	--	+0.0184	--	--
Tail Down:							
0	+0.010	-0.003	+0.013	+0.115	+0.013	0	0
10	+0.030	+0.007	+0.023	+0.204	+0.013	+0.010	+0.088
20	+0.040	+0.020	+0.020	+0.177	+0.012	+0.008	+0.071
30	+0.050	+0.031	+0.019	+0.168	+0.011	+0.008	+0.071
40	--	--	--	--	--	--	--
45	+0.065	+0.045	+0.020	+0.177	+0.009	+0.011	+0.097

TABLE 3B

CROSS AXIS DATA

Date: 28 Oct 77 Aircraft Configuration: Upside Down

Pitch	Pitch Inclinometer Data				Serial 1790		
			Difference			Difference	
1. Angle (Degrees)	2. Measured Voltage	3. Voltage due to Roll	4. Voltage 2.-3	5. Angle (Degrees)	6. Voltage due to out of Level	7. Voltage 4.-6	8. Angle (Degrees)
Left Wing Down:							
0	-0.035	0	-0.035	-0.310	-0.035	0	0
10	-0.020	+0.020	-0.040	-0.354	-0.034	-0.006	-0.053
20	0	+0.039	-0.039	-0.345	-0.033	-0.006	-0.053
30	+0.010	+0.057	-0.047	-0.416	-0.030	-0.017	-0.150
40	+0.035	+0.073	-0.038	-0.336	-0.027	-0.011	-0.097
45	+0.040	+0.081	-0.041	-0.363	-0.025	-0.016	-0.142
Right Wing Down:							
0	-0.030	0	-0.030	-0.265	-0.030	0	0
10	-0.040	-0.016	-0.024	-0.212	-0.029	+0.005	+0.044
20	-0.055	-0.031	-0.024	-0.212	-0.028	+0.004	+0.035
30	-0.063	-0.045	-0.018	-0.159	-0.026	+0.008	+0.070
35	-0.068	-0.051	-0.017	-0.150	-0.025	+0.008	+0.070
40	-0.071	-0.058	-0.013	-0.115	-0.023	+0.010	+0.088
50	-0.075	-0.064	-0.011	-0.097	-0.021	+0.010	+0.088

TABLE 4A

CROSS AXIS DATA

Date: 31 Mar 78 Aircraft Configuration: Right Side Up

Pitch	Roll Inclinometer Data					Serial 1791	
			Difference			Difference	
1. Angle (Degrees)	2. Measured Voltage	3. Voltage due to Pitch	4. Voltage 2.-3	5. Angle (Degrees)	6. Voltage due to Initial out of Level	7. Voltage 4.-6	8. Angle (Degrees)
Nose Down:							
0	+0.013	-0.003	+0.016	+0.142	+0.016	0	0
10	+0.002	-0.014	+0.016	+0.142	+0.016	0	0
20	-0.008	-0.024	+0.016	+0.142	+0.015	+0.001	+0.009
30	-0.020	-0.034	+0.014	+0.124	+0.014	0	0
40	-0.029	-0.043	+0.014	+0.124	+0.012	+0.002	+0.017
45	-0.035	-0.047	+0.012	+0.106	+0.011	+0.001	+0.009
Tail Down:							
0	+0.012	-0.003	+0.015	+0.133	+0.015	0	0
10	+0.025	+0.008	+0.017	+0.150	+0.015	+0.002	+0.018
20	+0.038	+0.020	+0.018	+0.159	+0.014	+0.004	+0.035
30	+0.050	+0.031	+0.019	+0.168	+0.013	+0.006	+0.053
40	+0.061	+0.041	+0.020	+0.177	+0.012	+0.008	+0.071
50	+0.066	+0.045	+0.021	+0.186	+0.011	+0.010	+0.088

TABLE 4B

CROSS AXIS DATA

Date: 31 Mar 78 Aircraft Configuration: Right Side Up

Roll	Pitch Inclinometer Data				Serial 1790		
			Difference			Difference	
1. Angle (Degrees)	2. Measured Voltage	3. Voltage due to Roll	4. Voltage 2.-3	5. Angle (Degrees)	6. Voltage due to Initial out of Level	7. Voltage 4.-6	8. Angle (Degrees)
Left Wing Down:							
0	+0.056	0	+0.056	+0.491	+0.056	0	0
10	+0.067	+0.020	+0.047	+0.412	+0.055	-0.008	-0.071
20	+0.075	+0.039	+0.036	+0.316	+0.053	-0.017	-0.150
30	+0.084	+0.057	+0.027	+0.237	+0.049	-0.022	-0.195
40	+0.089	+0.073	+0.016	+0.140	+0.043	-0.027	-0.239
45	+0.091	+0.081	+0.010	+0.088	+0.039	-0.029	-0.257
Right Wing Down:							
0	+0.057	0	+0.057	+0.500	+0.057	0	0
10	+0.047	-0.016	+0.063	+0.553	+0.056	+0.007	+0.062
20	+0.035	-0.031	+0.066	+0.579	+0.054	+0.012	+0.106
30	+0.023	-0.045	+0.068	+0.597	+0.049	+0.019	+0.168
40	+0.012	-0.058	+0.070	+0.614	+0.044	+0.026	+0.230
45	+0.004	-0.064	+0.068	+0.597	+0.040	+0.028	+0.248

TABLE 5

ERROR SOURCES TAKEN FROM RADC TR-77-299

1.	Establishing Reference Coordinate System	
	a. Placing Reference Marks on Aircraft	0.003°
	b. Leveling Aircraft with Spirit Level	0.004°
2.	Pedestal Deformation	
	a. Gravitational Loading	0.14°
	b. Thermal Distortion	0.05°
3.	Aircraft Deformation	0.03°
4.	Electrical or Mechanical Synchro Readout Error	0.05°
5.	Inclinometer Readout Error	0.05°

TABLE 6

ERROR SOURCES DETERMINED DURING THIS TEST PROGRAM

1. Positioning Aircraft on Pedestal (Initial Out-of-Level)

A. Prior to 2 Nov 78

(1)	Upside Down - Pitch	0.26° Nose High
(2)	Upside Down - Roll	0.18° Right Wing High
(3)	Right Side Up - Pitch	0.49° Nose High
(4)	Right Side Up - Roll	0.15° Left Wing High

B. After 2 Nov 78

(1)	Upside Down - Pitch	0.02° Tail High
(2)	Upside Down - Roll	0.05° Left Wing High

2. Establishing Upper Turntable Position for Aircraft Centerline Normal to Elevation Axis (See Appendix A)	0.010°
3. Leveling of Inclinometer Platform	0.004°
4. Establishing Inclinometer Axes Perpendicular to and Parallel with Aircraft Centerlines	0.01°
5. Inclinometer Error (See Appendix B)	0.15°

TABLE 7

MAXIMUM DIFFERENCE BETWEEN ELEVATION SYNCHRO READINGS AND INCLINOMETER READINGS

Pitch Test			
	Right Side Up		
		Nose Down	0.03°
		Tail Down	0.04°
	Upside Down		
		Nose Down	0.02°
		Tail Down	0.01°
Roll Test			
	Right Side Up		
		Right Wing Down	0.21°
		Left Wing Down	0.09°
	Upside Down		
		Right Wing Down	0.20°
		Left Wing Down	0.20°

TABLE 8

ITEMS TO BE INCLUDED IN ERROR SUMMATION

1. Placing Reference Marks on Aircraft (Table 5, Item 1a): 0.003°
2. Leveling Aircraft (Table 5, Item 1b): 0.004°
3. Aircraft Deformation (Table 5, Item 3): 0.030°
4. Leveling Inclinometer Platform (Table 6, Item 3): 0.004°
5. Inclinometer Error (Table 6, Item 5): 0.150°
6. Initial Out-of-Level (Table 6, Item 1)
7. Difference Between Synchro and Inclinometer Readings (Table 7)

TABLE 9

TOTAL SYSTEM ERROR

(Maximum Probable Difference Between Elevation Synchro Readings and True Aircraft Position)

	1.RSS of Para VIIC,Items 1, 2,3,4,5	2.Initial Out-of-Level	3.Difference Between Synchro & Inclinometer Readings	4.Error
Pitch:				
Right Side Up				
Nose Down	0.153	0.49	0.03	0.673
Tail Down	0.153	0.49	0.04	0.683
Upside Down (a)				
Nose Down	0.153	0.26	0.02(c)	0.393
Tail Down	0.153	0.26	0.01	0.423
Upside Down (b)				
Nose Down	0.153	0.02	0.02(c)	0.153
Tail Down	0.153	0.02	0.01	0.183
Roll:				
Right Side Up				
Right Wing Down	0.153	0.15	0.21	0.513
Left Wing Down	0.153	0.15	0.09(c)	0.213
Upside Down (a)				
Right Wing Down	0.153	0.18	0.20	0.533
Left Wing Down	0.153	0.18	0.20(c)	0.173
Upside Down (b)				
Right Wing Down	0.153	0.05	0.20	0.403
Left Wing Down	0.153	0.05	0.20(c)	0.303

