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REPORT ZA-7-137

DATE 27 November 1956

MODEL Seven

TITLE

A METHOD OF OBTAINING LINEAR AND ANGULAR ACCELERATIONS USING LINEAR ACCELEROMETERS

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FOREWORD

This study was undertaken to determine the minimum number of linear accelerometers necessary to determine the aerodynamic characteristics of the XSM-65 missiles from flight tests and to obtain the equations for the linear and angular accelerations about the three reference axes in terms of the accelerometer readings.

The final results are dependent on the geometric location of the accelerometers so it is recommended that the locations of the instrumentation accelerometers be checked before using the final equations that are set forth here.

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SUMMARY

In order to determine the aerodynamic force and moment characteristics of a missile from flight tests, it is necessary to have measurements of the linear and angular accelerations about the three reference axes. Since angular accelerometers having the desired accuracy and capable of withstanding the environment of the XSM-65 missiles are not available, it has become necessary to obtain these measurements through the use of linear accelerometers. This report presents the results of a study to determine the minimum number of accelerometers required to acomplish these measurements and a study to determine the relative contribution of each instrument toward the net measured acceleration.

By analyzing the general equations for the net measured acceleration, it is shown that the contributions of the centripetal accelerations are negligible providing the angular velocities are moderate. This permits a reduction of the required linear acceleration measurements from nine to six.

Then, using the instrument locations current in September 1956, from Reference 1 through 3, a numerical analysis was made to determine the relative contribution of each instrument. The results are given in Equations 7 to 18.

Equations 7 to 12 are valid for the general case, but Equations 13 to 18 are valid only for the configuration used in this report.

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INTRODUCTION

During the design of a missile, estimates are made of the aerodynamic forces and moment characteristics based on theoretical and wind tunnel data. The theoretical values are, of necessity, based on certain assumptions regarding the effects of viscosity and compressibility while the wind tunnel data contains some interference from the system used to support the model. Consequently, it is most desirable to obtain a final check on the accuracy of the predicted characteristics, from flight tests of the full-scale vehicle.

Furthermore, since the XSM-65 is statically unstable, a certain angle of attack limit exists beyond which the gimballed rocket thrust chambers cannot trim the missile. Should this limit inadvertantly be exceeded in the flight test it should be possible to define the limit from the data obtained and thus provide a check on the predicted limit.

In obtaining these aerodynamic characteristics, two primary measurements are the linear and angular accelerations about the three reference axes. Current instrumentation planning includes the use of servo accelerometers to obtain the linear accelerations, but no angular accelerometers that provide the required accuracy and which meet the XSM-65 environmental specification are available in time for the first flight vehicles. Consequently, it is necessary to obtain angular accelerations by using linear accelerometers and a "base-line" technique.

The study reported herein was undertaken to determine the minimum number of linear accelerometers required to define the linear and angular accelerations about the three reference axes. As a supplement, equations were obtained to show these net accelerations in terms of the acceleration measured by each instrument.

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DISCUSSION

The instrument locations current in September 1956 for the XSM-65A S/N4 missile from References 1 through 3 are shown in Figure 1. The geometry is presented in Table I.

As shown in the detailed development of Appendix A, the analysis of the general acceleration of a body requires the measurement of linear accelerations, angular velocity and angular acceleration about each of three orthogonal reference axes. To accomplish this, nine measurements are necessary. However, when the equations for the output of the instruments are written and the maximum expected values of the linear and angular accelerations and angular velocities are substituted from Reference 4, it is evident that for the moderate angular velocities used, the centripetal accelerations are small. Consequently, the number of measurements may be reduced from nine to six leaving only the linear and angular accelerations to be determined. The six equations are:

$$A_{x1} = a_x - \alpha_z (y_1 - y_{cg}) + \alpha_y (z_1 - z_{cg}) \quad (1)$$

$$A_{x2} = a_x - \alpha_z (y_2 - y_{cg}) + \alpha_y (z_2 - z_{cg}) \quad (2)$$

$$A_{x3} = a_x - \alpha_z (y_3 - y_{cg}) + \alpha_y (z_3 - z_{cg}) \quad (3)$$

$$A_{y4} = a_y - \alpha_z (x_4 - x_{cg}) + \alpha_x (z_4 - z_{cg}) \quad (4)$$

$$A_{y5} = a_y - \alpha_z (x_5 - x_{cg}) + \alpha_x (z_5 - z_{cg}) \quad (5)$$

$$A_{z6} = a_z + \alpha_y (x_6 - x_{cg}) + \alpha_y (y_6 - y_{cg}) \quad (6)$$

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Solving for the six unknown accelerations as shown in Appendix B, results in:

$$\alpha_x = \frac{A_{y4} - A_{y5} + (X_4 - X_5)\alpha_z}{Z_4 - Z_5} \tag{7}$$

$$\alpha_y = \frac{A_{x1}[y_2 - y_3] + A_{x2}[y_3 - y_1] + A_{x3}[y_1 - y_2]}{(y_3 Z_2 - y_2 Z_3) + (y_1 Z_3 - y_3 Z_1) + (y_2 Z_1 - y_1 Z_2)} \tag{8}$$

$$\alpha_z = \frac{A_{x1}[Z_2 - Z_3] + A_{x2}[Z_3 - Z_1] + A_{x3}[Z_1 - Z_2]}{(y_3 Z_2 - y_2 Z_3) + (y_1 Z_3 - y_3 Z_1) + (y_2 Z_3 - y_1 Z_2)} \tag{9}$$

$$a_x = A_{x1} + \alpha_z (y_1 - y_{cg}) - \alpha_y (Z_1 - Z_{cg}) \tag{10}$$

$$a_y = A_{y4} + \alpha_z (X_4 - X_{cg}) - \alpha_x (Z_4 - Z_{cg}) \tag{11}$$

$$a_z = A_{z6} - \alpha_y (X_6 - X_{cg}) - \alpha_x (y_6 - y_{cg}) \tag{12}$$

Using the geometry of Figure 1 and Table I, and the center of gravity location from Reference 5 which corresponds to an initial gross weight of 201,254 pounds, the above equations were evaluated. The time chosen, t = 60 seconds, is the time of maximum dynamic pressure and minimum allowable angle of attack. The following equations were obtained in Appendix C:

$$\alpha_x = -.001888 A_{x1} + .001888 A_{x3} + .019490 A_{y4} - .019490 A_{y5} \tag{13}$$

$$\alpha_y = .009361 A_{x1} - .019490 A_{x2} + .010129 A_{x3} \tag{14}$$

$$\alpha_z = -.094637 A_{x1} + .094637 A_{x3} \tag{15}$$

$$a_x = .404194 A_{x1} + .204239 A_{x2} + .391567 A_{x3} \tag{16}$$

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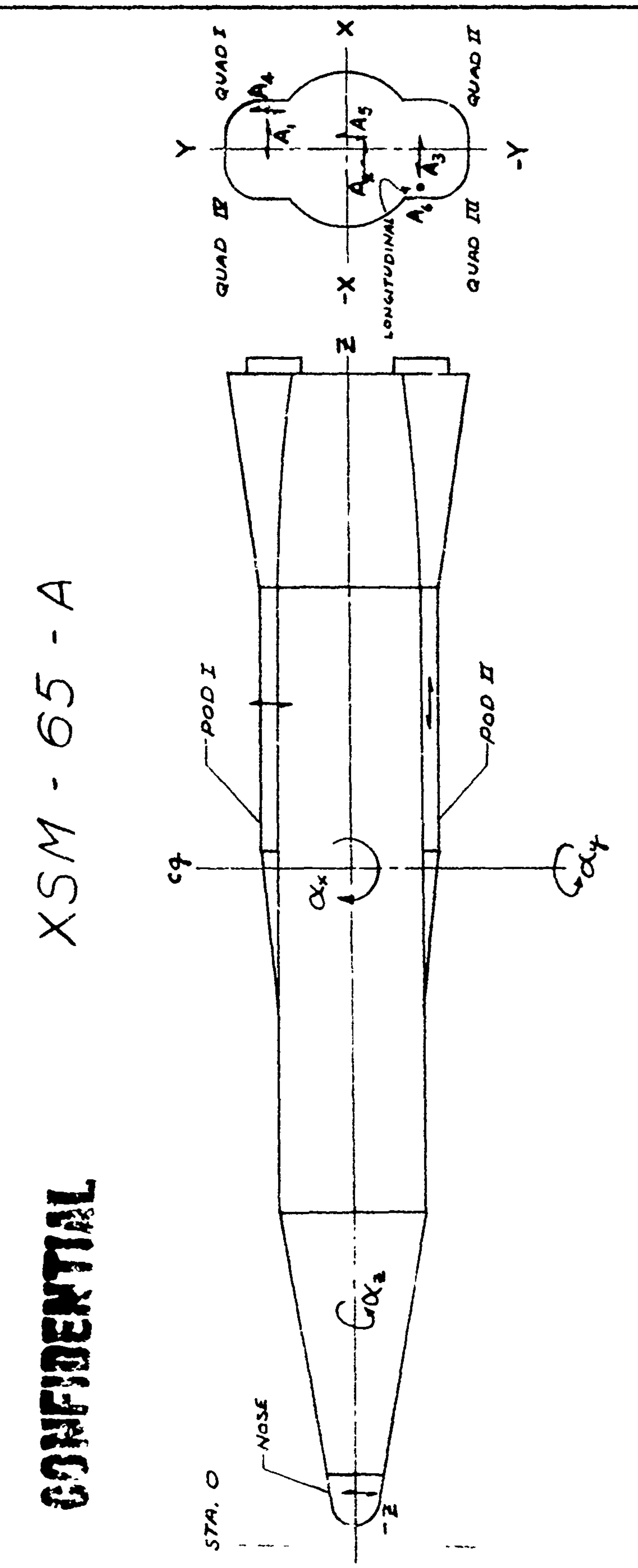
$$a_y = -.099458\,A_{x1} + .099458\,A_{x3} + .795761\,A_{y4} + .204239\,A_{y5} \qquad (17)$$

