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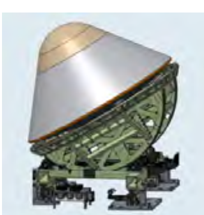
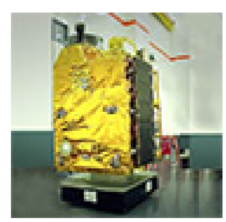
# Static Balancing a Device with Two or More Degrees of Freedom – (The Key to Obtaining High Performance On Gimbaled Missile Seekers)

By
Richard Boynton, President
Kurt Wiener, Chief Engineer
Paul Kennedy, Operations Manager
Brandon Rathbun, Assistant Chief Engineer
**Space Electronics, Inc.**







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# 1 Abstract

When a police officer in a helicopter is trying to use a telescope to read a license plate on a car, it is vital that the image not jitter; otherwise, it will be too blurred to read. There is a constant vibration on a helicopter, plus there are g forces introduced by the motion of the helicopter. Normally, these external forces would cause the telescope image to jump around. However, if the telescope is balanced so its CG is exactly at the center of rotation of the gimbaled mount, then the image miraculously settles down.

The same dramatic improvement in performance occurs when a gimbaled seeker in a missile or smart weapon is balanced. In addition to affecting targeting accuracy, the degree of balance is the driving force that determines the torque requirement of the positioning motors in the seeker. If the seeker can be balanced with high precision, then the motors can be made much smaller, allowing the entire seeker to decrease in size. So this is a case where center of gravity control drives the limits of performance and also sets the requirements for basic elements in the design.

In addition to unbalance due to CG offset, unbalance due to product of inertia is a critical factor in the performance of a seeker. Rapid changes in direction introduce disturbing forces if the principal axes of the seeker are not coincident with the rotational axes.

This paper outlines the current state of the art in gimbal balance. Some questions answered in this paper are:

1. How do you balance a gimbaled device (such as a missile seeker)?
2. Where should you locate the ballast weights on the gimbaled device for optimum reduction of unbalance?
3. How do you calculate the position and mass of the ballast weights, given that the seeker has at least two degrees of freedom, and sometimes has as many as five?
4. How do you fixture the seeker in the gimbal balance instrument?
5. How do you minimize practical limitations to minimum unbalance such as wire bundle movement and uncertainty in protective cover location?
6. What considerations should be given to minimizing product of inertia?

The gimbal balance machine described in this paper is one of the most accurate mechanical measuring devices in the world. The full-scale moment of each axis is 10,000 g-cm. The readability of the moment measurement is 0.03 g-cm, and the combined error due to drift, moment uncertainty, and linearity when measuring the final unbalance of a gimbal after ballast correction is 0.1 g-cm. This is a 0.001% error expressed in terms of full-scale moment! In other words, the gimbal balance machine is capable of reliably detecting unbalance as small as 1 part in 100,000. It is often hard for engineers to fully appreciate the incredible accuracy of this balancing machine. What makes this even more remarkable is that we now are able to achieve this with a single range of readout. It is no longer necessary to switch ranges as the unbalance is reduced. This extraordinary performance has driven the industry. Missile seekers can now be made smaller and lighter, because the higher degree of balance has reduced the torque requirements on the positioning motors.

# 2 Introduction

For a telescope to view in all directions, its mount must contain at least two bearing axes, which are generally mounted at right angles (i.e. orthogonal). {Note: The exception to this would be a spherical bearing that inherently permitted rotation about orthogonal axes.} There are a number of ways to implement these two axes. One way is shown in figure 1. If this were a ground based astronomical telescope, then the position of axis B could be carefully adjusted to point directly at the North Astronomical Pole. As the earth rotated, a motor could then drive this axis in opposition to the earth's rotation, resulting in an image that remained fixed with time for excursions of an object from horizon to horizon. In astronomical terms, this would be the "right ascension" axis. The other axis, which is labeled A in figure 1, would be used to set the altitude of the telescope. In astronomical terms, this would be the "declination" axis.

