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This TOP describes the mass properties measurement procedures necessary for the set-up of spin balance equipment, fixture installation and alignment; test article installation and measurement of run out; and spin balance operations for munitions. This document specifically addresses testing of missile payload front end hardware. This procedure determines the mass properties, balance configurations, and balance specification(s) of live or inert munitions; namely, the Center of Gravity (CG), the Moment of Inertia (MOI), and the Product of Inertia (POI).

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U.S. ARMY TEST AND EVALUATION COMMAND
TEST OPERATIONS PROCEDURE

*Test Operations Procedure 05-2-519 9 March 2015
DTIC AD No.

MUNITION MASS PROPERTIES MEASUREMENT PROCEDURES USING A SPIN BALANCE MACHINE

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*Approved for public release; distribution unlimited.

1. SCOPE.

This TOP describes the mass properties measurement procedures necessary for the set-up of spin balance equipment, fixture installation and alignment; test article installation and measurement of run out; and spin balance operations for munitions. This document specifically addresses testing of missile payload front end hardware. This procedure determines the mass properties, balance configurations, and balance specification(s) of live or inert munitions; namely, the Center of Gravity (CG), the Moment of Inertia (MOI), and the Product of Inertia (POI).

1.1 Purpose.

The purpose of this TOP is to establish guidelines and procedures such that mass property measurements can be performed using a spin balance machine in a uniform manner and result in accurate and repeatable test data. The results of mass property measurements of the total vehicle are used to prevent the payload from tumbling end over end after launch or to prevent the vehicle from quickly using up its thruster capacity in an attempt to point in the correct direction.

1.2 Application.

a. These test procedures are specifically targeted at missiles, rockets and their components, however, the procedures may be applied to other items as well.

b. The procedures are applicable for obtaining Center of Gravity, Moment of Inertia, and Product of Inertia measurements.

1.3 Limitations.

a. This TOP only provides an overview of mass properties measurement of the missile payload front end hardware. Specific test items and or test requirements should be examined individually and the test procedures should be tailored accordingly to reduce the errors between a measurement and the true (standard) value. The success of a missile flight is highly dependent on the accuracy of the measurement of the missile mass properties before flight and the proper ballasting of the payload to bring the mass properties within tight limits.

b. This TOP does not describe the techniques for combining the mass properties of subassemblies to yield the composite mass properties of the total vehicle. Boynton and Wiener[1]** describe techniques for combining the mass properties of sub-assemblies to yield the composite mass properties of the total vehicle.

** Superscript numbers correspond to those in Appendix G, References.

2. FACILITIES AND INSTRUMENTATION.

2.1 Facilities.

a. The facility should have ample working space for the spin balance machine, for various test item adapter/alignment fixtures, and the calibration tools (fixtures, laser alignment/pointing device, mechanical dial indicator, etc). There should be a crane hoist for positioning the test article onto the spin balance machine. The facility should adhere to all local fire regulations and provide an overall safe working environment. Information pertaining to any on site hazards should be documented and made available to any site visitors. Standard Operating Procedures should be kept current and updated with the facility's latest capabilities. When testing explosive items, the test facilities must provide adequate protection for personnel. Remote control of the spin balance equipment is required for personnel safety and closed circuit video will permit observation of munition tests.

b. Facilities to perform visual inspections and performance checks of the test items may be required before and after to ensure that all vitally important functions are operational and that there are no areas of concern about the tested unit. Other non-destructive tests such as radiographic inspection may be required for explosive items to ensure they are in a safe condition.

2.2 Instrumentation.

Device for Measuring	Permissible Measurement Uncertainty
Center of Gravity	± 0.0001 inch (0.0025 millimeter (mm))
Moment of Inertia	± 0.1%
Product of Inertia	± 0.1%
Weight (Load Cell)	± 1 pounds (lbs)
Torque	± 2%

3. REQUIRED TEST CONDITIONS.

3.1 Test Planning.

3.1.1 General.

Proper test planning should be conducted prior to performing any testing. It is important to identify the errors between a measurement and the true (standard) value. The success of a missile flight is highly dependent on the accuracy of the measurement of the missile mass properties before flight and the proper ballasting of the payload to bring the mass properties within tight limits. Failure to properly control mass properties can result in the payload tumbling end over end after launch, or the vehicle to quickly use up its thruster capacity in an attempt to point in the correct direction.

3.1.2 Test Objectives/Criteria.

Clear and obtainable test objectives and test item criteria should be defined when developing a test plan. The objectives should state in sufficient detail the purpose of the test and any special considerations required during testing. The criteria should provide the means of analyzing if the test item meets the required performance and/or structural integrity specifications.

3.1.3 Test Item Inspection Procedures.

Visual inspection of the test items should be made prior to test. Ensure that all components are flight representative and installed correctly within the physical structure of the vehicle.

3.1.4 Test Item Configuration.

The test item should be in the flight representative configuration. The physical dimensions, mass, center of gravity, operational state, configuration, and orientation of the test item is vital information required to develop the appropriate test procedures. Note, measurements of the more complex unbalanced configurations (non-cylindrical items) can be addressed with “spinning” methods or the multiple orientation MOI method. See Wiener, et. al.[2] for further guidance.

3.1.5 Atmospheric Conditions.

Standard ambient would be the preferred condition for conducting mass properties measurement procedures; however, test specifications may call for other controlled conditions. Local ambient conditions may be acceptable if the equipment calibration remains valid over the operating range. The test item requirements and equipment specifications should be accommodated and appropriate climatic adjustments made. For example, the heating, ventilation, and air conditioning (HVAC) may need to be turned off to reduce air flow around the test article to prevent impacting results of both dynamic and static measurements.

3.2 Test Preparation.

3.2.1 Measurement Machine.

Choose the correct type of measuring machine. There are a wide variety of mass properties measuring machines available today. Equipment selection depends on what properties are desired to be measured, the accuracy required and budget restrictions. At the U.S. Army White Sands Missile Range (WSMR), the machine is the model POI-3500-BL from Space Electronics, Inc.*** This machine is designed to measure POI, dynamic and static CG, and MOI of objects weighing up to 3,500 lbs (1,600 kg). The machine is of the “vertical” type (rotation axis vertical) with two plane measurement and correction capability. There are three modes of measurement;

*** The use of brand names does not constitute endorsement by the Army or any other agency of the Federal Government, nor does it imply that it is best suited for its intended application.