$$a_z = .000463\,A_{x1} - .021829\,A_{x2} + .021365\,A_{x3} + .103443\,A_{y4} - .103443\,A_{y5} + A_{z6} \qquad (18)$$

These equations, 13 to 18, are good only for the specified geometry and center of gravity location.

Equations 13 to 18 show the relative contribution of each instrument toward the measurement of the net acceleration about any of the three axes. These equations may be then used to evaluate the effect of an error in any instrument upon the final acceleration measurement accuracy.



POD I — YAW-ROLL ACCELEROMETER.... A_1 QUAD I — STA. 1045.25
POD I — PITCH ACCELEROMETER..... A_4 QUAD I — STA. 1045.25

NOSE — YAW-ROLL ACCELEROMETER..... A_2 QUAD III — STA. 429.55
NOSE — PITCH ACCELEROMETER...... A_5 QUAD II — STA. 429.55

POD II — YAW-ROLL ACCELEROMETER... A_3 QUAD III — STA. 1045.25
POD II — AXIAL ACCELEROMETER...... A_6 QUAD III — STA. 1045.25

FIG. 1 RELATIVE ACCELEROMETER LOCATIONS

TABLE I

XSM-65A Accelerometer and

Center of Gravity Locations

Accelerometer	Accelerometer Locations		
	Inches	Inches	Inches
A1	11.33	63.40	1045.25
A2	- 0.45	- 2.50	429.55
A3	-11.33	-63.40	1045.25
A4	14.28	63.40	1045.25
A5	2.00	- 0.30	429.55
A6	-14.28	-63.40	1045.25
C.G. Location at t = 60 sec. G. Wt = 201,254 Lbs.	- 0.84	0.29	919.50

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REFERENCES

1. Paul, John, "Transducer Installation Station 426 Nose," Convair Drawing 7-11798, October 1956.

2. Paul, John, "Transducer Installation Station 1045 Quad I," Convair Drawing 7-11796, October 1956.

3. Paul, John, "Transducer Installation Station 1045 Quad III," Convair Drawing 7-11799, October 1956.

4. Lukens, D., "Basic Autopilot & Aeroelastic Data for the XSM-65 A and C Series Missiles During the Boost Phase," Convair Technical Note ZU-7-050-TN, December 15, 1955.

5. Allenson, J. M., "XSM-65A Mass Distribution Centers of Gravity Moments and Products of Inertia," AW-A-35, September 25, 1956.