(a) indicates prior to 2 November 1978

(b) indicates after 2 November 1978 (releveling accomplished)

(c) indicates cases where columns 2 and 3 must be subtracted from each other in the summation

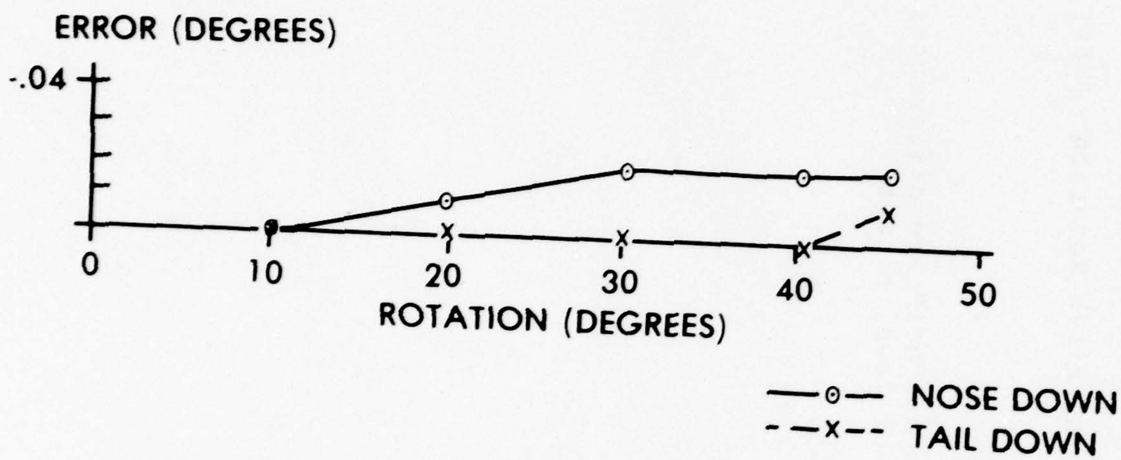
TABLE 10

PREDICTED MAXIMUM CROSS AXIS ROTATIONS

1.	Pitch During Roll Rotation (Total)	0.61°
2.	Roll During Pitch Rotation (Total)	0.23°
3.	Pitch During Roll Rotation (Net)	0.26°
4.	Roll During Pitch Rotation (Net)	0.10°

Values shown as "net" are differences remaining after removal of initial out-of-level effects.

FIGURE 1A OBSERVED ERROR FOR PITCH TEST (28 OCTOBER 1977)
ERROR *
VS
PITCH ROTATION
AIRCRAFT UPSIDE DOWN



* ERROR IS DEFINED AS THE CHANGE IN SYNCHRO READOUT MINUS THE CHANGE IN ANGLE DETERMINED FROM INCLINOMETER READOUT

FIGURE 1B OBSERVED ERROR FOR ROLL TEST (28 OCTOBER 1977)
ERROR *
VS
ROLL ROTATION
AIRCRAFT UPSIDE DOWN

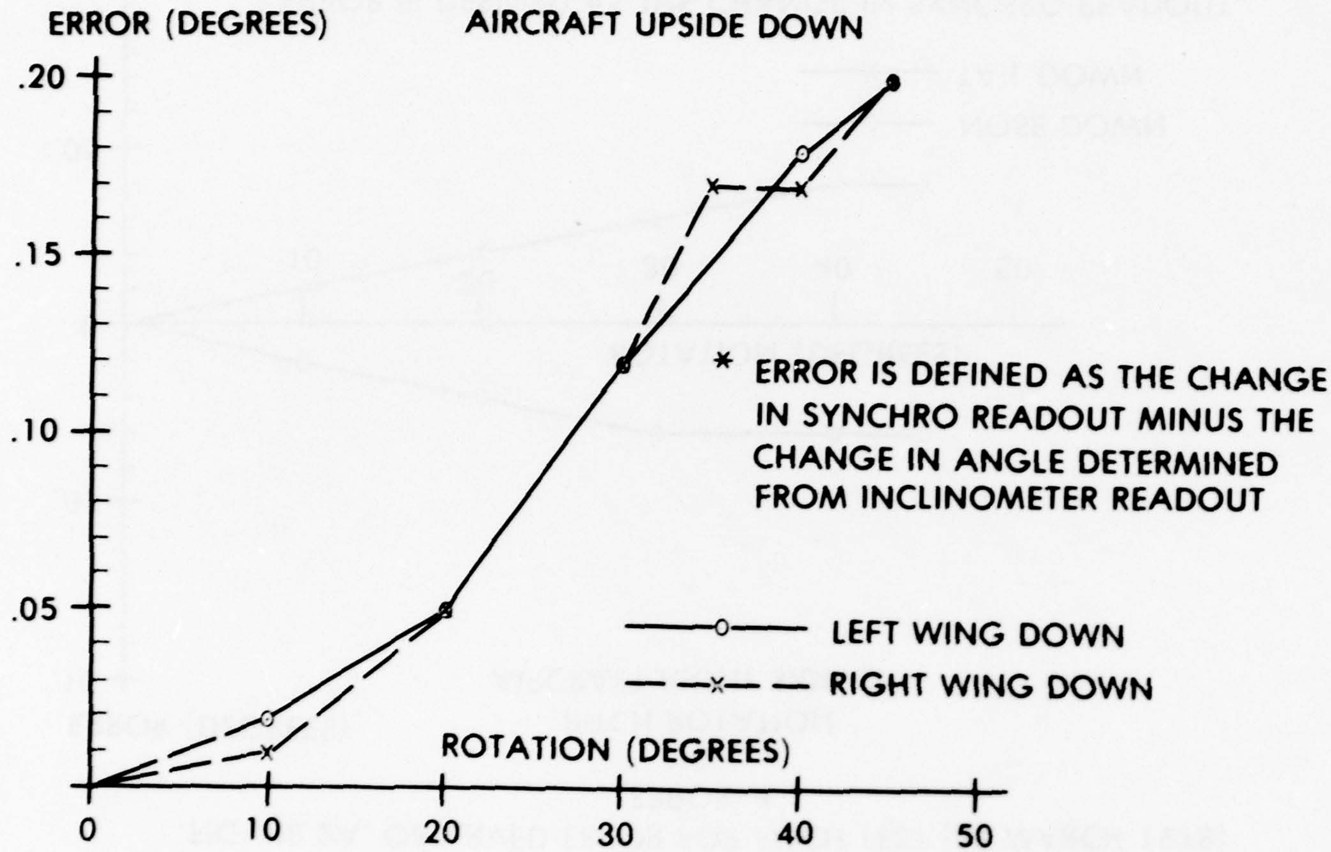
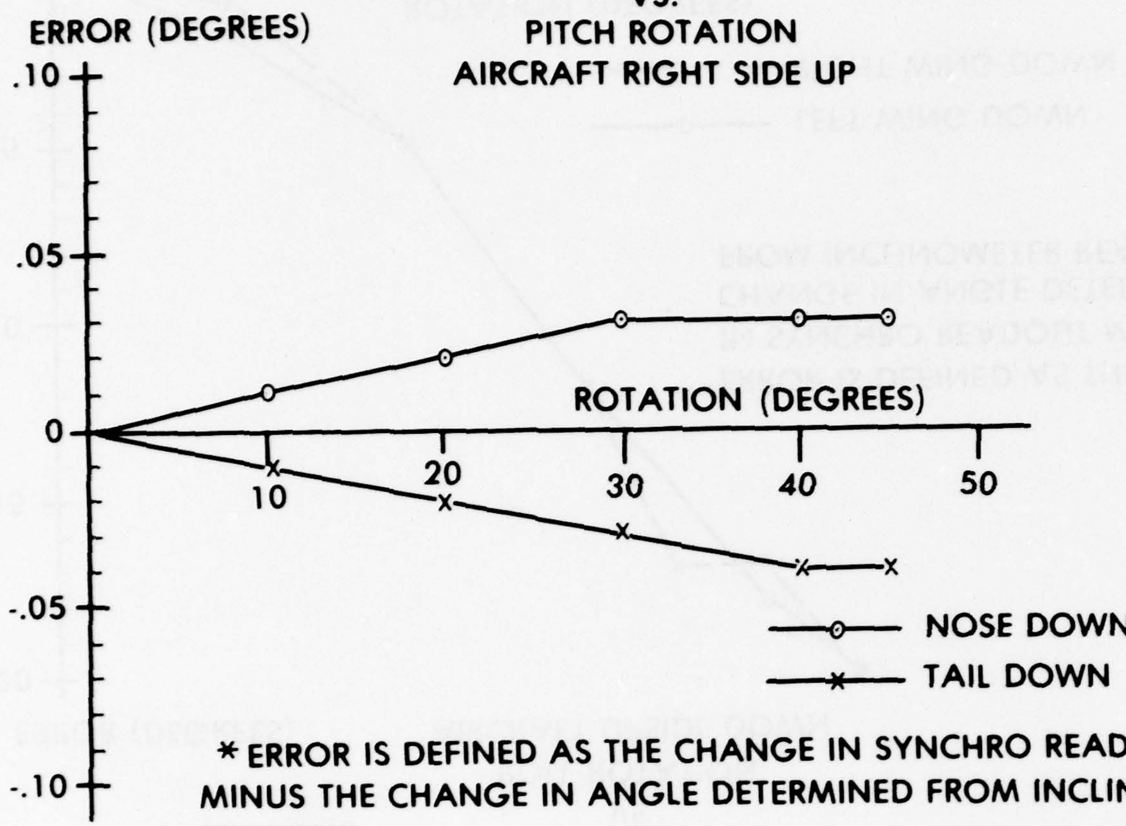


FIGURE 2A. OBSERVED ERROR FOR PITCH TEST (31 MARCH 1978)
ERROR *
VS.
PITCH ROTATION
AIRCRAFT RIGHT SIDE UP



* ERROR IS DEFINED AS THE CHANGE IN SYNCHRO READOUT MINUS THE CHANGE IN ANGLE DETERMINED FROM INCLINOMETER READOUT.