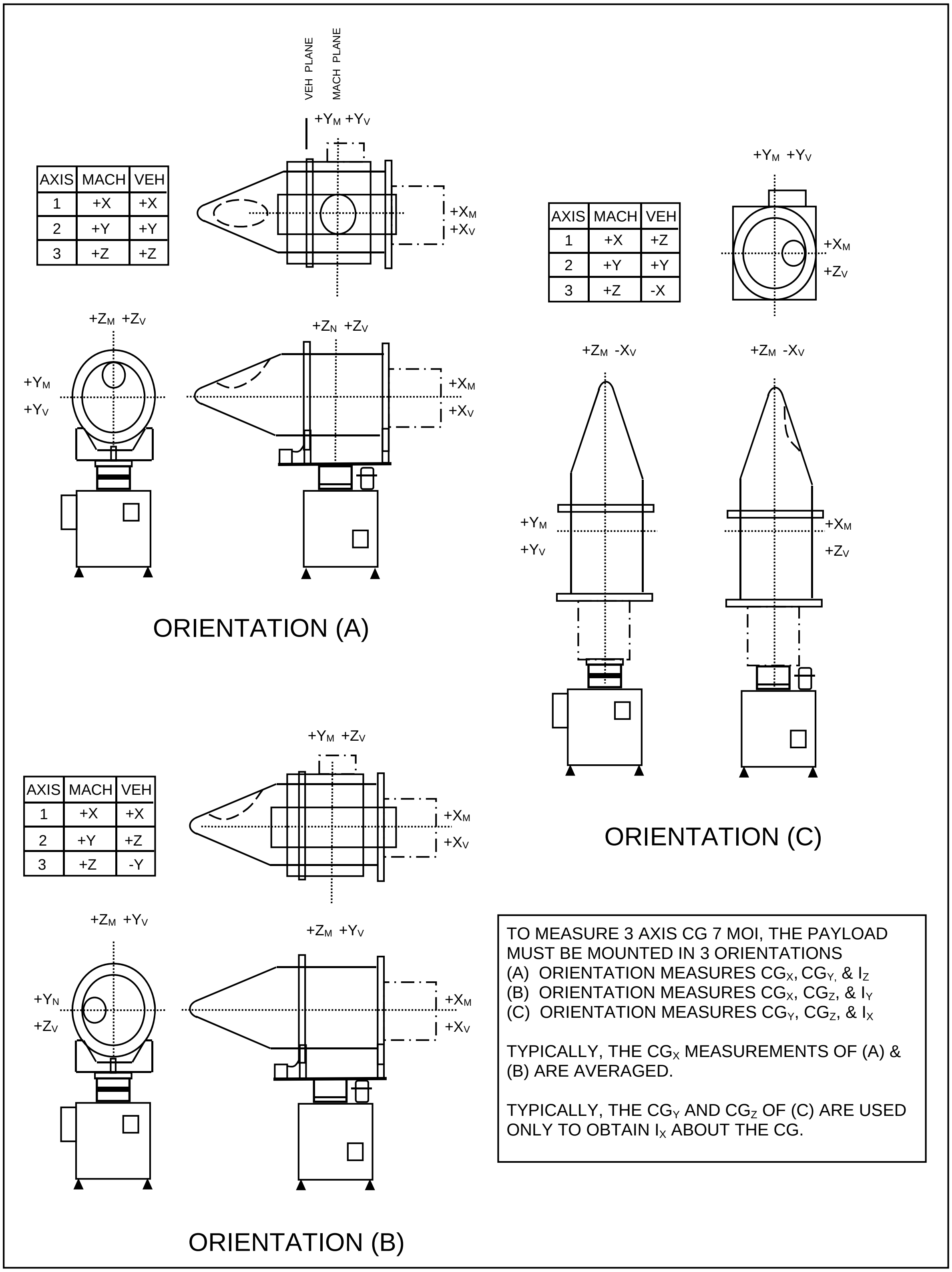
Spin testing to measure POI and CG offset unbalance, Torsion Pendulum Oscillation to measure MOI, and Static Measurement of CG offset moment. The WSMR measuring machine is shown in Figure 1.

Figure 1. WSMR mass properties measurement machine.

3.2.2 Coordinate System and Payload Position.

a. Coordinate System. The location of the reference axes must be assigned prior to calculating mass properties of the test item. The axes may be related to the geometric centerline of the vehicle, a line of thrust, or may depend on the attachment interface to another stage of the vehicle. The CG coordinates and POI can be positive or negative. Determine whether the positive axis agrees with the definition of axes used by the recipient of the data. The CG distance can be expressed along a coordinate system defined by the geometry of the vehicle or along the principle axes. The POI can also be positive or negative since this quantity is derived by multiplying the incremental masses by two distances. Note, the MOI is always a positive value, so there is never any uncertainty regarding the sign. It is highly recommended that a sketch, similar to Figure 2, be provided to clearly show the axes and their algebraic signs.

b. Payload Position. There are an infinite number of ways a payload can be mounted on the mass properties machine. While the mass properties of the payload are fixed, the measured data will depend on the orientation of the payload relative to the measurement coordinate system. For example, a nose tip can be mounted with its nose up or its nose down. It is recommended that a sketch or a drawing of the position of the payload on the machine be provided so the measured data can be correctly interpreted.



Orientation (A):

AXIS	MACH	VEH
1	+X	+X
2	+Y	+Y
3	+Z	+Z

Orientation (B):

AXIS	MACH	VEH
1	+X	+X
2	+Y	+Z
3	+Z	-Y

Orientation (C):

AXIS	MACH	VEH
1	+X	+Z
2	+Y	+Y
3	+Z	-X

TO MEASURE 3 AXIS CG 7 MOI, THE PAYLOAD MUST BE MOUNTED IN 3 ORIENTATIONS
(A) ORIENTATION MEASURES CG_X, CG_Y, & I_Z
(B) ORIENTATION MEASURES CG_X, CG_Z, & I_Y
(C) ORIENTATION MEASURES CG_Y, CG_Z, & I_X

TYPICALLY, THE CG_X MEASUREMENTS OF (A) & (B) ARE AVERAGED.

TYPICALLY, THE CG_Y AND CG_Z OF (C) ARE USED ONLY TO OBTAIN I_X ABOUT THE CG.

Figure 2. Axes orientation diagram.

3.2.3 Fixturing.

The fixture must position the object in a repeatable and rigid manner relative to the mass properties machine. It must provide a means to precisely relate the object coordinate system to the mass properties machine coordinate system, so that measurements made relative to the machine axes can be expressed relative to the object axes. The fixture should be balanced relative to the measuring machine. For horizontal measurements of payloads, Vee Block fixtures are commonly used. For vertical cylinders or cones, a standard round fixture or an adjustable fixture is often used. Center the fixture and payload on the machine using a mechanical dial indicator for improved accuracy. A fixture circumference accuracy of 0.0005 inch is typical for munition mass properties measurements. Figure 3 shows example test fixtures.

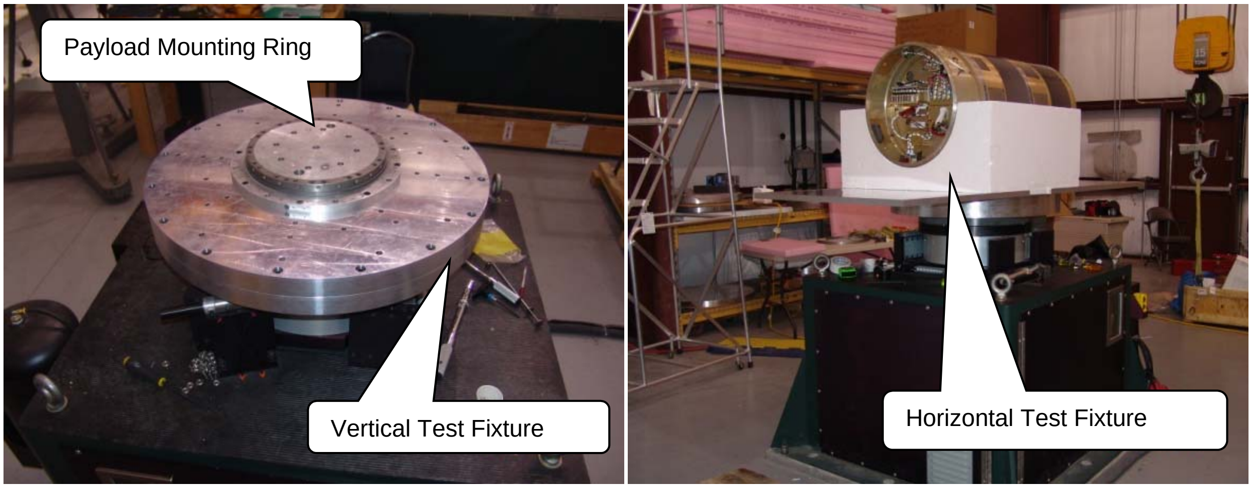


Figure 3. Example test fixtures.

