

## Space Electronics' Mass Properties Laboratory Measurement Services



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## Measuring Mass Properties

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Whether it's a spacecraft travelling to Mars, a golfer driving the green, or an endoscopy camera easily swallowed by the patient, proper performance—during the spacecraft's cruise and entry flight phases, the golf club's contact and follow-through, or the PillCam® capsule's passage through the intestinal tract—requires that the system's mass properties fall within specific design tolerances. Design engineers need to know that calculations of dynamic motion are made using mass properties that represent the true physical characteristics of the system.



Space Electronics measured the mass properties of the Massachusetts Institute of Technology's Odyssey AUV in our Mass Properties Measurement Laboratory

### A History of Mass Properties Measurement Services

Since 1975, Space Electronics has provided our customers with contract mass properties measurement services as an alternative to the purchase of their own measurement instruments. These services were provided in a dedicated 300 square foot laboratory located at our Berlin,

Connecticut headquarters. Owing to an ever increasing demand, we have long since outgrown that space. So in the spring of 2016 we embarked upon a major expansion project, increasing our lab's size sevenfold and assembling an expanded suite of dedicated instruments that allows us to fully characterize the static and dynamic mass properties of everything from a computer hard drive armature weighing a few grams up to an entire spacecraft weighing as much as 6,500 lb. This new state-of-the-art facility is helping us better serve our customers, providing faster turnaround times with greater efficiency, all at lower prices than before.

### Why Measure Mass Properties?

In spite of the excellent computer models that are available, the only way to assure that a system's mass properties—its mass, center of gravity (CG) location, moments of inertia (MOI), products of inertia (POI)—are correct is to measure them at various stages of system development. Models of the inertia tensor, no matter how sophisticated, are still just theoretical approximations.

A computer model rarely includes the epoxy, piping, or wiring contained in an aerospace system. The model doesn't recognize that the density of foam and composite materials varies in complex and sometimes unpredictable ways. It often fails to account for variations in skin thickness. These omissions and variations can easily account for 30% of the system's moment of inertia and can result in a CG offset that is beyond correction.

So what, then, should be measured? And when should measurements be made? What measurement accuracy is required? What measurement equipment is available to you?

The short answer is, measure early and measure often. The full answer is that a mass properties measurement plan must be developed in parallel and coordinated with your design and testing plans.

## Mass Properties Measurement = Risk Mitigation

Why have customers come to rely on Space Electronics for their measurement services needs?

### Quality Assurance

Many programs now insist on mass properties verification as a final risk mitigation measure. As the world leader in the field, Space Electronics' certification is universally recognized as the highest standard available.

### High Performance

Without accurate measurement or balancing, many systems fail to meet their performance parameters. Space Electronics is there when your system has to work first time, every time.

### Rapid Results

Measurement services can often be completed within just a few days of your initial request.

### Economy

When a project budget might not stretch to the purchase of a dedicated mass properties measurement instrument, Space Electronics' measurement services offer an affordable alternative.

## Our In-House Laboratory

So if your project doesn't justify the purchase of a new instrument, let us perform the measurement for you—at our facility or yours. Many of our dedicated lab instruments are available for setup

at your facility in support of your test program. Service offerings include:

- ♦ Weight measurement
- ♦ Center of gravity measurement
- ♦ Moment of inertia measurement
- ♦ Product of inertia measurement
- ♦ Dynamic unbalance measurement
- ♦ Dynamic balancing
- ♦ Static unbalance measurement
- ♦ Static balancing
- ♦ Gimbale assembly unbalance measurement
- ♦ Gimbale assembly balancing
- ♦ Turbine blade moment weight measurement (blade balance)
- ♦ Turbine blade distribution optimization

## Our New and Expanded Facility

Our 2,300 square foot climate controlled mass properties measurement laboratory also serves as a customer showroom and a classroom for our regular mass properties measurement and gimbal balancing seminars (information at [www.Space-Electronics.com/Services/Seminars](http://www.Space-Electronics.com/Services/Seminars)). Customers can see our instruments in an operationally representative setting, and students put their newly gained knowledge of mass properties fundamentals to practical use by setting up and running measurements on a range of Space Electronics weight platforms, KSR Series CG and MOI measurement instruments, POI Series spin balancing machines, and GM Series gimbal balancing machines.