FIGURE 2B. OBSERVED ERROR FOR ROLL TEST (31 MARCH 1978)
ERROR *
VS
ROLL ROTATION
AIRCRAFT RIGHT SIDE UP

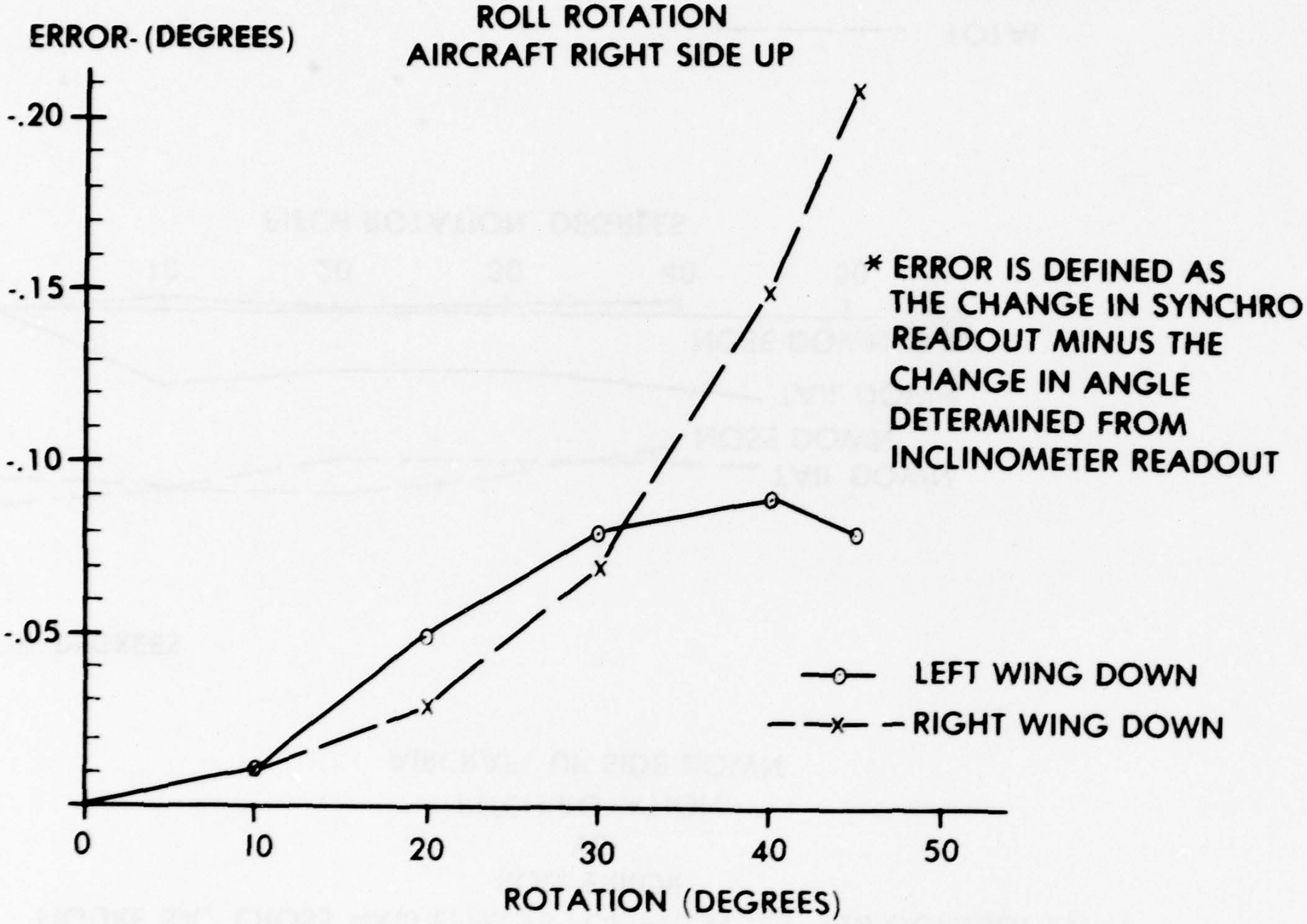


FIGURE 3A. CROSS AXIS EFFECTS FOR PITCH TEST (28 OCTOBER 1977)
ROLL ERROR
VS
PITCH ROTATION
AIRCRAFT UP SIDE DOWN

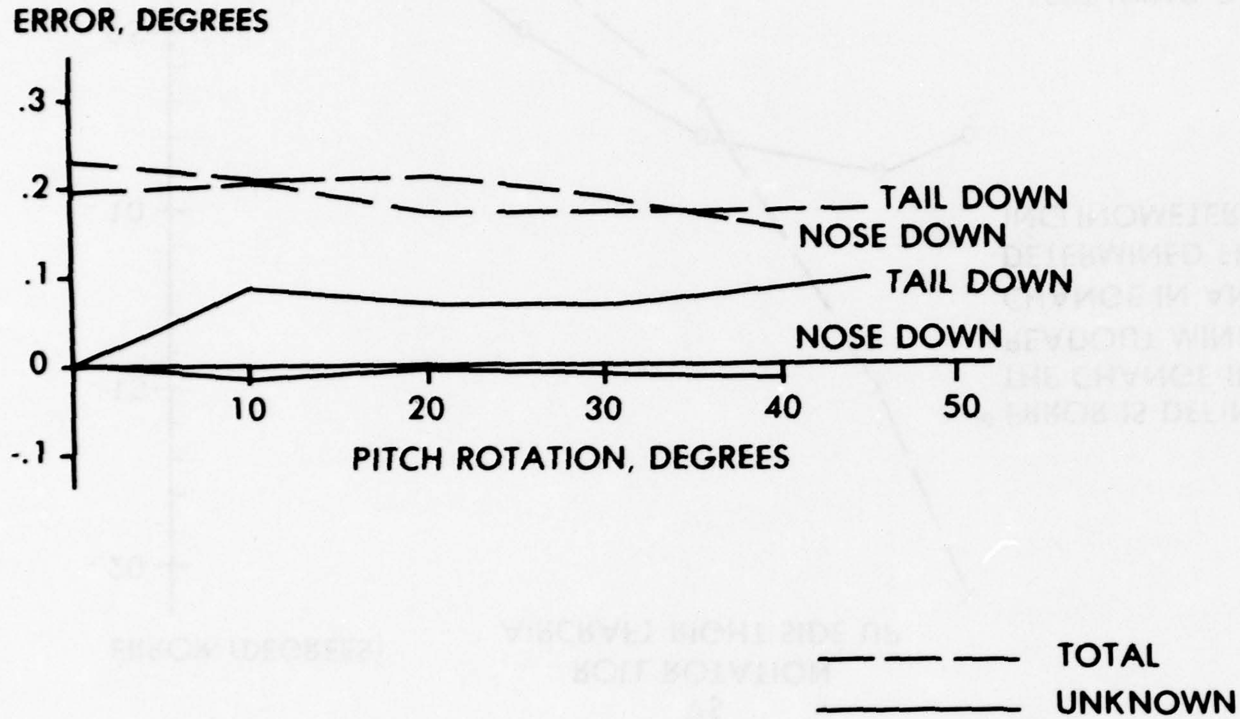


FIGURE 3B. CROSS AXIS EFFECTS FOR ROLL TEST (28 OCTOBER 1977)