4. TEST PROCEDURES.

4.1 General.

Once the mass properties test specification and test equipment have been determined, verify the mass properties machine is functioning and recording data properly. Ensure the measurement unit settings of the spin balance software package are correct. For static measurements, the units are set to be in ounce-inches (oz-in); for dynamic measurements, the units are set in oz-in^2; for MOI measurements, the units are set in slug feet^2; and for distance measurements, the units are to be in inches.

4.2 Test Conduct.

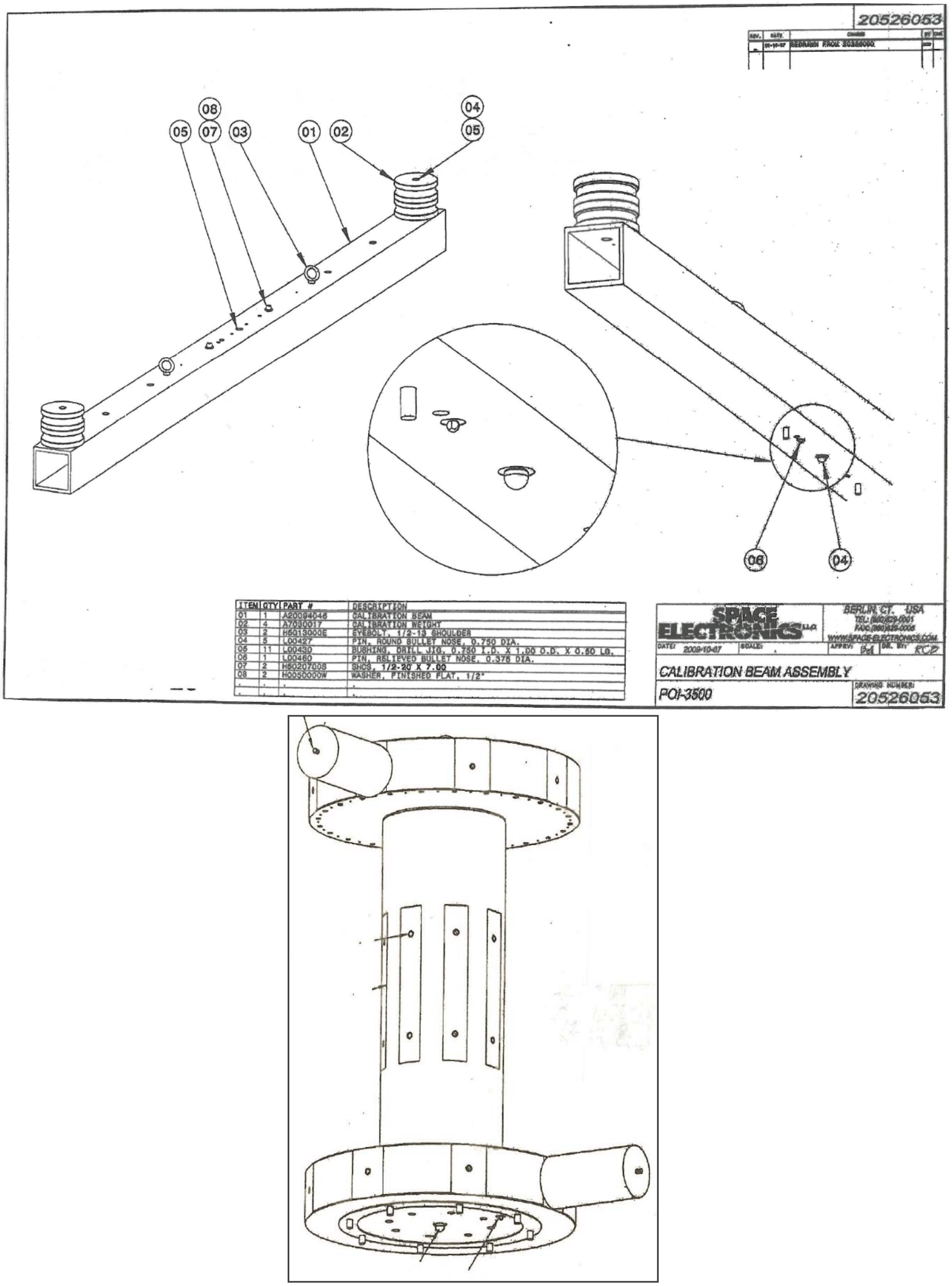
4.2.1 Perform a visual inspection of the test item and the mass properties machine. Ensure the working area is free of tools, trash, or objects that could interfere with the test or cause a safety concern.

4.2.2 Mount the test fixture and payload interface adapter to the machine. Center the fixture using a mechanical dial indicator as shown in Figure 4. Torque all bolts to the required value.

Figure 4. Fixture evaluation.

4.2.3 Verify the calibration records for all mass properties measurements instruments. It is recommended that the calibration procedure be repeated at 6 months intervals unless accuracy checks indicate that more frequent calibration is required. If the calibration record is not up to date, perform calibration runs in CG, POI, and MOI in accordance with the spin table machine operating manual using the calibration tools provided. Each machine is setup and operated differently. For more information, refer to the machine operating instructions such as those found in Boynton and Wiener[3]. Some of the calibration tools to be used for CG and POI calibration are the calibration beam assembly and the proving rotor shown in Figure 5.

4.2.4 Perform the POI Measurement. There are four major steps required to conduct the POI measurement of the payload: 1) POI calibration, 2) POI tare measurement, 3) POI calculation, 4) balance the test part. The POI measurement will be conducted in the thrust (vertical) axis only. Each measurement procedural step is described below. Further guidance is provided in Appendix B.



ITEM	QTY	PART #	DESCRIPTION
01	1	A20094046	CALIBRATION BEAM
02	4	A7030017	CALIBRATION WEIGHT
03	2	H5013000E	EYEBOLT, 1/2-13 SHOULDER
04	5	L00427	PIN, ROUND BULLET NOSE, 0.750 DIA.
05	11	L00430	BUSHING, DRILL JIG, 0.750 I.D. X 1.00 O.D. X 0.50 LG.
06	1	L00460	PIN, RELIEVED BULLET NOSE, 0.375 DIA.
07	2	H5020700S	SHCS, 1/2-20 X 7.00
08	2	H0050000W	WASHER, FINISHED FLAT, 1/2"

Figure 5. Typical calibration tools (courtesy Space Electronics, Inc).

a. POI Calibration. Perform calibration in accordance with paragraph 4.2.3 and the machine operating instructions manual.

b. POI Tare Measurement. Before making a measurement, be certain to have a test fixture which accurately supports the payload on the machine. This fixture must be designed so that the test item CG is within about 0.1 inch or less of the center of rotation of the machine. The fixture should be balanced. Fixture balance and payload CG offset greatly affect the POI measurement accuracy.

(1) Mount the test fixture and the payload interface adapter vertically to the spin balance table.