Space Electronics' loading dock and handling equipment can accommodate virtually any test item that can be transported in a standard semi-trailer. Your test articles are stored in a secure location and handled in strict accordance with all local, state, and federal safety regulations and US Department of State regulations for the handling of items on the US Munitions List.

Space Electronics' mass properties measurement laboratory includes ESD-safe workbenches for the

proper handling of test articles that are sensitive to electrostatic discharge.

## Arranging Measurement Services

Our engineering team will work with you to build a test program that fully meets your measurement needs—schedule, accuracy, analysis, and reporting. Your engineers and technicians are welcome to participate in the testing, or you can hand the project over to our team of mass properties experts.

## Measurement Instruments

Space Electronics’ mass properties measurement laboratory is equipped with a wide range of instruments—typically over 20 machines at any given time. The lab is currently equipped with the following suite of instruments:

### Weight

Our lab has three super-high-resolution weight platforms. Space Electronics’ **YST Series** uses state-of-the-art electromagnetic force compensation technology to achieve a resolution at least an order of magnitude finer than typical load cell platforms. Higher resolution means wider useable range of measurement. These platforms are well suited for measuring incremental weight such as the weight of fuel or ballast added to a

of Standards and Technology (NIST). Instruments are corrected to read the weight equivalent of a certified mass at standard gravity.

Model	Capacity (lb)	Resolution (lb)	Table (in)
YST2FR	2	$1 \times 10^{-4}$	8 × 9
YST13FR	13	$9 \times 10^{-4}$	12 × 16
YST1000FR	1,000	0.07	36 × 36

Table 1 High-Resolution Weight Platforms (Gallery Photo No.1)

## Weight and Center of Gravity

### High-Volume Production Environment

Our lab is equipped with several instruments designed for the accurate measurement of center of gravity. Weight and CG can be measured simultaneously using one of our **SE90168 Series** instruments. The SE90168 Series of weight and CG instruments is designed for the rapid measurement of weight and CG with the level of accuracy associated with a high-volume production environment. They use the multi-point weighing method to simultaneously measure both weight and two coordinates of center of gravity. The third CG coordinate is obtained by simply rotating the test item 90°. The instruments listed in **Table 2** can handle test articles weighing from 2 to 1,100 pounds.

Model	Capacity (lb)	CG Accuracy (in)	Weight Uncertainty	Weight Sensitivity (lb)	Table (in)
SE90168-60	2 - 60	0.04	0.3%	0.01	18 × 18 Square
SE90168-300	50 - 300	0.06	0.3%	0.06	30% × 35½ Triangle
SE90168-1100	100 - 1,100	0.08	0.3%	0.22	60 × 48 Rectangle

Table 2 Combined Weight and CG Platforms (Gallery Photo No. 3)

missile or other test object. Our current complement of scales, shown in **Table 1**, can handle test items weighing anywhere from a few grams to 1,000 lb.

All of our weight platforms are calibrated by comparing the instrument measurement with a standard mass traceable to the National Institute

### Ultra-High Sensitivity

Space Electronics’ **SE199 and SE300** microbalances (**Table 3**) measure the weight and precisely locate the CG of very small test objects. They are particularly well suited to locating the axial position of the center of gravity of bullets and other small projectiles. With proper fixturing,

the CG of computer hard drive heads, gyro rotors, small turbine buckets, and other small objects can also be determined accurately. The CG of a typical small caliber bullet can be determined to within  $\pm 0.002$  inches. These instruments use the active moment transducer concept developed by Space Electronics to achieve a sensitivity 100 times greater than is usually possible with instruments of this type.

Model	Capacity (lb)	Full-Scale Moment (lb-in)	Moment Sensitivity (lb-in)	Weight Sensitivity (lb)
SE199	0.22	0.04	$1.7 \times 10^{-6}$	$1.1 \times 10^{-5}$
SE300	1.1	0.22	$9.0 \times 10^{-6}$	$1.1 \times 10^{-5}$

Table 3 Microbalances (Gallery Photos No. 2 & 7)

capable of measuring test articles with MOIs as low as  $0.002 \text{ lb-in}^2$  up to items weighing 6,500 lb.