PITCH ERROR
VS
ROLL ROTATION
AIRCRAFT UP SIDE DOWN

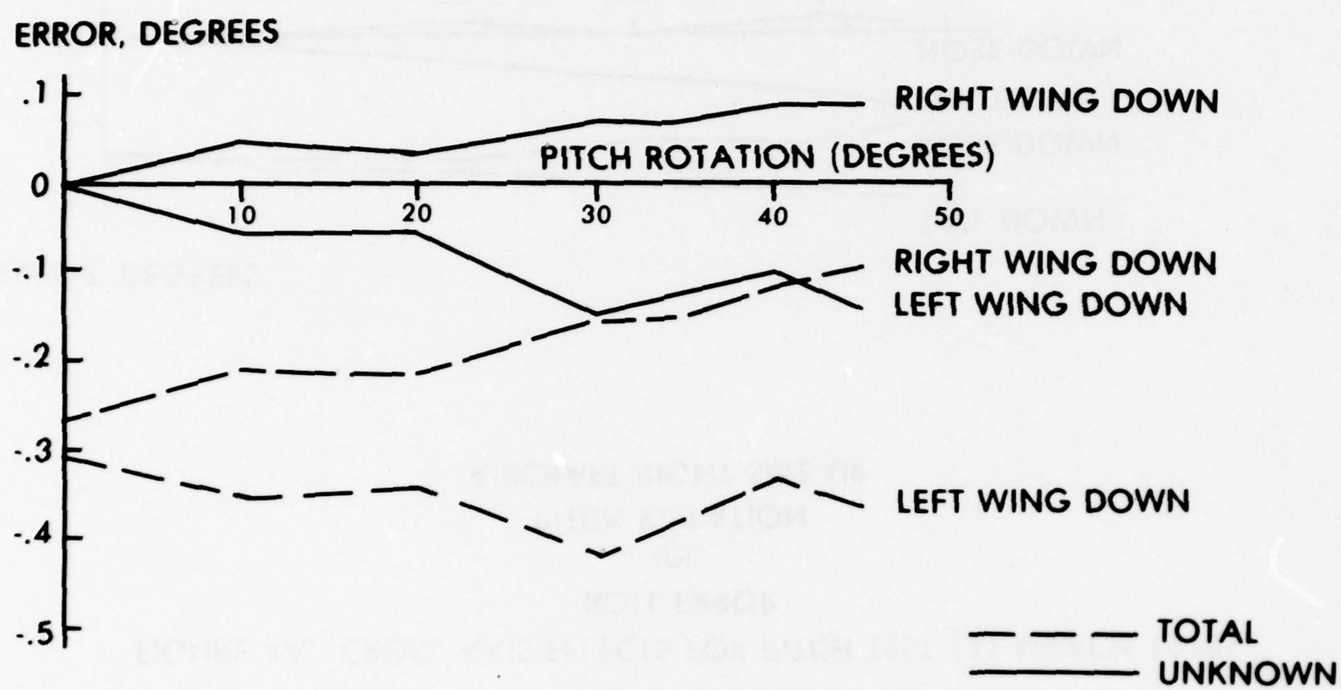


FIGURE 4A. CROSS AXIS EFFECTS FOR PITCH TEST (31 MARCH 1978)
ROLL ERROR
VS
PITCH ROTATION
AIRCRAFT RIGHT SIDE UP

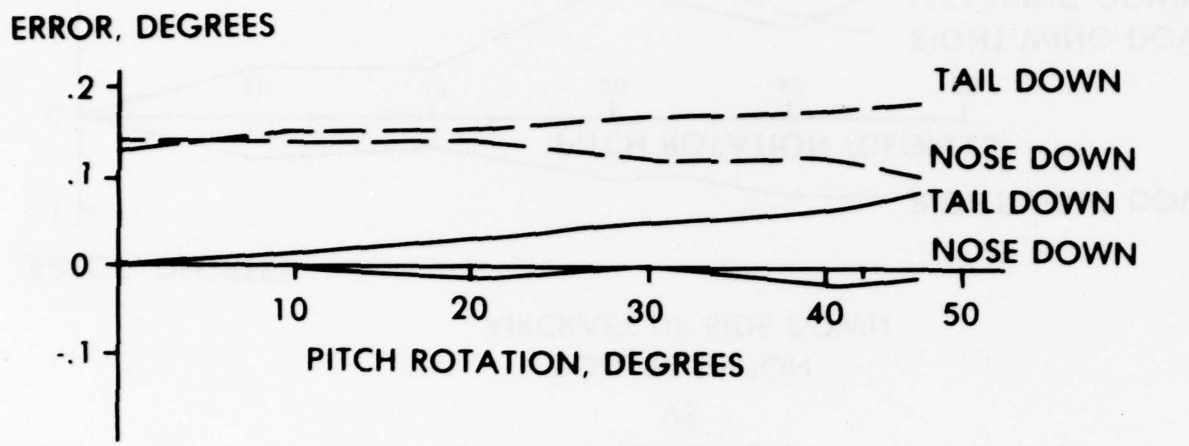
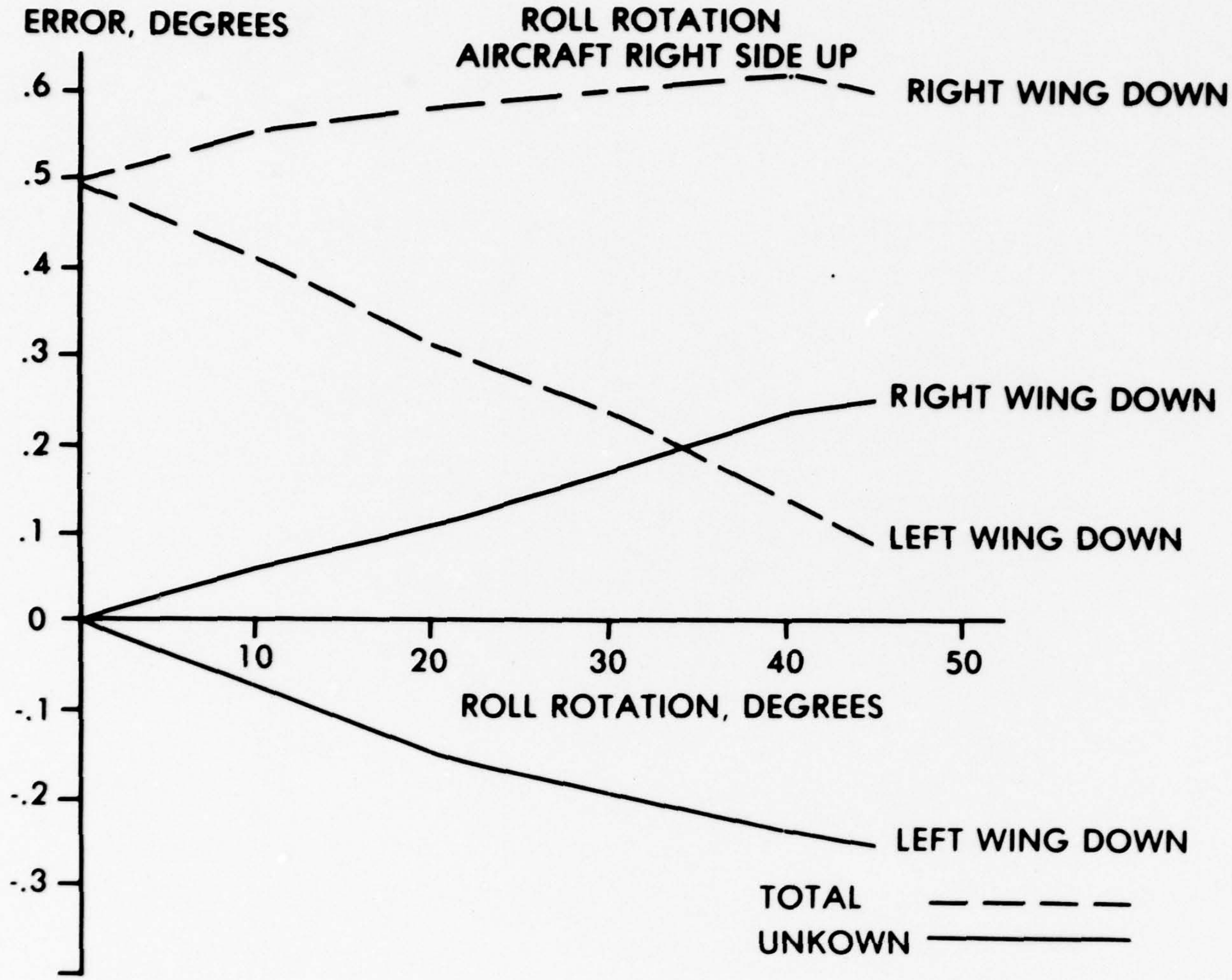


FIGURE 4B. CROSS AXIS EFFECTS FOR ROLL TEST (31 MARCH 1978)
PITCH ERROR
VS
ROLL ROTATION
AIRCRAFT RIGHT SIDE UP



APPENDIX A

CALIBRATION AND ALIGNMENT EFFORTS FOR A-10 TESTS

This project is divided into two parts. Part I is associated with only the airplane, i.e., centerline determination and leveling operations. Part II is associated with the accuracy of the entire system, i.e., the airplane, the support pedestal, and the angle sensing devices (the upper and lower azimuth and the elevation readouts) of the support pedestal.