(2) Spin the machine at the desired rotational speed and in the desired direction. Ensure to spin the machine at the same speed and direction used during calibration. If the spin speed or direction changed, it would result in a measurement error. The “target speed” can be any number between 20 and 300 revolutions per minute (rpm), but generally it should be as high a speed as possible without over-ranging the machine or causing excessive windage. The WSMR machine’s optimal rpm range is 100 to 150 rpm. The signal-to-noise ratio of a balancing machine is much better at high speeds, which allows the unbalance data to be acquired quickly. When the balancing machine is operated at slow speeds (i.e., under 30 rpm), the measurement time must be increased in order to measure reliably because the small force transducer signals will be below the background noise. The deceleration / acceleration rate is usually 10 rpm/sec. Make it slower if the payload is very fragile. Once the measurement is complete, the mass properties machine will stop spinning and display/store the POI tare measurement data. The next step is to conduct the POI calculation.

c. POI Calculation.

(1) Mount the payload on the interface adapter vertically to the mass properties machine table.

(2) Spin the machine at the same speed and direction as the POI tare measurement. If the spin speed or direction changes, it would result in a measurement error. Once the measurement is complete, the balancing table stops. The computer will accumulate data, and perform the POI calculation and displays the correction weight polar plot results in terms of upper and lower forces achieved (magnitude and angle). The next step is to mount the external weight at the upper and lower planes and balance the test part.

d. Balance the Test Part.

(1) Mount the weights externally to two different locations on the payload (upper and lower planes). These locations cannot be at the same height. Correction points should be accessible without unbolting any heavy items in the payload, otherwise, each time the item is unbolted; the unbalance of the payload will change. For cylindrical objects, the ideal correction planes are usually the two ends. This is because plane separation distance is a maximum and

these surfaces are usually exposed so that correction weights can be added and /or removed without removing any cover plates.

(2) Once the correct external weights and location have been obtained, spin the machine at the same speed and direction as the POI tare measurement. If the spin speed or direction changes, it would result in a measurement error. Once the measurement is complete, the balancing table stops. The computer will accumulate data, and perform the POI calculation and provide the dynamic calculation results. The computer will display the calculated dynamic CG moment, CG offset, and POI measurement.

(3) It the test specification is met, remove the weights, mount internally and repeat the test. The process may have to be repeated until the test specification is met.

4.2.5 CG Measurement.

There are three major steps required to measure the CG of the object: 1) CG calibration, 2) CG tare measurement, 3) CG payload measurement (dynamic and static). The CG measurement will be conducted in the thrust, pitch and yaw axes. Each measurement procedural step is described below. Further guidance is provided in Appendix C.

a. CG Calibration. Perform calibration in accordance with paragraph 4.2.3 and the machine operating instructions manual.

b. CG Tare Measurement.

(1) Conduct a pretest measurement without the test fixture and the payload adapter. The pretest will be required prior to performing the CG tare measurement. The machine's mass properties computer is programmed to average moment readings at each of the quadrant positions (0°, 90°, 180° and 270°). The motor drive on the mass properties machine will automatically rotate the interface table to each of the four measurement positions, pausing briefly at each quadrant while data are taken. The computer will sequentially display messages while the machine automatically rotates to each position and takes a moment reading.

(2) Upon completion of the pretest, mount the test fixture and the payload interface adapter vertically to the mass properties machine table for the CG tare measurement. The end stops and mounting hardware (if any) should be in exactly the position they will be in when the payload is installed. If the fixture is changed or moved, then a new tare value must be established. When ready, start the machine to automatically make and record all required measurements.

c. CG Payload Measurement (Dynamic and Static). For the calculated dynamic CG moment and CG offset, the CG payload measurement can be established during the POI measurement. For the static CG measurement, the following procedure will be applied.

(1) Install the payload vertically in the fixture and the interface adapter on the spin balance machine table. Note, when mounting the test payload on the fixture, be careful not to

alter the position of any part of the fixture, or the tare readings will become invalid. The same is true if the order is reversed when taking tare readings after measuring the payload properties.

(2) The machine/interface plate will then automatically rotate and take readings at each of the four quadrants. the computer will accumulates data at each of the four quadrant angles (0°, 90°, 180°, 270°), average, and perform the CG calculation and provide the static calculation results in terms of calculated static CG moment and calculated static CG offset.

(3) Upon completion of the CG measurement, verify the results between the calculated dynamic CG measurement and static CG measurement. It should be within a 1% error.

4.2.6 Moment of Inertia Measurement.

There are four major steps required to measure the MOI of the object: 1) MOI Calibration, 2) MOI tare measurement, 3) MOI payload measurement, and 4) MOI calculation. The MOI measurement shall be conducted in three axes; thrust, pitch, and yaw. Each measurement procedural step is described below. Further guidance is provided in Appendix C.

a. MOI Calibration. Perform calibration in accordance with paragraph 4.2.3 and the machine operating instructions manual.

b. MOI Tare Measurement.

(1) Install the proper MOI fixture on the spin balance table. For the thrust axis, generally the same fixture is used for both POI and MOI, so the fixture may already be in place. The MOI tare measurement requires that the fixture be in exactly the same configuration to be used with the payload. If mounting hardware is used, it must be in place during tare measurements. For the pitch/yaw axis, install the proper MOI fixture on the spin balance table. An example of a MOI fixture is shown in Figure 6.

Figure 6. MOI test fixture (pitch/yaw axis).

(2) With the test fixture in place, perform the MOI tare measurement. The interface plate will automatically rotate to the MOI measurement position and measure the period of oscillation. When the computer finds acceptable data, the tare period is stored by the computer. The next step is to perform the MOI payload measurement.

c. MOI Payload Measurement.

(1) Mount the payload onto the fixture. Position the payload accurately in this fixture. If necessary, use a dial indicator to measure and adjust its position. The MOI measurement accuracy will be poor if the payload is not positioned accurately.

(2) The interface plate will automatically rotate to the MOI measurement position and measure the period of oscillation. When the computer finds acceptable data, the payload period is stored on the computer.

d. MOI Calculation. Upon completion of the tare and payload measurements, the computer will calculate the MOI and display the MOI static calculation results. The results should be presented in tabular form for reporting purposes. See Section 6 and Appendix C for further information.

4.3 Data Verification Procedures.

All munition mass properties measurement data should be examined for any anomalies such as those described below.

a. Calibration methods and machine maintenance records should be verified prior to test. Routine machine checks (noise levels, drift, linearity, etc.) should be performed prior to test. Examine documentation of routine maintenance activity to ensure analytical reliability.

b. Look for signs of signal termination. This is indicative of internal transducer failure in the machine.

c. Examine and document the fixtures to be used for the measurements. The effect of all the non-ideal conditions (for example, flat surfaces are not perfectly flat; round surfaces are not perfectly round; concentric surfaces are not exactly on the same center; perpendicular surfaces are not exactly perpendicular), is that the datum for the payload coordinate system can be no better than the accumulated uncertainties of the datum surfaces.

4.4 Data Analysis Procedures.

a. The Center of Gravity can be positive or negative. The operators should determine whether the positive axis agrees with the definition of axes used by the recipient of the data. A sketch showing the axes and their algebraic sign will be helpful for analytical reliability.

b. The Product of Inertia can also be positive or negative. Since this quantity is derived by multiplying the incremental masses by two different distances, the POI sign is even more prone to error than the sign of the CG data. A sketch showing the axes and their algebraic sign will be helpful for analytical reliability.

c. CG and POI must have a frame of reference. MOI needs only one reference axis. When several coordinate systems are involved axis signs and name must be clearly defined.