*MOI Only*

Our lab includes a **Model XR10 (Table 5)**, designed to quickly measure MOI of test articles under 10 pounds with high accuracy (0.25%). Space Electronics' XR Series of MOI instruments employs our patented inverted torsion flexure technique to

Model	Capacity (lb)	Full-Scale Moment (lb-in)	Moment Sensitivity (lb-in)
SE8913C	33	10	0.015

Table 4 Dual Axis Center of Gravity Instrument (Gallery Photo No. 4)

Model	Capacity (lb)	Overturning Moment (lb-in)	Max. CG Height	Tare MOI (lb-in <sup>2</sup> )	Accuracy (lb-in <sup>2</sup> )
XR10	10	15	10 lb @ 10 in	0.014	$0.25\% + 1 \times 10^{-5}$

Table 5 XR Series MOI Instrument (Gallery Photo No. 9)

**Center of Gravity**

In addition to our combination weight and CG instruments, Space Electronics' measurement lab includes a **Model SE8913C** dual axis center of gravity instrument for high accuracy measurement of the CG location of objects weighing up to 33 pounds (**Table 4**). This is achieved by measuring the unbalance moment due to the test item's CG displacement from the center of the rotary table.

support the weight of the test article by a torsion rod, resulting in negligible damping in the restraint system.

Space Electronics has developed a novel method for quickly measuring the MOI of aircraft control surfaces. Our lab is equipped with this latest addition to our large catalog of mass properties measurement systems. Our **Control Surface MOI Instrument (Table 6)** suspends the test article in

Model	Capacity (lb)	Span (in)	Max. Chord (in)	Hinge Point Spacing (in)	Accuracy
Control Surface MOI	50 - 500	54 - 288	72	48 - 112	3%

Table 6 Aircraft Control Surface MOI Instrument (Gallery Photo No. 6)

**Moment of Inertia**

Space Electronics is the world leader in MOI measurement. We manufacture 60 different instruments ranging in accuracy from 0.5% to an extremely high 0.05%. The current complement of MOI instruments in our measurement lab is

a horizontal orientation to create a gravity-driven pendulum. The pendulum oscillation is initiated manually. The frequency of oscillation and damping coefficient are measured, and forces are recorded using a high-accuracy force transducer to measure control surface center of gravity.

Inertia is derived from the oscillation period, the mass of the control surface, and CG offset distance. Measured MOI is accurate to  $\pm 3\%$ .

### Center of Gravity and Moment of Inertia

The backbone of Space Electronics' family of mass properties measurement systems is the **KSR Series** of CG and MOI instruments. KSRs are the most accurate instruments in the world for the measurement of center of gravity and moment of inertia. They are ideal for determining the mass properties of satellites, rockets, missiles, and other ballistic systems.

For rapid measurement of weight, CG, and MOI—all in under a minute—our lab features the **MP6500** instrument (**Table 8**). Using the multipoint weight method, the MP6500 simultaneously measures weight and CG. This instrument is well suited to a production environment and to the measurement of a limited range of test items.

### Dynamic Balancing

Space Electronics builds two types of instruments for the high-accuracy spin balancing of rotating systems: the POI Series of vertical two-plane spin

Model	Capacity (lb)	Full-Scale Moment (lb-in)	Overturning Moment (lb-in)	Max. CG Height	Tare MOI (lb-in <sup>2</sup> )	CG Accuracy (lb-in)	MOI Accuracy (lb-in <sup>2</sup> )
KSR330-60	3 - 120	60	600	120 lb @ 24 in	130	0.1% + 0.003	0.1% + 0.03
KSR1320-150	50 - 800	150	4,000	500 lb @ 24 in	350	0.1% + 0.01	0.1% + 0.2
KSR1320-1500	100 - 1,320	1,500	4,000	1,000 lb @ 48 in	350	0.1% + 0.06	0.1% + 0.2
KSR6000	200 - 6,000	5,000	25,000	3,000 lb @ 100 in	7,500	0.1% + 0.3	0.1% + 2

Table 7 KSR Series CG and MOI Instruments (Gallery Photos No. 5, 8 & 12)

Model	Capacity (lb)	Max. CG Offset (in)	Tare MOI (lb-in <sup>2</sup> )	Weight Accuracy (lb)	CG Accuracy	MOI Accuracy (lb-in <sup>2</sup> )
MP6500	200 - 6,500	4	N/A	10	0.1 in @ 6,500 lb	0.25% + 2.5

Table 8 MP6500 Weight, CG, and MOI Instrument (Gallery Photo No. 13)

The KSR Series features a spherical gas bearing that supports a rotary table and acts as a pivot axis for measuring unbalance moments due to the displacement of the test item CG relative to the central axis of the bearing. MOI is determined by clamping the lower end of a torsion rod attached to the gas bearing, thus converting the instrument to an inverted torsion pendulum.