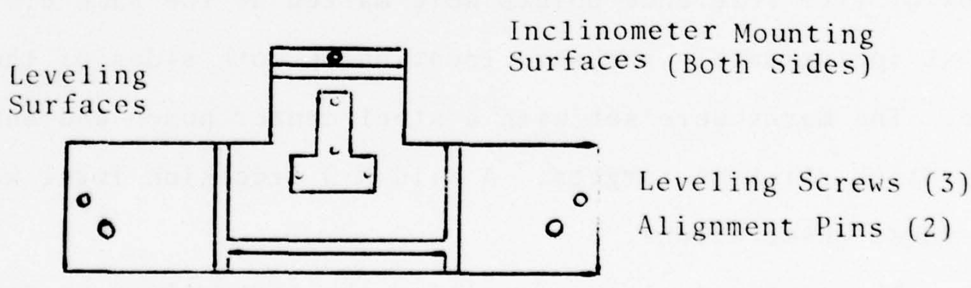
Part I

a. During the time the A-10 was in the hangar being prepared for installation on the pedestal at Irish Hill, it was placed on two pedestals and leveled. RADC/OCSA personnel assisted in this operation by monitoring the level checkpoints on the aircraft. A 10-inch bench type precision bubble level was used for the level determinations. The aircraft was suspended right side up on two pedestals, one under each wing. When leveling was completed, a row of five reference points were marked at the same elevation and at approximately the same location on both sides of the fuselage. The marks were set with a steel center punch and encircled with black stick-on targets. A Wild N-3 precision level was used for these observations.

b. The vertical plane containing the centerline was determined and marked on the top and bottom of the aircraft. This was accomplished by selecting initial points under the tail and ahead of the windshield and transferring these to tape on the floor beneath the aircraft. A line connecting these two points was extended in both directions to provide points from which a theodolite could be used to locate additional points on the vertical centerline on the top and bottom of the aircraft.

c. To establish a "waterline" reference for the horizontal plane level line, Drawings 160D891497 and 160D891597 were studied to locate a surface whose waterline was known and from which measurements could be made. It was determined that the bottom of the trailing edge of the retracted inboard flap is located between W.L.74.55 and 74.64. A nominal value of 74.6 was used. A level was set up and measurements made resulting in the determination that the level line is at W.L.87.6 inches approximately.

d. To insure that the Schaevitz inclinometers could be installed level, and parallel and perpendicular respectively with the aircraft centerline, a mounting plate was fabricated for installation in the aircraft. The plate is shown schematically as follows:



With the aircraft in a level position as previously determined, the plate was mounted near station 540 on the three leveling jack screws shown. The bench type level was placed on the leveling surfaces provided in both directions and the plate was leveled to within 0.004 degrees. Following this, in order to establish the axes of the inclinometers parallel and perpendicular with the aircraft centerline, a point was established on the floor exactly under the centerline of the aircraft and approximately under the alignment pins on the mounting plate. A theodolite was set up precisely over the point and a line perpendicular to the centerline of the aircraft was established, including a point approximately 35 feet from the aircraft. The theodolite was set up over the point and a scale which was held up horizontally to first one and then the other alignment pin was read through the theodolite. The readings were identical, and the alignment of the plate with the aircraft centerline was considered complete. The level of the plate was reverified.

Part II

After the A-10 was installed on the pedestal, the following procedures were performed:

1. A target was set up at the vertical axis (center point of rotation) of the lower azimuth table. This was done by aligning the target over the center of the hole in the lower azimuth table.

2. Two targets (surveying type) were attached directly to the previously established centerline reference points located on top of the aircraft.

3. A theodolite was set up over station IRISH ECC which is approximately 1600 feet west of the radar pedestal.

4. The telescope of the theodolite was then pointed at the target set on the vertical axis of the lower azimuth table. The airplane was then observed through the telescope. The upper and lower azimuths were adjusted until the two targets on top of the airplane came into precise alignment with the theodolite. The elevation axis was then lowered (nose down) to its maximum depression while observing the targets through the theodolite telescope. Minor adjustments were made to upper and lower azimuth settings such that the targets remained in line throughout the movement. The upper and lower azimuth readings were then recorded. They were 0.05 degrees and 304.20 degrees respectively.

Accuracy

1. Points on the top and sides of the airplane (prior to mounting on pedestal): plus or minus 0.5 millimeter from defined line.

2. Precision of repeated attempts at lining up the targets on top of the airplane: plus or minus 0.01 degrees.

3. Precision of leveling the inclinometer mounting plate in the aircraft: 0.004 degrees.

4. Precision of installing the inclinometer mounting plate perpendicular to the aircraft centerline: 0.01 degrees.

APPENDIX B

I CALIBRATION OF INCLINOMETERS

To establish that the accuracy of the calibration data for the Schaevitz inclinometers was adequate prior to the start of testing, a calibration check was made on each of the devices described in Table 1, Schaevitz Servo Inclinometer Data. The check was performed on the surface plate in the Machine Shop in Bldg 101.

Instrumentation:

Inclinometers	Schaevitz Model No. LSOC-50^{o}
	Serial Nos. 1790 & 1791
Precision Machinists Level	DoAll
Sine Plate	Omer E. Robbins Co.
Gage Blocks	Standard Gage Co.
	Weber
	Pratt and Whitney
Digital Voltmeter	Hewlett-Packard
Power Supply	Acopian
Switch Box	Fabricated In-House

The sine plate is an instrument having a stationary base plate to which is hinged an inclinable plate designed to be supported by gage blocks of known thickness and thus held stationary at accurately determinable angles. The design of the plates and support points are such that the sine of the angle made by the inclined table with the horizontal is equal to the height of the support multipled by .2

TABLE B1

SCHAEVITZ SERVO INCLINOMETER DATA

Data Item	SN 1790	SN 1791
Power supply voltage	$\pm$15 volts	$\pm$15 volts
Power supply current	15 ma	15 ma
Frequency response (1-3 db)	48 cps	48 cps
Range	50 degrees	50 degrees
Full range output	$\pm$4.990 volts	$\pm$4.998 volts
Cross-axis sensitivity	0.023 volts/g	0.008 volts/g
Noise	0.003 volts rms	0.003 volts rms
Linearity	$\pm$0.004 percent	$\pm$0.01 percent
Output impedance	5.23 K ohms	5.23 K ohms
Zero offset [1]	0.001 volts	-0.0008 volts
Scale factor temperature coefficient [2]	0.0005%/^{o}F	0.0001%/^{o}F
Null temperature coefficient [3]	0.0%/^{o}F	0.001%/^{o}F
Tilt applied so that connector end is lower causes output voltage to become more		

(1) voltage signal output in perfectly level orientation

(2) change in output voltage per degree Fahrenheit divided by output voltage

(3) change in output per degree Fahrenheit divided by full scale output (10 volts)

The inclinable table has two fixed, raised edges respectively perpendicular to and parallel with the axis about which the table is hinged. These edges were used to locate the inclinometers in each of the four orientations desired for the test as shown in Figure 1.

The digital voltmeter and power supply are permanently connected in a unit which is used at the Newport Test Site to provide the required power to the inclinometers and to measure and display the inclinometer output voltage. The switch box provides the means of switching from the pitch inclinometer to the roll inclinometer without changing connections in the field. This instrumentation was used for the calibration check to duplicate the test conditions at the site as nearly as possible. The only departure from this was the interconnecting cable which is permanently installed at the site and was not available for the test. A new cable was made up for the test. Since only one connector was available at the inclinometer end, switching was done by changing connections, although the switch box was retained in the circuit.

II PROCEDURE

The sine plate was placed on the surface plate which had been roughly leveled. With the inclinable plate in the horizontal position, the surface plate was adjusted until the inclinable plate was level to less than 1/2 division on the machinists level in two perpendicular planes. One half division is equal to 0.0012 degrees. Combinations of gage blocks were selected to give angles of 10^{o}, 20^{o}, 30^{o}, 40^{o}, and 50^{o}. After completion of the test, it was determined that the thickness of one block which was used for each angle was in error. The corrected value was used in calculating the angles which were determined to be $8^{o}16'$, $28^{o}8'$, $39^{o}58'$, and $47^{o}30'$.

For each angle setting, each inclinometer was placed in each of the four orientations shown in Figure 1 and the voltage reading was read and recorded. Thus, eight readings were obtained for each angle including 0^{o}. Note that Cases A and B provide sensitive axis readings while cases C and D provide cross axis or nonsensitive axis. The data is shown in Table 2.