5. DATA REQUIRED.

The following test data are required.

a. Test equipment description.

b. Test item description, configuration, and payload.

c. Test item orientation and coordinate system identification drawings, along with any written descriptions, as applicable.

d. Data recordings to include CG locations, POI measurements (added weight values and locations on the upper and lower planes), and MOI measurement data, as required.

e. Documentary photographs of the test setup, as applicable.

6. PRESENTATION OF DATA.

The CG, POI, and MOI data are processed and presented in tabular form for reporting purposes. Example tables are shown in Appendix A.

APPENDIX A. EXAMPLE DATA FORMS.

TABLE A-1. CG CALCULATION RESULTS

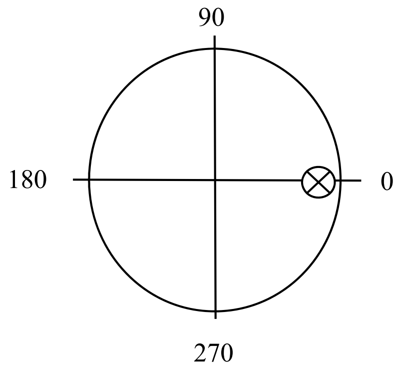
Operator:
Run Number:
Payload Identification:
Payload Serial Number:
Payload Part Number:
Payload Total Weight (lbs):
Payload Estimated CG height (in.):

CG Moment and Offset Results

Calculated Dynamic / Static CG Moment	Calculated Dynamic / Static CG Offset
X Moment (oz-in):	X Offset (in.):
Y Moment (oz-in):	Y Offset (in.):
CG Moment Magnitude (oz-in):	CG Offset Magnitude (in.):
CG Moment Angle (degree):	CG Offset Angle (degree):

Machine Status CG Offset Polar Plot

CG Offset
Magnitude (in.):
Angle (degree):



APPENDIX A. EXAMPLE DATA FORMS.

TABLE A-2. POI CALCULATION RESULTS

Operator:

Run Number:

Payload Identification:

Payload Serial Number:

Payload Part Number:

Payload Total Weight (lbs):

Target Speed (rpm):

Machine Direction:

POI Results:

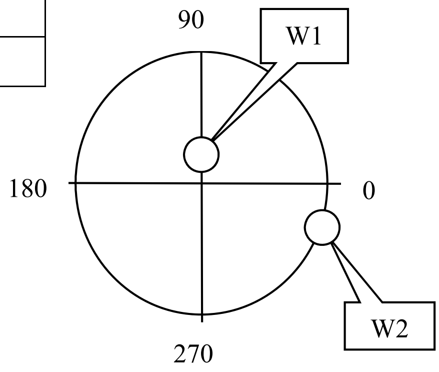
Magnitude (oz-in^2):
Angle (deg):

CG Moment and Offset Results:

Calculated Dynamic CG Moment	Calculated Dynamic CG Offset
Magnitude (oz-in):	Magnitude (in:
Angle (degree):	Angle (degree):

Correction Weights Polar Plot

Upper Correct Weight (W1)	Lower Correct Weight (W2)
Magnitude (lb):	Magnitude (lb):
Angle (degree):	Angle (degree):
Radius (in.):	Radius (in.):
Height (in.):	Height (in.):



APPENDIX A. EXAMPLE DATA FORMS.

TABLE A-3. MOI CALCULATION RESULTS

Operator:
Run Number:
Payload Identification:
Payload Serial Number:
Payload Part Number:
Payload Total Weight (lbs):
MOI Calculation Results:
MOI About Machine Center Line (slug feet^2):

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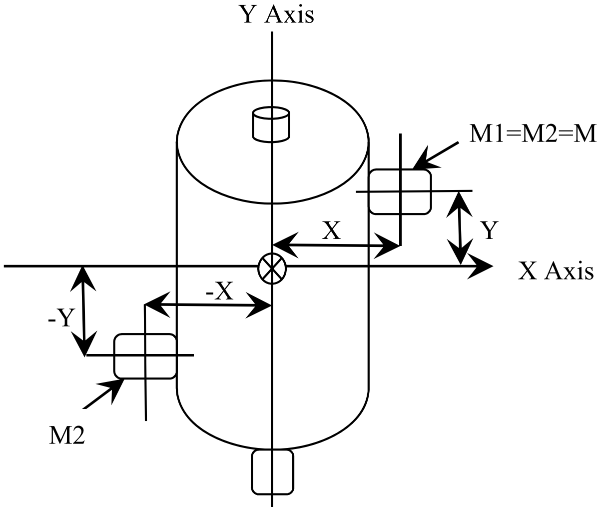
APPENDIX B. PRODUCT OF INERTIA.

B.1 PRODUCT OF INERTIA (POI).

The POI causes dynamic unbalance. To generate POI, unbalanced masses must be displaced from the CG along 2 axes (i.e., X and Y). This relationship is shown in Figure B-1.



$POI = M * X * Y$ (for any point mass in the body). Where:

POI = Product of inertia in a given (X-Y) plane for any element of mass in the object.
M = Mass of the element
X and Y = X &Y coordinates of the element

$POI\ 1 = X*Y*M1$

$$POI\ 2 = (-X)*(-Y)*M2$$
$$= X*Y*M2$$

The Product of Inertia of the object is the summation (Σ) of POI of the point masses making up the object.

$P= \Sigma\ (M * X * Y)$ is the POI of the body in the (X-Y) plane.

$POI\ Total = 2X*Y*M$

Figure B-1. POI relationships.

B.2 The POI may be positive or negative. The algebraic signs of the element coordinates must be used to get the correct sign of the POI sum. The product of inertia is not detectable by static measurement methods. The payload must rotate or oscillate to detect POI. The center of gravity offset is also detectable when measuring POI.

B.3 BALANCING MACHINE THEORY.

When the test object spins, there are two forces acting through the CG of the object; gravity forces act downward and centrifugal forces act inward. The magnitude of the downward gravity force is equal to the weight of the object in pounds (M1). The magnitude of the horizontal centrifugal force is:

$$\text{Centrifugal Force (lbs) } F1 = M1 * R1 * \omega^2$$

APPENDIX B. PRODUCT OF INERTIA.

Where:

M1 = mass of unbalance in slugs
R = radius of CG in feet
ω = rotation speed in radians per second

Converting the mass into weight and the speed into rpm gives:

$$\text{Centrifugal Force (lbs) } F1 = W1 * R1 * (rpm)^2 / 35207$$

Where:

W1 = weight of unbalance mass in lbs
R1 = radius of CG of unbalance in inches
rpm = speed of rotation in rpm
35207 = constant to transform units

B.4 POI causes interaction between pitch, yaw, and roll controls. POI is not detectable by static measurement methods. In fact, static balancing may worsen POI. The part must rotate or oscillate in order to detect POI. The static balance POI and dynamic POI comparison is described below in Figure B-2.