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APPENDIX A

Reducing the Number of Unknowns

The output of each accelerometer will include components of acceleration resulting from translational acceleration, angular acceleration and angular velocity. The outputs of the various instruments may be written as:

$$A_{x1} = a_x - \omega_z^2(x_1 - x_{cg}) - \omega_y^2(x_1 - x_{cg}) - \alpha_z(y_1 - y_{cg}) + \alpha_y(z_1 - z_{cg}) \quad (A1)$$

$$A_{x2} = a_x - \omega_z^2(x_2 - x_{cg}) - \omega_y^2(x_2 - x_{cg}) - \alpha_z(y_2 - y_{cg}) + \alpha_y(z_2 - z_{cg}) \quad (A2)$$

$$A_{x3} = a_x - \omega_z^2(x_3 - x_{cg}) - \omega_y^2(x_3 - x_{cg}) - \alpha_z(y_3 - y_{cg}) + \alpha_y(z_3 - z_{cg}) \quad (A3)$$

$$A_{y4} = a_y - \omega_z^2(y_4 - y_{cg}) - \omega_x^2(y_4 - y_{cg}) - \alpha_z(x_4 - x_{cg}) + \alpha_x(z_4 - z_{cg}) \quad (A4)$$

$$A_{y5} = a_y - \omega_z^2(y_5 - y_{cg}) - \omega_x^2(y_5 - y_{cg}) - \alpha_z(x_5 - x_{cg}) + \alpha_x(z_5 - z_{cg}) \quad (A5)$$

$$A_{z6} = a_z - \omega_x^2(z_6 - z_{cg}) - \omega_y^2(z_6 - z_{cg}) + \alpha_y(x_6 - x_{cg}) + \alpha_x(y_6 - y_{cg}) \quad (A6)$$

These six equations contain nine unknowns, a_x, a_y, a_z, w_x, w_y, w_z, and $\alpha_x, \alpha_y, \alpha_z$ so that in theory three more equations are required for solution. However, by examining the magnitude of each term, three unknowns may be eliminated.

At t = 60 seconds, the time corresponding to maximum dynamic pressure, the instrument outputs were evaluated, using the maximum expected values of the accelerations and angular velocities. The values used are:

$$a_x \sim 16 \text{ ft/sec}^2$$
$$a_y \sim 16 \text{ ft/sec}^2$$
$$a_z \sim 2.15g = 69.166 \text{ ft/sec}^2$$

$$\omega_x \sim 3 \text{ deg/sec} = 0.05236 \text{ rad/sec}$$
$$\omega_y \sim 3 \text{ deg/sec} = 0.05236 \text{ rad/sec}$$
$$\omega_z \sim 3 \text{ deg/sec} = 0.05236 \text{ rad/sec}$$

$$\alpha_x \sim 25 \text{ deg/sec} = 0.43633 \text{ rad/sec}$$
$$\alpha_y \sim 25 \text{ deg/sec} = 0.43633 \text{ rad/sec}$$
$$\alpha_z \sim 25 \text{ deg/sec} = 0.43633 \text{ rad/sec}$$

where -

$a \sim$ translational acceleration

$\omega \sim$ angular velocity

$\alpha \sim$ angular acceleration

Substituting these values and the geometry from Table I into equations A1 to A6 results in:

$$A_{x1} = 16 - 0.003 - 0.003 - 2.295 + 4.572 \qquad (A7)$$

$$A_{x2} = 16 - 0.00009 - 0.00009 + 0.101 - 17.815 \qquad (A8)$$

$$A_{x3} = 16 + 0.002 + 0.002 + 2.316 + 4.572 \qquad (A9)$$

$$A_{y4} = 16 - 0.014 - 0.014 - 0.550 + 4.572 \qquad (A10)$$

$$A_{y5} = 16 + 0.0001 + 0.0001 - 0.103 - 17.815 \qquad (A11)$$

$$A_{z6} = 69.166 - 0.029 - 0.029 - 0.489 - 2.316 \qquad (A12)$$

It is evident in each equation that the contributions of the second and third terms, which are due to the angular velocities, are quite small. Therefore, these terms may be neglected. The six remaining unknowns then are the three translational accelerations and three angular accelerations.

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Depending upon the direction of the angular accelerations, when the translational acceleration is at a maximum the instrument outputs may vary between:

$$9.127 \leq A_{x1} \leq 22.873$$

$$-1.917 \leq A_{x2} \leq 33.917$$

$$9.107 \leq A_{x3} \leq 22.893$$

$$10.849 \leq A_{y4} \leq 21.151$$

$$-1.929 \leq A_{y5} \leq 33.929$$

$$66.304 \leq A_{z6} \leq 72.028$$

Therefore, it is not necessarily apparent from the output of a single instrument whether the translational acceleration has reached its maximum amplitude at any instant of time. This should be kept in mind when analyzing flight records.