III CALCULATIONS

The inclinometer angle for each inclinometer, for Cases A and B, Figure 1, was determined from the inclinometer output voltage. This was accomplished by interpolating data from the table (3 or 4) as follows:

Let

Measured Inclinometer Angle $= \theta$

Inclinometer Output Voltage $= V$

Next Larger Voltage From Table $= V_L$

Next Smaller Voltage From Table $= V_S$

Angle Represented by V_L $= \theta_L$

Angle Represented by V_S $= \theta_S$

$$\theta = \sin^{-1} \frac{V-V_S}{V_L-V_S} \quad \sin\theta_L - \sin\theta_S \quad + \quad \sin\theta_S$$

The sine plate angle α was determined by multiplying the gage

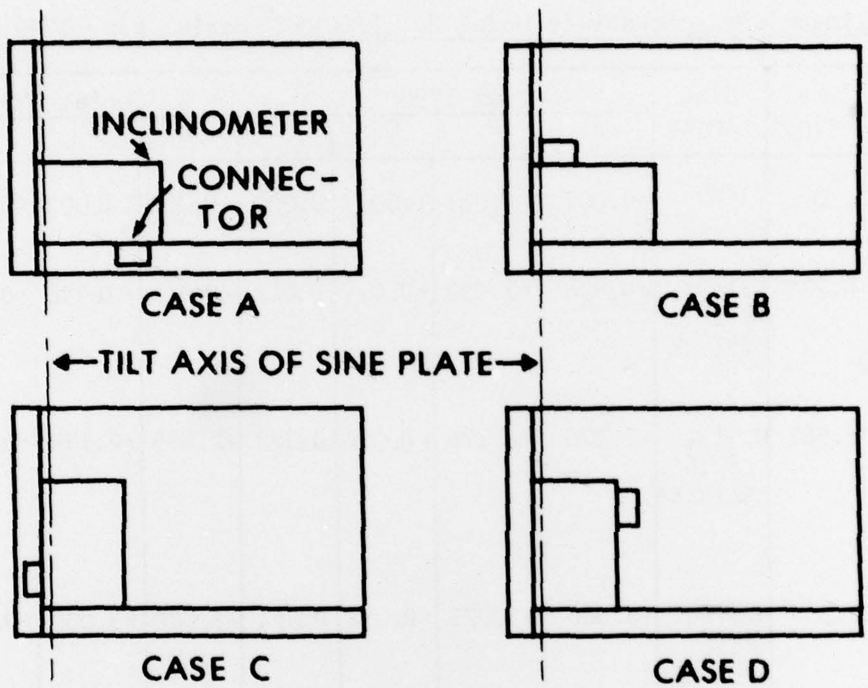


FIGURE B1 INCLINOMETER CALIBRATION

PLAN VIEW OF FOUR ORIENTATIONS OF INCLINOMETER ON SINE PLATE

TABLE B2

INCLINOMETER CALIBRATION

Machine Shop, 21 June 1977

Inclinometers: Schaevitz Model No. LSOC-50° Serial Nos. 1790, 1791

Gage Block Used	Total Height	Sine Angle	Serial 1790				Serial 1791			
			A	B	C	D	A	B	C	D
0	0	0	+0.001	+0.001	0.000	0.000	-0.002	-0.003	-0.003	0.003
0.250 0.357 0.112	0.719	0.1438 8°16' 351°44'	-0.936	+0.938	+0.017	0.012	-0.945	+0.938	+0.006	0.012
1.000 0.357 0.150 0.060	1.567	0.3134 18°16' 341°44'	-2.170	+2.170	+0.034	0.028	-2.183	+2.179	+0.025	0.026
2.000 0.357	2.357	0.4714 28°8' 331°52'	-3.066	+3.071	+0.054	0.054	-3.080	+3.080	+0.033	0.032
3.000 0.109 0.103	3.212	0.6424 39°58' 320°2'	-4.178	+4.183	+0.079	-0.62	-4.196	+4.197	+0.061	0.041
3.000 0.357 0.250 0.050 0.030	3.687	0.7373 47°30' 312°30'	-4.793	+4.797	+0.082	0.063	-4.819	+4.823	+0.062	0.052

TABLE B3

Calibration data for Inclinometer SN 1790. Calibration performed by Schaevitz Engineering, Inc., using an optical index table with an accuracy of 10 arc seconds. Calibration performed for temperature 75° ± 1.

ANGLE	OUTPUT	ANGLE	OUTPUT	ANGLE	OUTPUT	ANGLE	OUTPUT
1°	-0.113	26°	-2.855	359°	+0.114	334°	+2.857
2	-0.227	27	-2.956	358	+0.228	333	+2.958
3	-0.341	28	-3.057	357	+0.341	332	+3.059
4	-0.454	29	-3.157	356	+0.455	331	+3.159
5	-0.567	30	-3.256	355	+0.569	330	+3.258
6	-0.681	31	-3.354	354	+0.682	329	+3.356
7	-0.794	32	-3.451	353	+0.794	328	+3.453
8	-0.906	33	-3.547	352	+0.907	327	+3.549
9	-1.019	34	-3.641	351	+1.020	326	+3.644
10	-1.130	35	-3.735	350	+1.132	325	+3.737
11	-1.242	36	-3.828	349	+1.244	324	+3.830
12	-1.354	37	-3.919	348	+1.355	323	+3.921
13	-1.465	38	-4.009	347	+1.467	322	+4.012
14	-1.575	39	-4.098	346	+1.577	321	+4.101
15	-1.686	40	-4.186	345	+1.687	320	+4.188
16	-1.795	41	-4.272	344	+1.797	319	+4.275
17	-1.904	42	-4.357	343	+1.906	318	+4.360
18	-2.013	43	-4.440	342	+2.014	317	+4.443
19	-2.120	44	-4.523	341	+2.122	316	+4.526
20	-2.227	45	-4.604	340	+2.229	315	+4.607
21	-2.334	46	-4.684	339	+2.335	314	+4.687
22	-2.440	47	-4.762	338	+2.441	313	+4.765
23	-2.545	48	-4.838	337	+2.546	312	+4.841
24	-2.649	49	-4.914	336	+2.651	311	+4.917
25	-2.752	50	-4.988	335	+2.754	310	+4.991

TABLE B4

Calibration data for Inclinometer SN 1791. Calibration performed by Schaevitz Engineering, Inc., using an optical index table with an accuracy of 10 arc seconds. Calibration performed for temperature 75° ± 1.

ANGLE	OUTPUT	ANGLE	OUTPUT	ANGLE	OUTPUT	ANGLE	OUTPUT
1°	-0.115	26°	-2.860	359°	+0.113	334°	+2.860
2	-0.229	27	-2.962	358	+0.227	333	+2.962
3	-0.343	28	-3.063	357	+0.341	332	+3.064
4	-0.456	29	-3.163	356	+0.455	331	+3.164
5	-0.570	30	-3.262	355	+0.568	330	+3.263
6	-0.683	31	-3.360	354	+0.681	329	+3.361
7	-0.797	32	-3.457	353	+0.795	328	+3.458
8	-0.910	33	-3.553	352	+0.908	327	+3.554
9	-1.022	34	-3.648	351	+1.020	326	+3.649
10	-1.134	35	-3.742	350	+1.132	325	+3.743
11	-1.246	36	-3.834	349	+1.244	324	+3.836
12	-1.357	37	-3.926	348	+1.356	323	+3.928
13	-1.469	38	-4.016	347	+1.467	322	+4.018
14	-1.579	39	-4.105	346	+1.578	321	+4.108
15	-1.690	40	-4.193	345	+1.688	320	+4.195
16	-1.799	41	-4.279	344	+1.798	319	+4.282
17	-1.908	42	-4.364	343	+1.907	318	+4.367
18	-2.017	43	-4.448	342	+2.016	317	+4.451
19	-2.125	44	-4.531	341	+2.124	316	+4.534
20	-2.232	45	-4.612	340	+2.231	315	+4.615
21	-2.339	46	-4.692	339	+2.338	314	+4.695
22	-2.445	47	-4.770	338	+2.444	313	+4.773
23	-2.550	48	-4.847	337	+2.549	312	+4.850
24	-2.654	49	-4.923	336	+2.654	311	+4.926
25	-2.758	50	-4.997	335	+2.757	310	+5.000

block height by 0.2. The inclinometer angle was then compared with the sine plate angle and the error obtained as follows:

$$\text{Error} = \theta - \alpha$$

This data is shown in Table 5 and 6.

Cross-axis sensitivity for each inclinometer for Cases C and D, Figure 1, is shown graphically on Figures 2 through 5, where inclinometer voltage is plotted versus the sine of the angle.

IV RESULTS

Tables 5 and 6 show that four data points are substantially inconsistent with the others. Since these points all represent data taken for the same position of the sine plate table, it is probable that the larger error is in table angle rather than inclinometer angle. Disregarding these points, the maximum error observed was 0.137. The larger values observed were for Serial Number 1791, and the error tends to increase with the size of the angle. This could possibly be due to the fact that greater numbers of gage blocks were used to obtain the larger angles. The maximum error associated with the sine plate angle is estimated to be not more than 0.02. The inclinometer voltage can be read to within about 2 millivolts, which represents an error of 0.017 degrees at 1 degree to 0.027 degrees at 50 degrees. Based on these facts, it is estimated that inclinometer angles can be in error by 0.05 to 0.15 degrees for large angles (40 to 50 degrees) of pitch and roll.