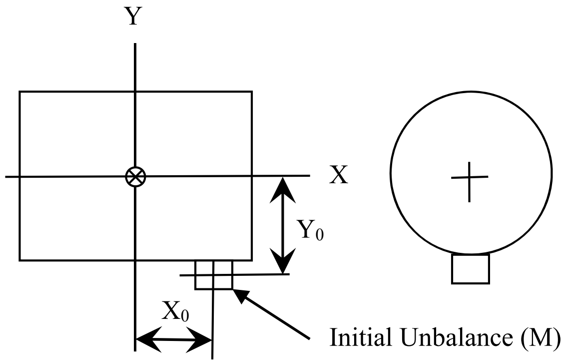
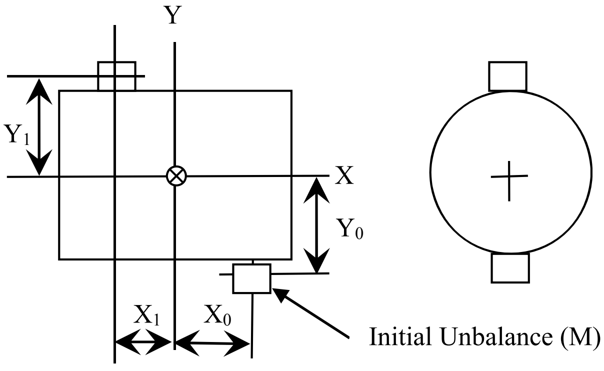
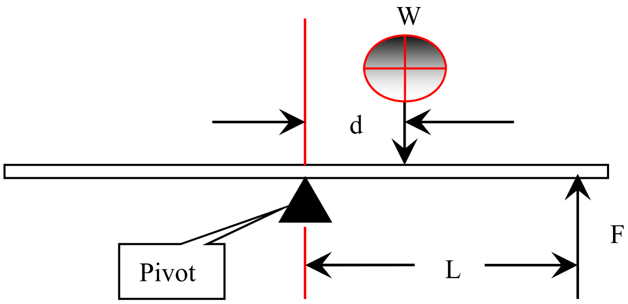
	Case 1: Static POI = $M * Y_0$ Dynamic POI = $M * Y_0 * X_0$
	Case 2: Static POI = $M * Y_0$ Dynamic POI = $M * Y_0 * X_0 + M * Y_1 * X_1$

Figure B-2. Comparison of static and dynamic POI.

APPENDIX C. CENTER OF GRAVITY.

C.1 The center of gravity (CG) is the center of an object's weight distribution, where the force of gravity can be considered to act. It is the point where the object is in perfect balance, no matter how it is turned or rotated around that point.

C.2 The CG offset moment about the pivot is measured and divided by the test item weight to obtain the CG offset. See Figure C-1.



Offset Moment = W*d
Restoring Moment = F*L
CG Offset = d = F*L/W

Any displacement of the CG from the pivot results in an overturning moment which can be sensed to determine the CG location with respect to the pivot.

Figure C-1. CG relationships.

C.3 The moment should be taken about a convenient datum to minimize calculation of unknowns or to avoid calculating quantities which are not needed.

C.4 To calculate the static center of gravity of an object follow these steps.

a. Measure the weight of the object. When calculating the center of gravity, the first thing to do is to find the weight of the object.

b. Choose a datum. The datum is an arbitrary starting point placed on one end of the payload.

c. Multiply each object's distance from the datum by its weight to find its moment. This gives you the moment for each object.

d. Add up the moments. Simply do the math.

e. Divide the total moment by the total weight to arrive at the static CG.

C.5 The center of gravity coordinates can be positive or negative. The operator should determine whether his positive axis agrees with the definition of axes used by the recipient of the data. A sketch which clearly shows the axes and their algebraic signs is recommended.

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APPENDIX D. MOMENT OF INERTIA.

D.1 The Moment of Inertia of an object is the summation of the MOI of each point mass making up the object. MOI must be referenced to a rotational axis and is dependent on mass distribution. The MOI of each element is

$$MOI = \Sigma Mr^2.$$

Where:

MOI = Moment of Inertia
M = mass of the object
r = is the distance from the pivot point to the centre of mass of the object

D.2 Radius of Gyration. For any object there exists a radius, called the radius of gyration (K), at which all the mass is considered concentrated for purposes of MOI calculations. See Figure D-1. In the example R=K. For any object, K equals the square root of MOI/M.

$$MOI = MK^2 \text{ and } K = \sqrt{MOI/M}$$

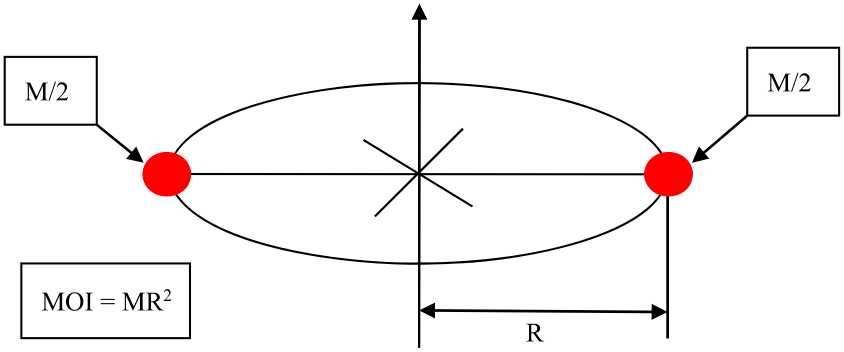
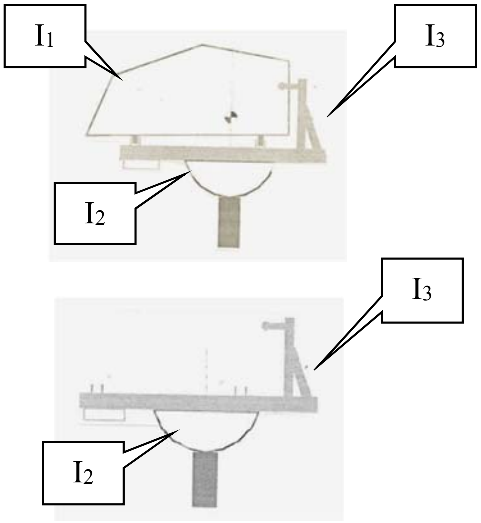


Figure D-1. Radius of gyration.

D.3 The Torsion Pendulum method is the method used in most commercial mass properties machines. This method suspends or supports the payload on a torsion wire or rod. The payload is then rotated through a small angle, causing a torque to be applied to the payload. When released, the payload will oscillate; the period of oscillation squared is directly related to the rotating MOI. MOI is always measured relative to the center of oscillation of the torsional pendulum. If the payload is mounted so its CG is directly over the center of oscillation, the MOI about CG will equal the measured CG. If there is a CG offset, the measurement will be larger than the MOI about the CG by the amount MR^2, where M is the payload mass and R is the CG offset.

D.4 MOI measurement is a two-step process of measuring the machine/fixture tare, mounting the payload and measuring again. Their periods of oscillation are entered in the equations shown in Figure D-2 to calculate the net payload MOI.



Payload Measurement

Eq. 1 MOI $= I_1 + I_2 + I_3 = (KT_1)^2$
I_1 = MOI of Control Surface
I_2 = MOI of Machine Motor
I_3 = MOI of Fixture

Tare Measurement

Eq. 2 MOI $= I_2 + I_3 = (KT_2)^2$

Subtracting Eq 2 from Eq 1
Eq. 1 MOI $= I_1 + I_2 + I_3 = (KT_1)^2$
Eq. 2 MOI $= I_2 + I_3 = (KT_2)^2$
Net MOI $= I_1 = K^2(T_1 - T_2)^2$

Figure D-2. MOI measurement equations.