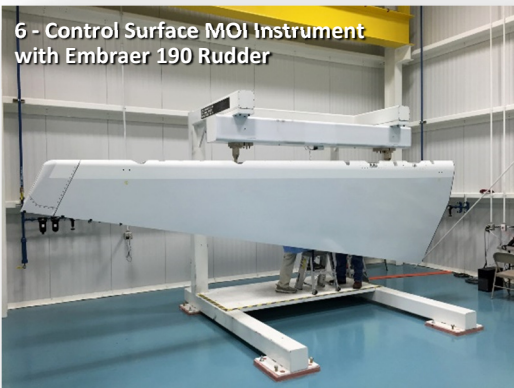
The unparalleled accuracy of our KSR instruments provides—CG measurement to 25 microns and MOI measurement to 0.1%. They accommodate the largest payload range of any MOI instrument anywhere. The same instrument can measure payloads weighting just 4% of the machine's capacity. Space Electronics' measurement lab currently includes the KSR instruments in **Table 7**.

balance machines and the FBD Series of force balance dynamometers.

### Full Mass Properties

Our POI Series are the only instruments in the world that measure all these mass properties: CG, MOI, product of inertia (POI), and dynamic unbalance. By eliminating the need for multiple machines, the time required to make measurements is reduced, as are the risks associated with handling the test articles. Alignment errors that occur during setup on different machines are eliminated.

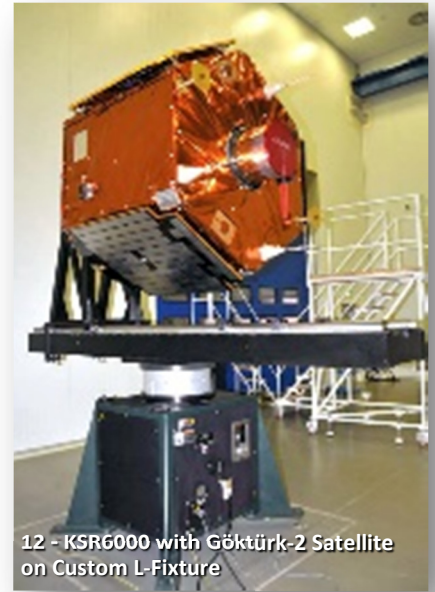
As with our KSR Series design, the test item is mounted on a spherical gas bearing that is suspended flexurally from the machine base.



10 – MW904 with Jet Engine Fan Blade



11 - MW900  
Moment Weight  
Scale with  
Jet Engine  
Turbine Blade



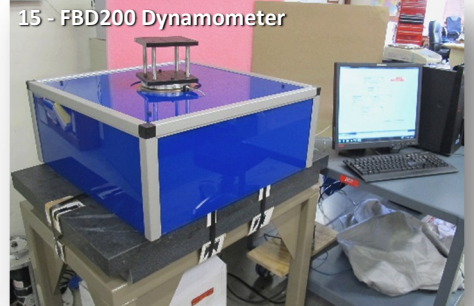
12 - KSR6000 with Gökürk-2 Satellite  
on Custom L-Fixture



13 - MP6500 Weight, CG & MOI Instrument



14 - GM904S Gimbal Balance  
Machine with AIM-7 Sparrow  
Missile Seeker



15 - FBD200 Dynamometer



16 - InTensino+ CG & Inertia Tensor  
Instrument with Automobile Engine



17 - POI1000 Spin Balance Instrument  
with MK12-A Reentry Vehicle

A tube extends from this bearing to a flexure-mounted lower gas bearing. Two independent force cells measure the reaction forces on both the upper and lower bearings due to an unbalance in the object being measured.

The only instrument to measure both dynamic unbalance and moment of inertia on a single machine, the POI is also the only instrument with true static CG measurement capability, which eliminates errors due to air turbulence on irregularly shaped objects such as spacecraft.