Cross-axis sensitivity observed in the calibration substantially exceeded that stated by the manufacturer. For Serial Number 1790, Table No. 1 shows a cross-axis sensitivity value of 0.023

TABLE B5

CALIBRATION ERROR

Schaevitz Inclinometer Serial No. 1790

Sine Plate Angle (degrees)	Interpolated Angle from Table 3 (degrees)	Difference (degrees)
8.268	8.265	-0.003
18.264	19.467	+1.203
28.125	28.090	-0.035
39.971	39.909	-0.063
47.510	47.408	-0.105
312.490	312.579	+0.091
320.029	320.057	+0.029
331.875	331.880	+0.006
341.736	340.551	-1.186
351.732	351.726	-0.006

TABLE B6

CALIBRATION ERROR

Schaevitz Inclinometer Serial No. 1791

Sine Plate Angle (degrees)	Interpolated Angle from Table 4 (degrees)	Difference (degrees)
8.268	8.312	+0.044
18.264	19.542	+1.277
28.125	28.170	+0.044
39.971	40.035	+0.064
47.510	47.636	+0.124
312.490	312.351	-0.139
320.029	319.977	-0.052
331.875	331.840	-0.036
341.736	340.486	-1.251
351.732	351.732	+0.001

FIGURE B2. NON-SENSITIVE AXIS CALIBRATION
INCLINOMETER 1790- CASE C

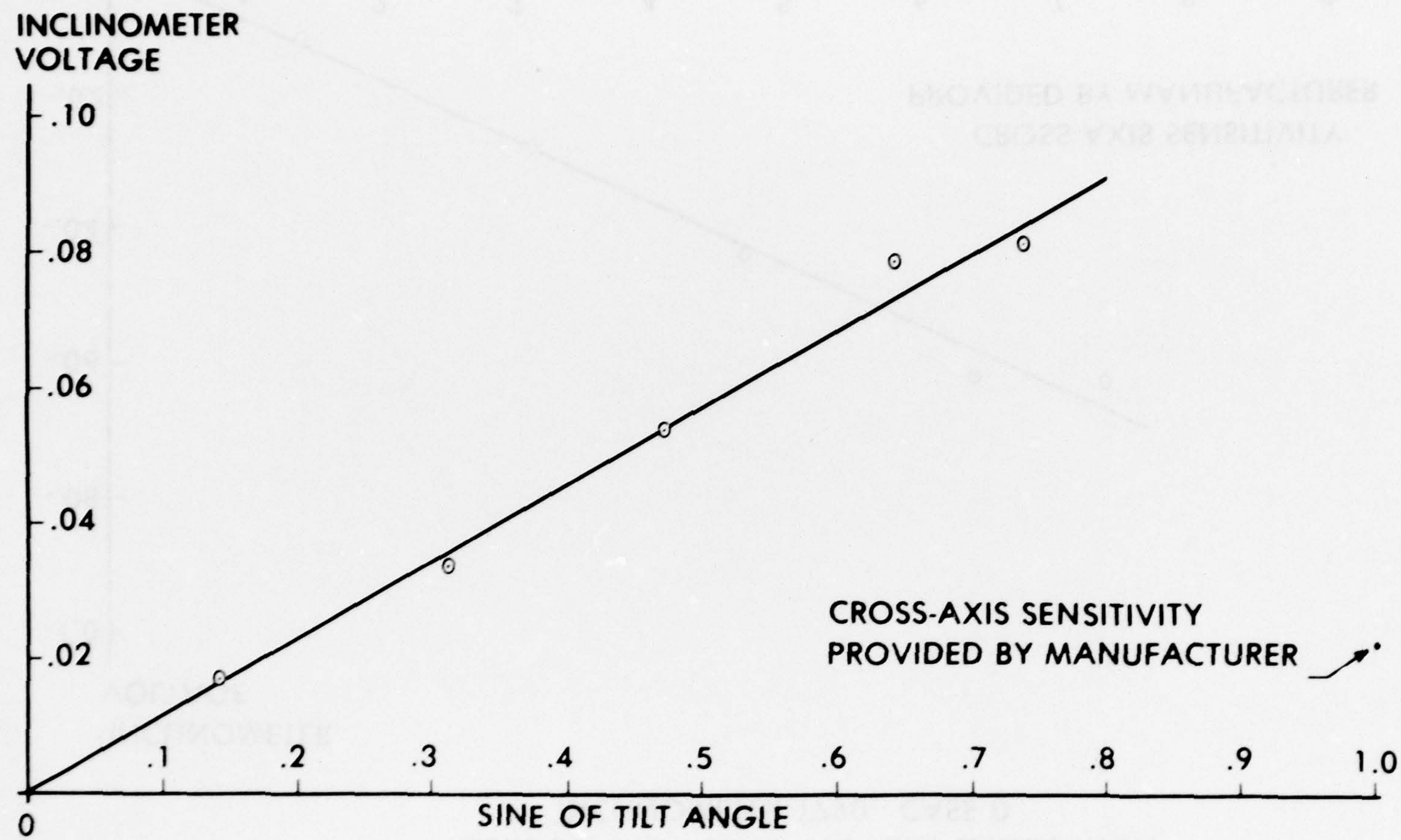


FIGURE B3. NON-SENSITIVE AXIS CALIBRATION
INCLINOMETER 1790- CASE D

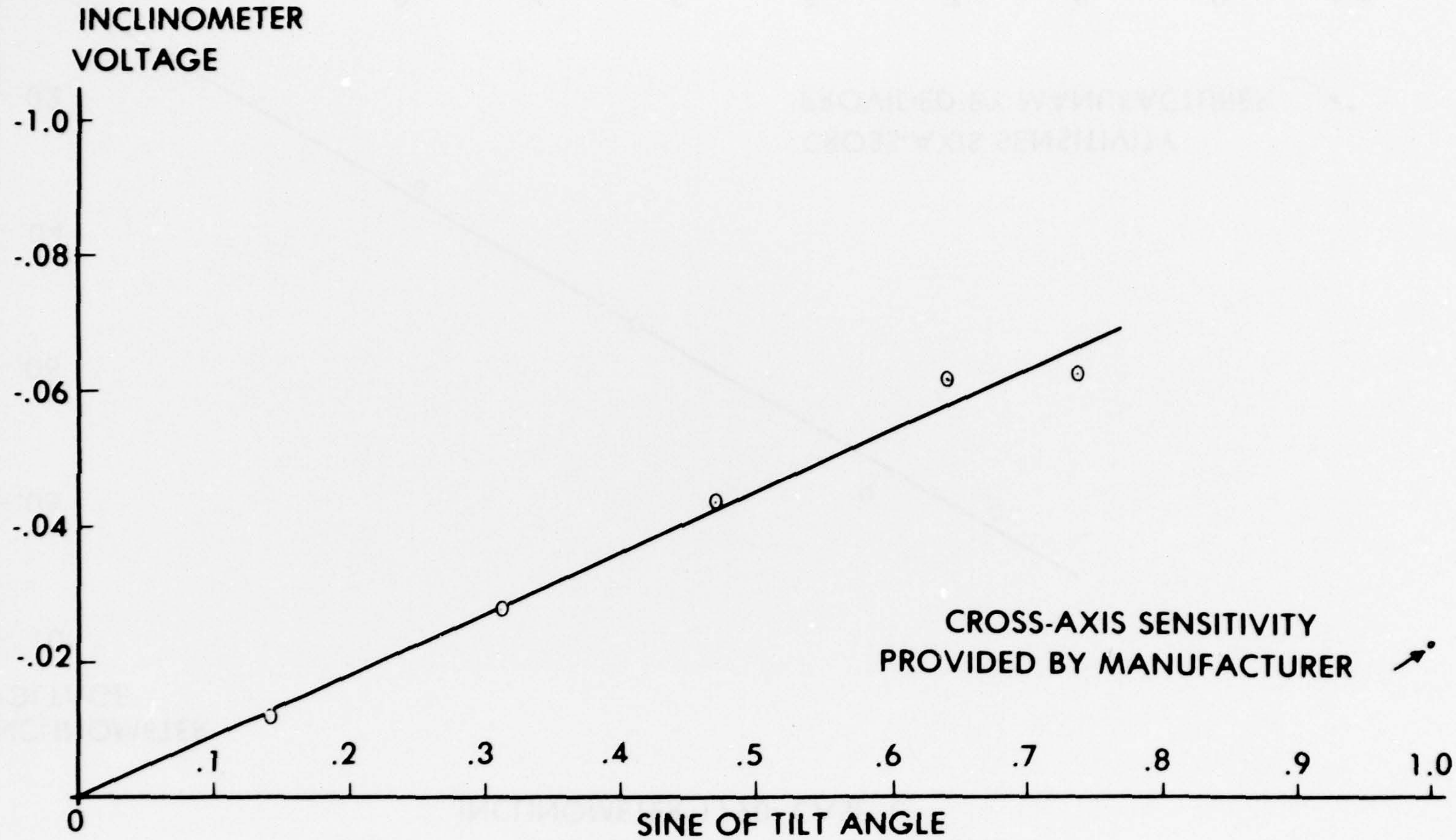


FIGURE B4. NON-SENSITIVE AXIS CALIBRATION
INCLINOMETER 1791-CASE C

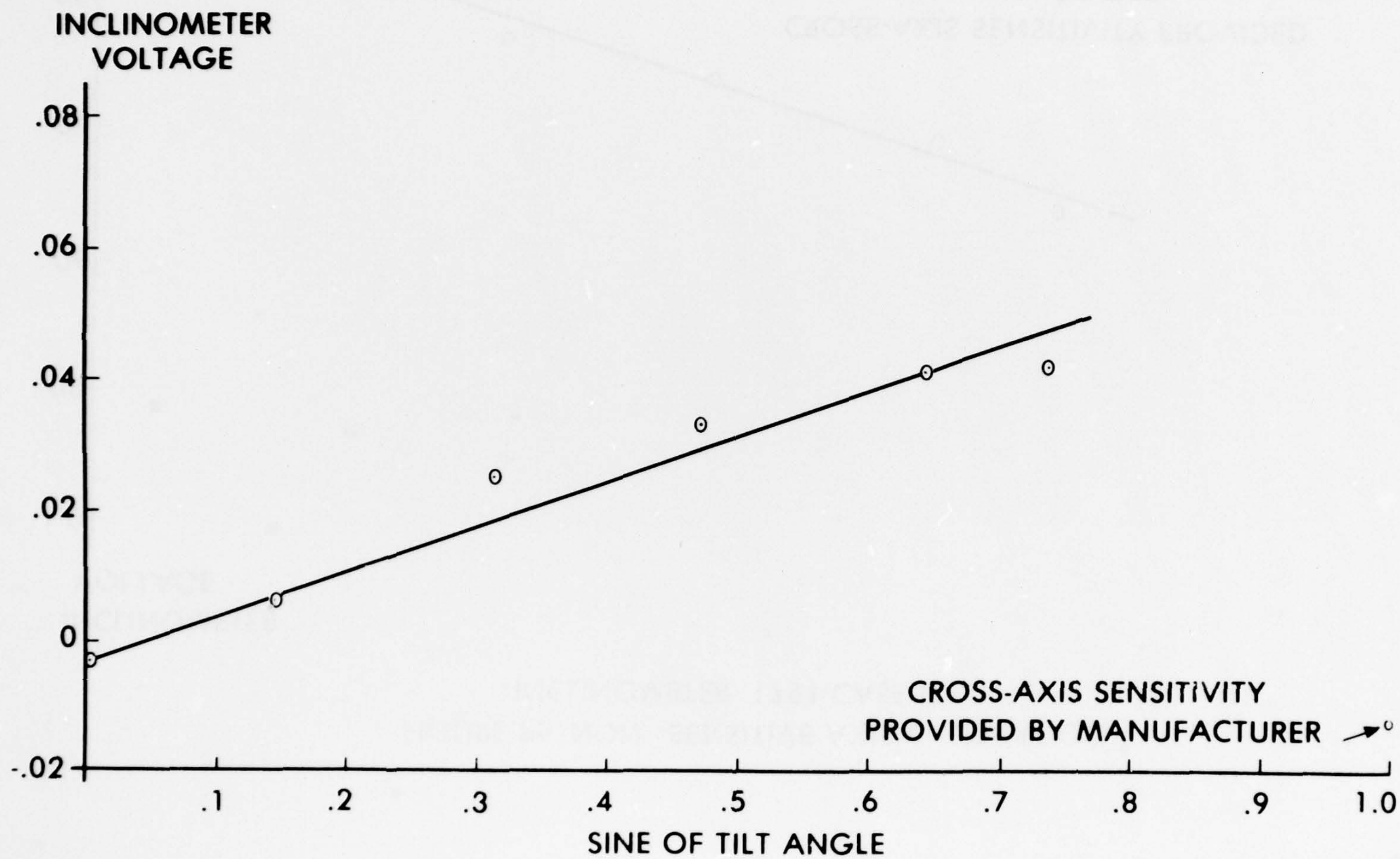
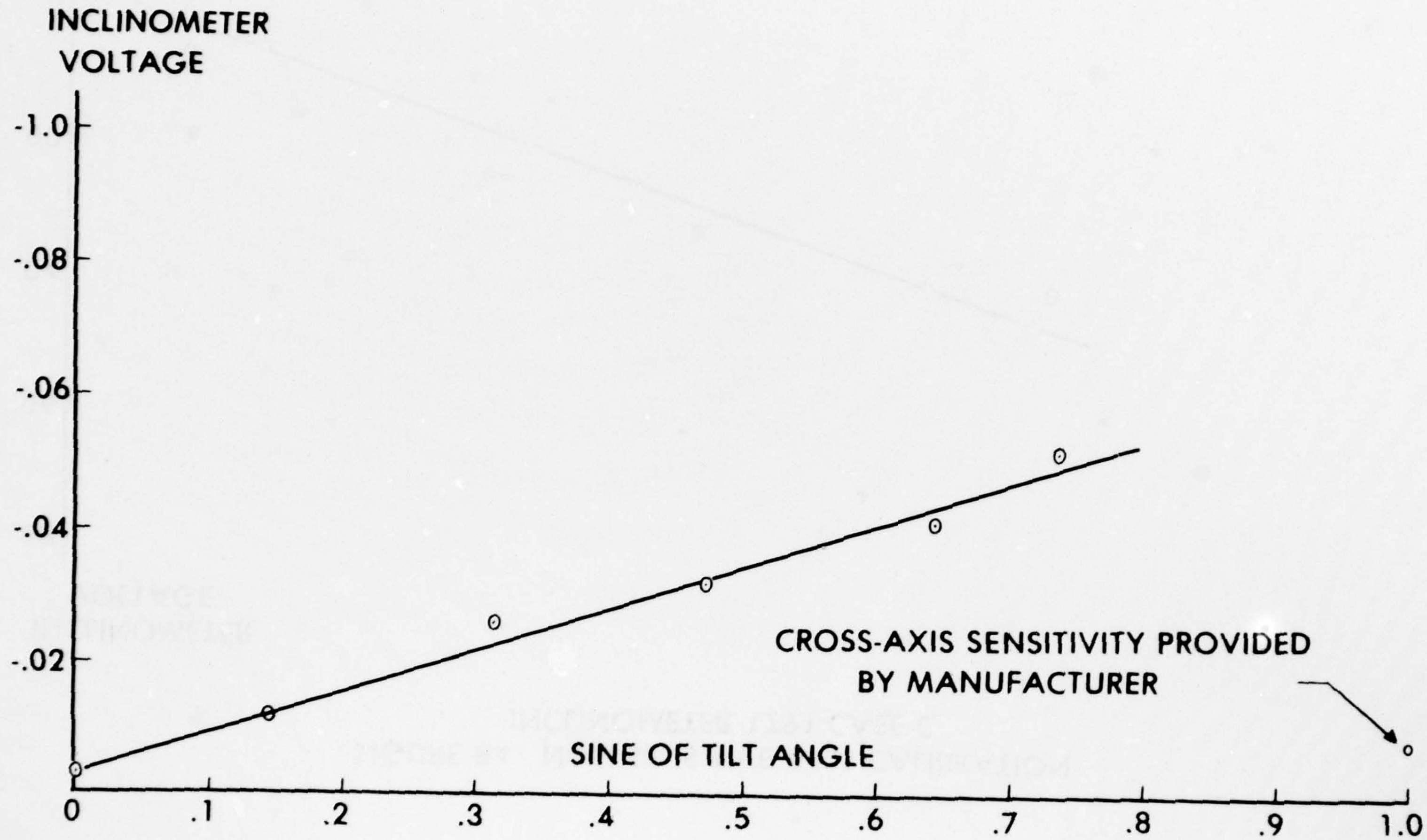


FIGURE B5 NON -SENSITIVE AXIS CALIBRATION
INCLINOMETER 1791-CASE D



volts/g, which is the value which should be obtained for a 90 degree rotation of the inclinometer about its nonsensitive axis. As can be seen from Figure 2, the value observed in the calibration increased with angle to a value of 0.082 volts at 50 degrees and remained at 0.082 volts, at 90 degrees. For Serial Number 1791, the