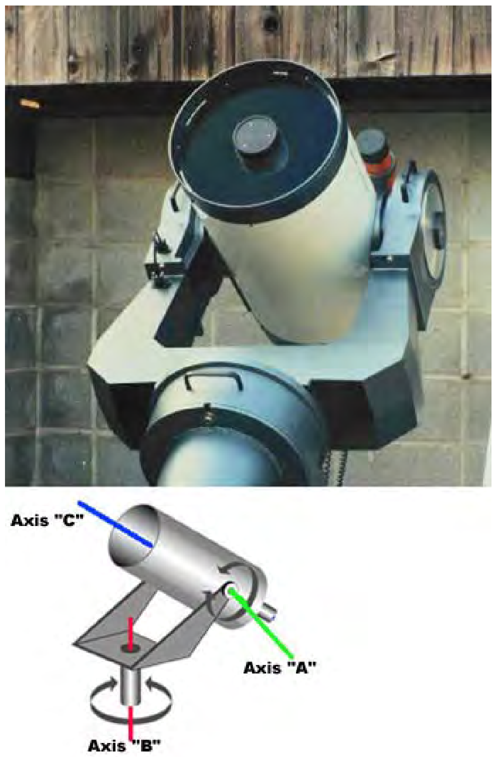



**Figure 1: Typical astronomical telescope mount**

Note that a different mass moves when the telescope is rotated about each axis. If rotated about axis A, only the telescope tube moves. When rotated about axis B, both the telescope tube and the yoke move. If the yoke is unbalanced about the B axis, then there will be a difference between the two C axis unbalance values, so that two different components of C unbalance must be reported.

1. There will be an unbalance along axis C when rotating about axis A.

2. There will be an unbalance along axis C when rotating about axis B.

If we were to characterize the location of the CG of the system, then there is a single CG location along axes A and B, but two CG locations along the C axis. This yields four coordinates for the CG:

A = offset along A axis
B= offset along B axis
$C_A$= offset along C when rotating about A
$C_B$= offset along C when rotating about B

Engineers who are used to defining CG location using 3 coordinates may be momentarily puzzled by the presence of 4 coordinates to define CG. You should remember that this is not a rigid body. The number of parameters required to define CG location increase as the number of degrees of freedom of the object increase. Furthermore, the location of ballast weights used to correct unbalance is critical. If you are not careful, adding ballast weight to a specific location can reduce the unbalance along one axis but simultaneously increase it along another axis. In general, a best-fit solution is obtained using sophisticated software. This is discussed in detail in later sections of this paper.

Another form of a gimbaled telescope can be created with concentric rings as shown in figure 2.

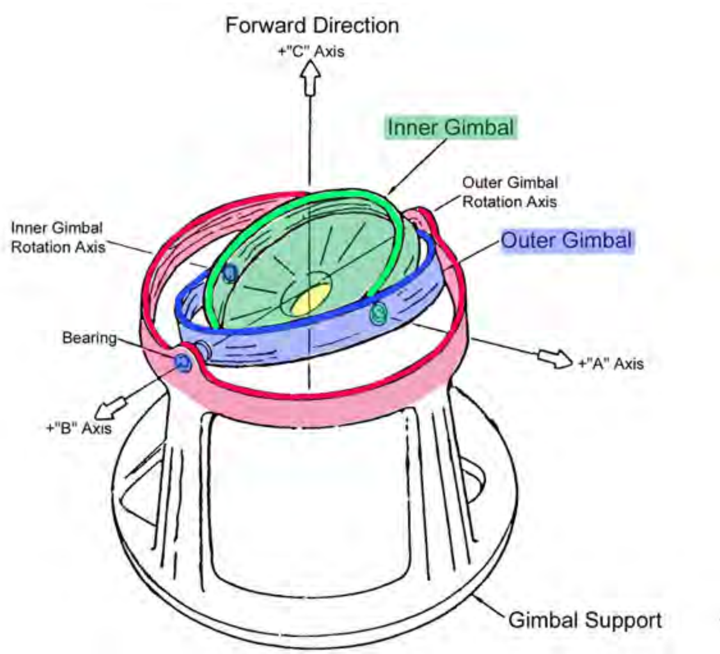



**Figure 2: Concentric shell type of gimbaled seeker**

The (green) mirror or lens or microwave antenna rotates about the inner axis, whose bearings are mounted to an intermediate ring or shell (blue). This intermediate shell in turn rotates about a pair of bearings, which define the “outer axis”. When the telescope is tipped toward the bearings on the outer axis, only the (green) inner mirror assembly moves. When it is tipped toward the bearings on the inner axis, both the inner mirror assembly and the (blue) intermediate shell move. This mechanism is fundamentally identical to the traditional telescope mount shown in figure 1, but it is more compact and inherently symmetrical, so that it can be balanced efficiently, making it ideal for an optical missile seeker design.