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APPENDIX B

Solving For the Accelerations

After eliminating the angular velocity terms from Equations A1 to A6 they may be rewritten as:

$$A_{x1} = a_x - \alpha_z(y_1 - y_{cg}) + \alpha_y(z_1 - z_{cg}) \qquad (B1)$$

$$A_{x2} = a_x - \alpha_z(y_2 - y_{cg}) + \alpha_y(z_2 - z_{cg}) \qquad (B2)$$

$$A_{x3} = a_x - \alpha_z(y_3 - y_{cg}) + \alpha_y(z_3 - z_{cg}) \qquad (B3)$$

$$A_{y4} = a_y - \alpha_z(x_4 - x_{cg}) + \alpha_x(z_4 - z_{cg}) \qquad (B4)$$

$$A_{y5} = a_y - \alpha_z(x_5 - x_{cg}) + \alpha_x(z_5 - z_{cg}) \qquad (B5)$$

$$A_{z6} = a_z + \alpha_y(x_6 - x_{cg}) + \alpha_x(y_6 - y_{cg}) \qquad (B6)$$

Forming a determinant from the first three equations leads to:

$$D = \begin{vmatrix} 1 & -(y_1 - y_{cg}) & (z_1 - z_{cg}) \\ 1 & -(y_2 - y_{cg}) & (z_2 - z_{cg}) \\ 1 & -(y_3 - y_{cg}) & (z_3 - z_{cg}) \end{vmatrix} \qquad (B7)$$

$$D_{a_x} = \begin{vmatrix} A_{x1} & -(y_1 - y_{cg}) & (z_1 - z_{cg}) \\ A_{x2} & -(y_2 - y_{cg}) & (z_2 - z_{cg}) \\ A_{x3} & -(y_3 - y_{cg}) & (z_3 - z_{cg}) \end{vmatrix} \qquad (B8)$$

$$D_{\alpha_z} = \begin{vmatrix} 1 & A_{x1} & (z_1 - z_{cg}) \\ 1 & A_{x2} & (z_2 - z_{cg}) \\ 1 & A_{x3} & (z_3 - z_{cg}) \end{vmatrix} \qquad (B9)$$

$$D_{\alpha_y} = \begin{vmatrix} 1 & -(y_1 - y_{cg}) & A_{x1} \\ 1 & -(y_2 - y_{cg}) & A_{x2} \\ 1 & -(y_3 - y_{cg}) & A_{x3} \end{vmatrix} \qquad (B10)$$

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Solving then for α_y, α_z and a_x yields

$$\alpha_y = \frac{D_{\alpha y}}{D} = \frac{A_{x1}\left[y_2 - y_3\right] + A_{x2}\left[y_3 - y_1\right] + A_{x3}\left[y_1 - y_2\right]}{(y_3 z_2 - y_2 z_3) + (y_1 z_3 - y_3 z_1) + (y_2 z_1 - y_1 z_2)} \tag{B11}$$

$$\alpha_z = \frac{D_{\alpha z}}{D} = \frac{A_{x1}\left[z_2 - z_3\right] + A_{x2}\left[z_3 - z_1\right] + A_{x3}\left[z_1 - z_2\right]}{(y_3 z_2 - y_2 z_3) + (y_1 z_3 - y_3 z_1) + (y_2 z_1 - y_1 z_2)} \tag{B12}$$

$$a_x = \frac{D_{ax}}{D} = \frac{A_{x1}\left[(y_3 z_2 - y_2 z_3) + y_{cg}(z_3 - z_2) + z_{cg}(y_2 - y_3)\right]}{(y_3 z_2 - y_2 z_3) + (y_1 z_3 - y_3 z_1) + (y_2 z_1 - y_1 z_2)}$$

$$- \frac{A_{x2}\left[(y_3 z_1 - y_1 z_3) + y_{cg}(z_3 - z_1) + z_{cg}(y_1 - y_3)\right]}{(y_3 z_2 - y_2 z_3) + (y_1 z_3 - y_3 z_1) + (y_2 z_1 - y_1 z_2)}$$

$$+ \frac{A_{x3}\left[(y_2 z_1 - y_1 z_2) + y_{cg}(z_2 - z_1) + z_{cg}(y_1 - y_2)\right]}{(y_3 z_2 - y_2 z_3) + (y_1 z_3 - y_3 z_1) + (y_2 z_1 - y_1 z_2)} \tag{B13}$$