Our measurement services lab currently houses instruments for dynamic balancing of test articles ranging from 1 to 1,000 lb (**Table 9**).

Measurement sensitivity of the FBD system is equivalent to the POI Series, which features the best accuracy in the world for low spin speed applications. Our lab is presently equipped with the 200-lb capacity Model FBD200 (**Table 9**).

### Center of Gravity and Inertia Tensor

In partnership with SMARTMechanical, a Polytechnic University of Milan spinoff company, Space Electronics has developed a brand new method of measuring the full mass properties of a system in a single setup. The **InTenso+** product line incorporates a non-linear pendulum. The payload is mounted to a platform suspended from cables. Weight is measured, and then the payload

Model	Capacity (lb)	Spin Rate (RPM)	Max. Loading Moment (lb-in)	Max. CG Height	MOI Accuracy (lb-in <sup>2</sup> )	Full-Scale Dynamic Unbalance (lb-in <sup>2</sup> )	Minimum Achievable Readout (lb-in <sup>2</sup> )	Unbalance Reduction Ratio
POI50	1 - 50	50 - 800	200	30 lb @ 40 in @ 200 RPM	0.1% + 0.1	1,024 @ 50 RPM 256 @ 100 RPM 64 @ 200 RPM 16 @ 400 RPM 4 @ 800 RPM	0.07 @ 50 RPM 0.01 @ 100 RPM 0.003 @ 200 RPM 0.0007 @ 400 RPM 0.0005 @ 800 RPM	95%
POI1000	10 - 1,000	30 - 300	5,000	750 lb @ 53 in @ 50 RPM	0.1% + 0.75	19,200 @ 50 RPM 4,800 @ 100 RPM 1,200 @ 200 RPM 533 @ 300 RPM	0.5 @ 50 RPM 0.1 @ 100 RPM 0.025 @ 200 RPM 0.015 @ 300 RPM	95%
FBD200	200	50 - 200	–	–	–	–	0.07 @ 50 RPM 0.01 @ 100 RPM 0.003 @ 200 RPM	85%

Table 9 Dynamic Balancing Instruments (Gallery Photos No. 15 & 17)

### Force Balance Dynamometer

The **Force Balance Dynamometer (FBD)** is a new series of spin balance instruments that measures both static unbalance due to CG offset and dynamic unbalance due to product of inertia. This instrument has the ability to spin-balance a payload in a vacuum environment, thereby providing a solution to eliminate errors due to aerodynamic forces. It is low profile, is permanently calibrated, has unmatched sensitivity, and can be used over a wide temperature range.

is sent into a gentle random oscillation. The non-linear vibration of the payload is recorded, together with the forces acting on it.

A mathematical model derives the full mass properties of the body from the collected data—center of gravity location in three axes as well as the full inertia tensor: moment of inertia in three axes and product of inertia in three planes. The advantage of the InTenso+ system resides in its ease of use. The payload is only mounted in one configuration and all the mass properties are measured in that orientation, making it ideal for measuring the inertia properties of a wide range

of rigid mechanical bodies—from small satellites to automobile engines and complete vehicles. Our measurement lab features a 1,000-lb capacity **InTensino+** (Table 10).

Model	Capacity (lb)	CG Accuracy (in)	MOI Accuracy	POI Accuracy (lb-in <sup>2</sup> )
InTensino+	65 - 1,000	0.06	0.5%	170

Table 10 InTensino+ (Gallery Photo No. 16)

facilitating blade matching to improve turbine or fan balancing and reduce vibrations. Space Electronics' moment weight scales are ten times more accurate than a knife-edge pivot. Because of

Model	Capacity (lb)	Max. Gimbal Size (in)	Height at Center (in)	Mounting Plate (in)	Sensitivity (lb-in)
GM904S	25	22 x 22	21	19 ½ x 17 ½	0.0001

Table 11 Gimbal Balance Machine (Gallery Photo No. 14)

Model	Max. Radial Moment That Can Be Measured (oz-in)	Max. Weight of Blade and Tooling (lb)	Max. Combined Moment of Blade and Tooling (oz-in)	Readout Resolution (oz-in)	Readout Sensitivity (oz-in)	Linearity (% of blade value)	Mounting Plate Radius (in)	Mounting Plate Dimensions (in)
MW900	900	30	3,000	0.002	0.01	0.03	5.000	4 x 3.5

Table 12 MW900 Single-Axis Moment Weight Instrument (Gallery Photo No. 11)

### Gimbal Balance

Space Electronics' gimbal balance machines, including our lab's **Model GM904S** (Table 11), are highly sensitive measuring instruments used to achieve state-of-the-art static balance of all types of gimbals with as many axes of rotation as desired. Typical applications include missile seekers, fast-steering mirrors, missile jammers, and airborne cameras mounted on UAVs, helicopters, and other aircraft.