D.5 MOMENT OF INERTIA MEASUREMENT ERROR SOURCES.

a. Gravity Pendulum. If the MOI measuring machine axis of oscillation is not vertical and if there is a CG offset, the payload will act as a gravity pendulum producing measurement errors. To avoid the problem, the machine should be accurately leveled and every attempt should be made to mount the payload so its nominal CG location is as close to the axis of oscillation as possible.

b. Payload Tilt. If a tall homogeneous cylindrical payload is mounted so its CG is centered, one would expected the measured MOI to be $I = MK^2$. However, if the cylinder is tilted about its CG, even slightly, a significant error can be introduced. The upper and lower portions of the cylinders can be treated as separate independent objects, each with the CG offset by an amount (d). The total error will be approximately $M*d^2$ just as though the entire payload were offset by (d). To avoid this problem, tall cylindrical payloads should be centered at two elevations using a Tilt/Translation Table or other means of correcting the tilt. If the CG is offset, it can be measured and corrected.

APPENDIX D. MOMENT OF INERTIA.

c. Excessive Center of Gravity Offset. If the MOI about the CG of a payload (I_o) is desired but the payload is mounted with its CG significantly offset from the axis of oscillation, the gross measurement ($I_g = I_o+Md^2+I_t$) may be large compared to the net payload MOI even if the tare is small. The corrected MOI will have an error proportional to the gross measurement. The error in I_o will be 0.1%*B, where B= I_g/I_o. To avoid this problem as well as some others, the payload should always be mounted so the CG is near the axis of oscillation.

d. Windage Errors. Windage errors are due to air currents around the MOI machine. They are most commonly the result of HVAC system operation. The machine and payload should be shielded from these air currents and, if necessary, the HVAC system shut off during measurement. Large control surfaces with low mass are most susceptible to windage errors.

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APPENDIX E. GLOSSARY.

ACCURACY - Accuracy is defined as the closeness with which a measurement agrees with the standard. Accuracy is usually specified as a tolerance on a measurement where the tolerance is the amount of uncertainty in the stated value. Accuracy data may be graphically displayed (calibration, correction, or error curve). Accuracy must be defined over a given range.

CENTER OF GRAVITY LOCATION - The balance point of an object. The point through which a force will cause pure translation. The center of gravity (CG) is the center of an object's weight distribution, where the force of gravity can be considered to act. It is the point where the object is in perfect balance, no matter how it is turned or rotated around that point.

CENTER OF GRAVITY OFFSET - CG offset moment is measured and divided by part weight to determine CG offset.

COORDINATION SYSTEMS - GLOBAL or overall aircraft system for all aircraft the origin is typically forward of the nose with +X aft.

COMPONENT COORDINATE SYSTEM - For aircraft typically a well defined ‘Station’ must be on the part and defined by close tolerances.

MUNITION MASS PROPERTIES MEASUREMENT MACHINE - The system on which all munition mass properties measurement procedures are made.

ERROR - Error is the KNOWN difference between a measurement and the true value. In a calibration procedure, a standard is measured and the error is the difference between the indicated measurement value and the standard value. Since the error is known, it can be corrected or compensated for. Some specific types of error are discussed below.

a. Linearity errors - where the (classical) sensitivity varies with the magnitude of the measured quantity and not in accordance with their mathematical relationship. This applies to non-linear relationships as well as linear. Flow, for example, is often measured by sensing a pressure drop across a restriction. The relationship is that the pressure varies as the square of the flow rate. Linearity error would still be an expression of the error between the true flow and the theoretical, (non-linear) relationship. Applied to CG measurement, this quantity is usually stated as a percent of measurement. Simply stated, this means that the measurement is more uncertain the larger the CG offset from the reference point on the measuring machine. In some cases this may be compensated for.

b. Hysteresis error - the difference in two measurements of the same quantity when the measurement is approached from opposite directions. In some measurement situations, a good operator can eliminate or minimize hysteresis error. This cannot usually be fully compensated for. Best approach is to always approach the measurement from the same direction to improve repeatability, if not accuracy.

APPENDIX E. GLOSSARY.

c. Thermal errors are caused when the temperature either varies during a measurement sequence or varies from the temperature at which the machine was calibrated. Errors of the second type can be compensated but short term variations during measurement cannot be tolerated for accurate results.

UNCERTAINTY - Uncertainty is the most troublesome quantity in any measurement. It is an accumulation of the unknowns. Even our best measurement standards introduce uncertainty since we have no means of duplicating and confirming these values identically every time. The farther removed we are from the primary standards, the greater the uncertainty introduced into a given measurement. Likewise, the more terms required to define a measurement the more uncertainties are introduced, and finally, the larger the mathematical effect of a given term in a measurement the greater the uncertainty (i.e., quantities raised to the third power in defining a measurement have a greater effect than those which have a linear, first power, relationship).

RESOLUTION - Resolution is the size of the smallest increment which can be shown on the measurement display. On a digital display, it is the value of the least significant digit. On an analog display it is the smallest display change detectable by a "qualified" operator.

SENSITIVITY - The classical definition of sensitivity is the ratio between the change in measurement to the change in measured quantity. It may also be expressed as a (dimensional) gain. This is most clearly applied to dimensional measurements, or analog displays; i.e., a typical micrometer indicator with a 0.5 inch diameter barrel moves one full turn, or 1.57 inches when the dimension being measured changes by 0.025 inches. This sensitivity would be 1.57/0.025 or 62.8 inches per inch (gain = 62.8). The sensitivity of an analog voltmeter would be stated as volts per inch of pointer travel. Sensitivity today is more commonly used to describe what was formerly called responsiveness. This is the smallest change in the measured quantity which consistently causes the output of the measuring machine to change. It is largely a function of friction in mechanical systems. In some systems, the resolution of the digital display is the limiting factor since it is often selected to be compatible with the transducer limitations.

REPEATABILITY - Repeatability is the degree to which a machine duplicates its measurement for the same input change. It is an overall measure of the quality of the measurement. Non-repeatability may be represented as the +/- % tolerance for an instrument. Repeatability is often the most important characteristic where small changes are being measured.

PRECISION - The term precision is one of the least useful terms in the measurement vocabulary. It is often not a valid measure of anything. The classical definition of precision is similar to the definition of resolution, that is, the number of significant digits to which a measurement may be read by a qualified operator. This definition is abused when the measurement system includes calculations or digital displays with high resolution where, for example, the average of several 2 decimal place readings is calculated and displayed to 6 decimal places. There is an implied degree of accuracy in a 6 place display which is not at all valid.

APPENDIX E. GLOSSARY.

FRAME OF REFERENCE - Two different vehicle frames of reference: The body frame, defined by the structure of the missile and the inertial frame, defined by the mass properties of the vehicle.

a. The body frame is a reference system which is related to the physical structure of the vehicle. This frame is easy to define for a perfect ideal vehicle shape, but may be hard to locate on a real vehicle, because of loose manufacturing tolerances and other practical problems.

b. The inertial frame is a reference system defined by the principal axes of the vehicle. This can be crudely calculated, but it is necessary to make measurements of the real vehicle to accurately determine the location of this inertial frame related to the body frame. Measurements are made on a mass properties machine which determines CG location, moment of inertia, and product of inertia. These measurements define the inertial frame relative to the body frame within the tolerance limitations of both the structure and the measuring machines.

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APPENDIX F. ABBREVIATIONS.

B	ratio of gross measurement MOI to the MOI at the CG
CG	center of gravity
cm	centimeter
d	center of gravity offset
deg	degree
DTIC	Defense Technical Information Center
F	force
HVAC	heating, ventilation, and air conditioning
I	moment of inertia
IAW	in accordance with
in.	inch
lbs	pounds
K	calibration constant
kg	kilogram
L	distance
M	mass of the object
mm	millimeter
MOI	moment of inertia
oz-in	ounce - inches
POI	product of inertia
r	the distance from the pivot point to the centre of mass of the object
R	radius of center of gravity
rpm	revolutions per minute
SAWE	Society of Allied Weight Engineers
TOP	Test Operations Procedure
t_p	part (gross) period of oscillation
t_t	tare period of oscillation

APPENDIX F. ABBREVIATIONS.