Alternate forms of the solution for a_x are

$$a_x = A_{x1} + \alpha_z (y_1 - y_{cg}) - \alpha_y (z_1 - z_{cg}) \tag{B14}$$

$$a_x = A_{x2} + \alpha_z (y_2 - y_{cg}) - \alpha_y (z_2 - z_{cg}) \tag{B15}$$

$$a_x = A_{x3} + \alpha_z (y_3 - y_{cg}) - \alpha_y (z_3 - z_{cg}) \tag{B16}$$

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Now using the solution for α_z and solving equations (B4) and (B5) for α_x yields

$$\alpha_x = \frac{A_{y4} - A_{y5} + \alpha_z (x_4 - x_5)}{(z_4 - z_5)} \qquad (B17)$$

$$\alpha_x = \frac{A_{y4} - A_{y5}}{z_4 - z_5} + \frac{x_4 - x_5}{z_4 - z_5}\left(\frac{A_{x1}[z_2 - z_3] + A_{x2}[z_3 - z_1] + A_{x3}[z_1 - z_2]}{(y_3 z_2 - y_2 z_3) + (y_1 z_3 - y_3 z_1) + (y_2 z_1 - y_1 z_2)}\right) \qquad (B18)$$

Then a_y may be obtained from either

$$a_y = A_{y4} + \alpha_z (x_4 - x_{cg}) - \alpha_x (z_4 - z_{cg}) \qquad (B19)$$

$$a_y = A_{y5} + \alpha_z (x_5 - x_{cg}) - \alpha_x (z_5 - z_{cg}) \qquad (B20)$$

Finally solving B6 for a_z yields

$$a_z = A_{z6} - \alpha_y (x_6 - x_{cg}) - \alpha_x (y_6 - y_{cg}) \qquad (B21)$$

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APPENDIX C

Evaluating the Contribution of Each Instrument

Substituting the geometry from Table I into the acceleration equations results in the following:

From (B 12)

$$\alpha_z = \left(\frac{-615.70\ A_{x1} + 0 + 615.70\ A_{x3}}{78070.76} \right) 12 \qquad (C1)$$

$$\alpha_z = -.094637\ A_{x1} + .094637\ A_{x3} \qquad (C2)$$

From (B 11)

$$\alpha_y = \left(\frac{60.9\ A_{x1} - 126.8\ A_{x2} + 65.9\ A_{x3}}{78070.76} \right) 12 \qquad (C3)$$

$$\alpha_y = .009361\ A_{x1} - .019490\ A_{x2} + .010129\ A_{x3} \qquad (C4)$$

From (B 17)

$$\alpha_x = \left(\frac{A_{y4} - A_{y5} + 12.28(-.094637\ A_{x1} + .094637\ A_{x3})}{615.70} \right) 12 \qquad (C5)$$

$$\alpha_x = .019490 A_{y4} - .019490 A_{y5} - .001888 A_{x1} + .001888 A_{x3} \qquad (C6)$$

From (B 13)

$$a_x = \frac{31555\ A_{x1} + 15945\ A_{x2} + 30569.9\ A_{x3}}{78070.76} \qquad (C7)$$

$$a_x = .404194 A_{x1} + .204239 A_{x2} + .391567 A_{x3} \qquad (C8)$$

From (B 19)

$$a_y = \frac{-125.75}{12}\left(.019490 A_{y4} - .019490 A_{y5} - .001888 A_{x1} + .001888 A_{x3}\right)$$

$$- \frac{15.12}{12}\left(-.094637\ A_{x1} + .094637\ A_{x3}\right) - A_{y4} \qquad (C9)$$

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$$a_y = -.099458 A_{x1} + .099458 A_{x3} + .795761 A_{y4} + .204239 A_{y5} \qquad (C10)$$

From (B 21)

$$a_z = A_{z6} + \frac{13.44}{12}\left(.009361 A_{x1} - .019490 A_{x2} + .010129 A_{x3}\right)$$

$$+ \frac{63.69}{12}\left(.019490 A_{y4} - .019490 A_{y5} - .001888 A_{x1} + .001888 A_{x3}\right) \qquad (C11)$$

$$a_z = .000463 A_{x1} - .021829 A_{x2} + .021365 A_{x3} + .103443 A_{y4}$$

$$- .103443 A_{y5} + A_{z6} \qquad (C12)$$

The numerical values of the coefficients are good only for the geometry specified in Table I. Since the location of center of gravity will change with time, these coefficients will vary with time. In addition, the location of the instruments may change which would also cause the coefficients to change from the values quoted herein. Consequently before using any of these relations in data reduction, all numerical quantities should be carefully checked.

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