Our machines measure the "unbalance," or lack of stabilization, of a gimbal about each of

its own axes of rotation to better than 0.0001 lb-in. The gimbal can be balanced in its fully assembled "ready-to-fly" configuration with wire bundle and fiber optic guide masses included.

### Single-Axis Moment Weight

Measuring the moment weight of turbine and fan blades is the first stage of balancing a turbine prior to stacking the rotor. Moment weighing scales measure the moment weight of a blade,

their exceptional measurement accuracy and repeatability, Space Electronics **MW Series** of moment weight scales can dramatically reduce your costs through smaller batch sizes and shorter cycle times. Our lab is currently equipped with a Model MW900 moment weight scale (Table 12).

### Multi-Axis Moment Weight

In addition to its use in gimbal balancing, the MW904 (Table 13) is capable of measuring the moment weight of turbine and fan blades in all

three axes—in the axial and radial directions in one orientation, and the

tangential direction when the blade adapter is rotated through 90°.

### Test Article Fixturing

All mass properties measurement results are referenced to your test article datum and are certified traceable to the US National Institute of Standards and Technology. Measurement accuracy is highly dependent on the fixture used

Model	Capacity (lb)	Internal Unbalance Accuracy (oz-in)	Weighing Accuracy (oz)	Range (oz-in)	Radial & Axial Moment Error (typ.) (oz)	Tangential Moment Error (typ.) (oz)
MW904	50	0.07	0.02	140	0.5	1.5

Table 13 MW904 Multi-Axis Moment Weight Instrument (Gallery Photo No. 10)

to support your payload on the measuring instrument. Space Electronics offers its extensive experience in designing and manufacturing fixtures—L-fixtures, vee blocks, roller vee fixtures, satellite positioners, and more—to suit a full range of test parts, from computer hard-drive components weighing a few grams to space satellites weighing 10 tons. Our experience in designing repeatable fixtures is an indispensable asset to those customers who are looking for the highest measurement accuracy.

### L-Fixtures

Our KSR and POI series machines measure 2-axis CG and MOI about a single axis, all in one setup. In order to measure the other mass properties of an



object, it is necessary to reposition the unit under test relative to the machine. Our L-fixture supports the object

horizontally and includes a rotary table that allows you to turn the object about its axis to obtain two additional MOI measurements and the third CG measurement.

### Roller Vees

Roller vee fixtures are used to position cylindrical



objects on a mass properties measurement instrument. They allow you to measure CG in two axes

and MOI in one axis, and then rotate the payload by 90° to measure the third CG coordinate and a second MOI.

### Tilt/Translation Tables

These fixtures allow translation of the payload in two horizontal axes and pivot about a vertical axis.

They are used to precisely adjust the verticality of the payload and the position of its

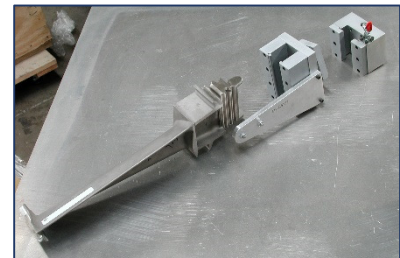


center of gravity over the centerline of our KSR and POI Series instruments.

### Blade Adapters for Moment Weight Scales

Space Electronics' "Gravity Wedge" blade adapters are specially designed single-axis adapters for dovetail, fir tree, and round hole blade roots. They are more repeatable and easier to use than any other style of adapter.

Tare moment is not altered by insertion of the blade. Repeatability is often better than 1 part in 100,000. There is no clamping knob to tighten, so operator effort is reduced and the disturbing force to the scale is minimized.