manufacturer's value is 0.008 volts/g, while the observed values were 0.062 volts for 50 degrees and 0.067 volts for 90 degrees. *To better understand the effect of this factor, go to* Figure 2, curve for inclinometer 1790, Case C. For a cross-axis angle of 1 degree (sine = 0.01745), the inclinometer voltage would be approximately 0.002, while for an angle of 45 degrees (sine = 0.707), the voltage would be about 0.080. Interpolation of Table 3 indicates that 0.002 volts is equivalent to a sensitive axis angle of 0.017 degrees at 1 degree or 0.027 degrees at 50 degrees while 0.080 volts is equivalent to 0.73 degrees at 1 degree or 1 degree at 50 degrees. It can be seen that in cases where the inclinometer cannot be maintained in an approximately level position with respect to its nonsensitive axis, additional substantial error will be introduced.

V CONCLUSIONS AND RECOMMENDATIONS

1. Maximum inclinometer error can approach 0.15 degrees for large rotations about the sensitive axis.

2. Rotations about the nonsensitive axis produce voltage readings greatly in excess of those predicted by the manufacturer.

3. It is recommended that inclinometers serials 1790 and 1791 be returned to the manufacturer for complete recalibration

and to determine the reason for the drastic nonsensitive axis increase in output.

4. Inclinometers should be recalibrated about both axes prior to the start of each major test program. Means should be developed to permit periodic rechecks between calibrations to insure that reinstallation of inclinometers after such things as changes in aircraft orientation does not result in inclinometer performance degradation.

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