ω	rotation speed in radians per second
W	weight
WSMR	U. S. Army White Sands Missile Range

APPENDIX G. REFERENCES.

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2. Wiener, Kurt, Kennedy, Paul, Otlowski, Daniel, and Rathburn, Brandon (2008) Space Electronics, Inc., SAWE Paper No. 3460, “Using a Two Plane Spin Balance Instrument to Balance A Satellite Rotor About Its Own Bearings”.

3. Boynton, Richard and Wiener, Kurt (1989) Space Electronics, Inc., “Operating Instructions Manual Mass Properties Instrument Model POI-3500-BL.

For information only (related publications).

a. Boynton, Richard and Wiener, Kurt (1988) Space Electronics, Inc., SAWE paper No. 1827, “A New High Accuracy Instrument for Measuring Moment of Inertia and Center of Gravity”.

b. Boynton, Richard and Wiener, Kurt (1988) Space Electronics, Inc., SAWE paper No. 2444, “Missile Mass Properties Measurement Handbook”.

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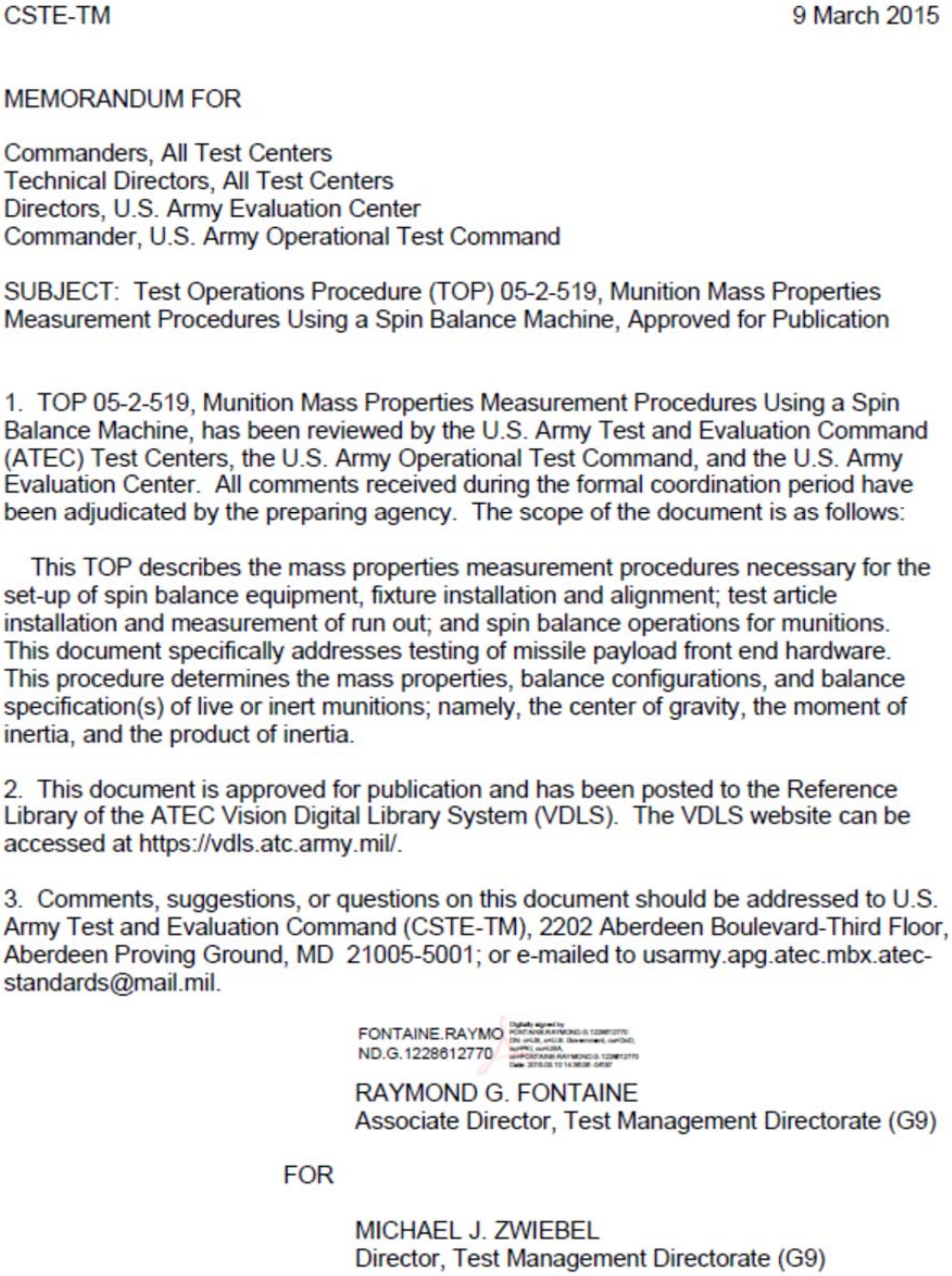
APPENDIX H. APPROVAL AUTHORITY.



CSTE-TM 9 March 2015

MEMORANDUM FOR

Commanders, All Test Centers
Technical Directors, All Test Centers
Directors, U.S. Army Evaluation Center
Commander, U.S. Army Operational Test Command

SUBJECT: Test Operations Procedure (TOP) 05-2-519, Munition Mass Properties Measurement Procedures Using a Spin Balance Machine, Approved for Publication

1. TOP 05-2-519, Munition Mass Properties Measurement Procedures Using a Spin Balance Machine, has been reviewed by the U.S. Army Test and Evaluation Command (ATEC) Test Centers, the U.S. Army Operational Test Command, and the U.S. Army Evaluation Center. All comments received during the formal coordination period have been adjudicated by the preparing agency. The scope of the document is as follows:

This TOP describes the mass properties measurement procedures necessary for the set-up of spin balance equipment, fixture installation and alignment; test article installation and measurement of run out; and spin balance operations for munitions. This document specifically addresses testing of missile payload front end hardware. This procedure determines the mass properties, balance configurations, and balance specification(s) of live or inert munitions; namely, the center of gravity, the moment of inertia, and the product of inertia.

2. This document is approved for publication and has been posted to the Reference Library of the ATEC Vision Digital Library System (VDLS). The VDLS website can be accessed at https://vdls.atc.army.mil/.

3. Comments, suggestions, or questions on this document should be addressed to U.S. Army Test and Evaluation Command (CSTE-TM), 2202 Aberdeen Boulevard-Third Floor, Aberdeen Proving Ground, MD 21005-5001; or e-mailed to usarmy.apg.atec.mbx.atec-standards@mail.mil.

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Forward comments, recommended changes, or any pertinent data which may be of use in improving this publication to the following address: Range Infrastructure Division (CSTE-TM), US Army Test and Evaluation Command, 2202 Aberdeen Boulevard, Aberdeen Proving Ground, Maryland 21005-5001. Technical information may be obtained from the preparing activity: U.S. Army White Sands Missile Range, TEDT-WSV, White Sands Missile Range, NM 88002-5178. Additional copies can be requested through the following website: http://itops.dtc.army.mil/RequestForDocuments.aspx, or through the Defense Technical Information Center, 8725 John J. Kingman Rd., STE 0944, Fort Belvoir, VA 22060-6218. This document is identified by the accession number (AD No.) printed on the first page.