The unique slanted aperture guides the blade into position. A wedge at the bottom of the adapter forces the blade forward, causing the lower surface of the blade to contact the adapter at the Z-plane. The gravity moment then rotates the blade downward, so that the upper surface of the Z-plane also contacts the precision interface surface.

Our adapters are made of hardened tool steel. Wear is minuscule, and thermal expansion is 30% of the expansion of an aluminum adapter. All adapters are custom designed based on the exact dimensions of the blade.

## Documentation and Reporting

Space Electronics generates and delivers a complete formal test report upon completion of all testing services. Our report and related data products include:

- ♦ Complete description of the test item(s) and fixtures, including a definition of all measurement reference data
- ♦ Coordinate axes definition
- ♦ Narrative description and discussion of any required data reduction and analysis
- ♦ DWG-formatted drawings of fixtures and interfaces, as applicable
- ♦ Photographs showing the horizontal and vertical configurations of the test article
- ♦ General setup and overview photographs and videos, as applicable
- ♦ Complete test data in a Microsoft Excel workbook, as required, to allow our customers the ability to perform your own post-processing analysis
- ♦ Calibration traceability information

## Remote Measurement Services

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For those instances where it is not practical to ship your test article to us—whether for size, security, or safety reasons—Space Electronics can ship our measurement equipment to your facility and conduct your mass properties test program on site. Contact us with your requirements so, together, we can develop the most efficient solution to your measurement needs.

## Mass Properties Measurement ‘101’

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### Mass vs. Weight

Mass and weight are often used interchangeably but they are NOT the same. Mass is the quantity of matter, while weight is the force exerted on the

mass by gravity. The relationship is  $W = Mg$  where  $M$  = Mass,  $W$  = Weight, and  $g$  = gravity. More generally,  $F = Ma$  where  $F$  is the force required to accelerate a Mass  $M$  at a rate  $a$ .

Typical units:

- ♦ Mass: kg, slug, lb-s<sup>2</sup>/in
- ♦ Weight: lb, Newtons, kg-m/s<sup>2</sup>

Mass is always a constant positive quantity. Weight is a positive quantity that varies with gravity. Neither weight nor mass requires a coordinate system for definition.

### Center of Gravity Location

Center of gravity location can be defined as:

- ♦ The balance point of an object
- ♦ The point through which a force will cause pure translation
- ♦ The point about which gravity moments are balanced

The center of gravity location must be referenced to a 3-dimensional coordinate system. CG location is directly a function of the coordinate system in which it is referenced. It is measured relative to a reference datum using moment balance equations.

### Moment of Inertia

Moment of Inertia is a quantity expressing a body's tendency to resist angular acceleration. The relationship is  $T = Ia$  where  $T$  is the torque applied to the object,  $I$  is the moment of inertia of the object, and  $a$  is the resulting rotational acceleration. MOI must be referenced to a rotational axis. It is dependent on mass distribution. The moment of inertia of an object is the summation of the MOI of point masses making up the object. The MOI of each element is  $I = Mr^2$  where  $M$  is the mass of the element and  $r$  is the distance of the element from the axis of rotation.

- ♦ Moment of inertia units: lb-in<sup>2</sup> or lb-in/s<sup>2</sup>

## Product of Inertia

Product of inertia is the characteristic of an object that causes dynamic unbalance. The relationship is  $P = M \times X \times Y$  where  $P$  is the product of inertia in a given (X-Y) plane for any (point) element of mass in the object,  $M$  is the mass of the element, and  $X$  and  $Y$  are the coordinates of the element. The Product of inertia of the object is the summation of POI of the point masses making up the object.

POI can be positive or negative. The algebraic signs of the element coordinates must be used to get the correct sign of the POI sum.

## Definition of Accuracy Terms

Mass properties measurement instruments use a wide variety of terms to describe the differences between the real quantity and the measured value.

There is considerable difference of opinion regarding the terms “error,” “uncertainty,” “precision,” “accuracy,” “sensitivity,” and “resolution.” Some of this is a lack of universally accepted definitions, and some is due to recent technology that has required redefining some traditional terms. When comparing mass properties instruments, make sure that the terms employed to describe accuracy refer to the same quantities.

The accuracy terminology below applies to all our mass properties instruments, including center of gravity and moment of inertia measurement instruments, and spin balance machines.

### Accuracy

No measurements have absolute 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 is generally stated as a percentage. But a percentage of what? Accuracy must be defined over a given range.

### Error (General)

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. Frequently it is known that certain errors exist but the degree to which they exist is unknown. These errors are then more correctly called uncertainty. Any time an uncertainty can be quantified it becomes an error and can be compensated.

### Some Specific Types of Error

**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 as well as linear relationships. 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 percentage of measurement. Simply stated, this means that the measurement is more uncertain the larger the CG offset from the reference point on the measuring instrument. In some cases this may be compensated for.

**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. The best method is to always

approach the measurement from the same direction to improve repeatability, if not accuracy.

### 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 (e.g., quantities raised to the third power in defining a measurement have a greater effect than those that have a linear, first-power relationship).

### Resolution

Resolution is the size of the smallest increment that 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 might also be expressed as a (dimensional) gain. This is most clearly applied to dimensional measurements, or analog displays, e.g., 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 that consistently causes the output of the measuring instrument 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 an instrument 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  $\pm$  percent 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 can 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 two-decimal-place readings is calculated and displayed to six decimal places. There is an implied degree of accuracy in a six-place display that is not at all valid.

## Contact Us

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Weight and Center of Gravity Instruments (pages 3 - 4)

Model	Capacity (lb)	Resolution (lb)	Weight Sensitivity (lb)	Moment Sensitivity (lb-in)
YST2FR	2	$1 \times 10^{-4}$	N/A	N/A
YST13FR	13	$9 \times 10^{-4}$	N/A	N/A
YST1000FR	1,000	0.07	N/A	N/A
SE90168-60	2 - 60	N/A	0.01	N/A
SE90168-300	50 - 300	N/A	0.06	N/A
SE90168-1100	100 - 1,100	N/A	0.22	N/A
SE199	0.22	N/A	$1.1 \times 10^{-5}$	$1.7 \times 10^{-6}$
SE300	1.1	N/A	$1.1 \times 10^{-5}$	$9.0 \times 10^{-6}$
SE8913C	33	N/A	N/A	0.015

Weight, Center of Gravity, and Moment of Inertia Instruments (pages 4 - 5)

Model	Capacity (lb)	Weight Accuracy (lb)	CG Accuracy	MOI Accuracy (lb-in <sup>2</sup> )
XR10	10	N/A	N/A	$0.25\% + 1 \times 10^{-5}$
Control Surface MOI	50 - 100	N/A	N/A	3%
KSR330-60	3 - 120	N/A	0.1% + 0.003 lb-in	0.1% + 0.03
KSR1320-150	50 - 800	N/A	0.1% + 0.01 lb-in	0.1% + 0.2
KSR1320-1500	100 - 1,320	N/A	0.1% + 0.06 lb-in	0.1% + 0.2
KSR6000	200 - 6,000	N/A	0.1% + 0.3 lb-in	0.1% + 2
MP6500	200 - 6,500	10	0.1 in @ 6,500 lb	0.25% + 2.5

Dynamic Balancing Instruments (page 5)

Model	Capacity (lb)	Spin Rate (RPM)	MOI Accuracy (lb-in <sup>2</sup> )	POI Accuracy (lb-in)	Unbalance Reduction Ratio
POI50	1 - 50	50 - 800	0.1% + 0.1	N/A	95%
POI1000	10 - 1,000	30 - 300	0.1% + 0.75	N/A	95%
FBD200	200	50 - 200	N/A	N/A	85%
InTensino+	65 - 1,000	N/A	0.5%	170	N/A

Single-Axis Moment Weight Instruments (page 9)

Model	Max Radial Moment (oz-in)	Max. Weight (lb)	Readout Resolution (oz-in)	Readout Sensitivity (oz-in)
MW900	900	30	0.002	0.01

Multi-Axis Moment Weight Instruments (page 9)

Model	Capacity (lb)	Unbalance Accuracy (oz-in)	Weighing Accuracy (oz)	Range (oz-in)	Radial & Axial Moment Error (oz)	Tangential Moment Error (oz)
MW904	50	0.07	0.02	140	0.5	1.5

Gimbal Balancing Instruments (page 9)

Model	Capacity (lb)	Max. Gimbal Size (in)	Sensitivity (lb-in)
GM904S	25	22 × 22	0.0001