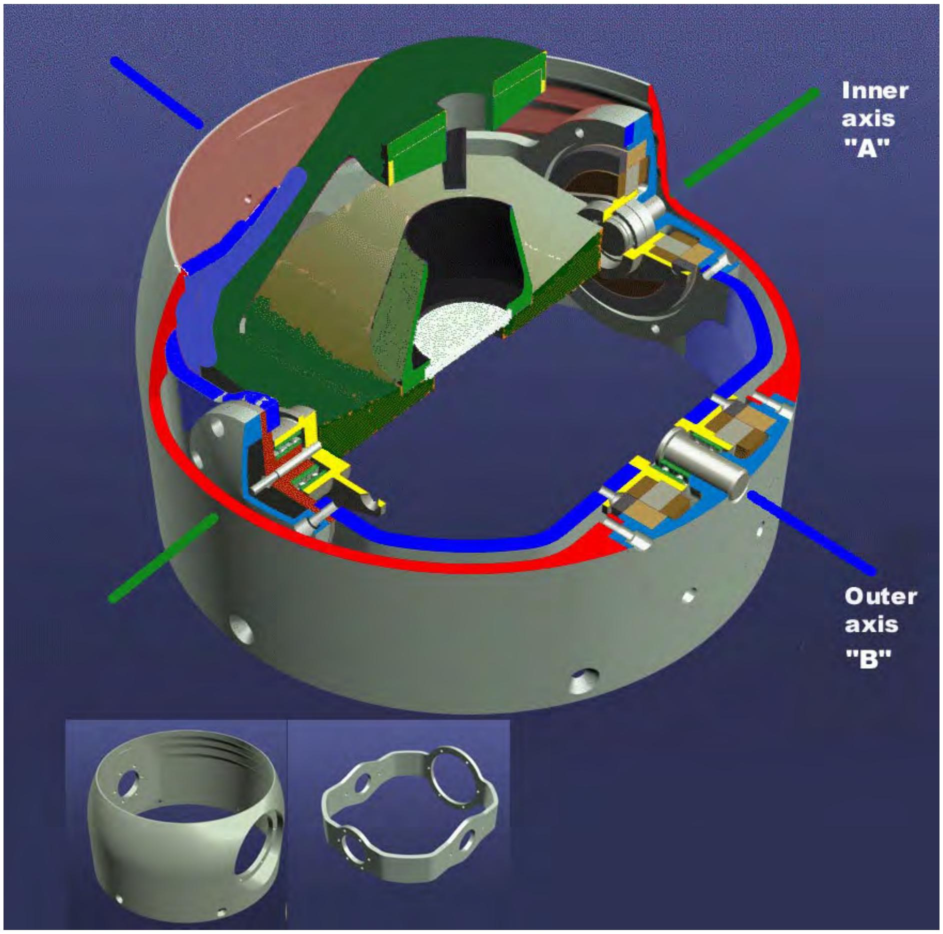



**Figure 3: Cutaway view of a concentric ring type of gimbaled seeker**

## 2.1 Definition of Gimbal Axes

When a seeker turns about one set of bearings, it is sometimes said to rotate about its PITCH axis; when it rotates about the second set, it rotates about its YAW axis. Sometimes the words AZIMUTH and ELEVATION are used to define these two axes. Pitch and yaw (or azimuth and elevation) have a specific meaning when referring to an airplane, which flies horizontal to the ground. For a rocket, which travels to outer space, the definitions are arbitrary; one man's pitch is another man's yaw. The most meaningful terms to use when talking about gimbal balance are INNER GIMBAL AXIS and OUTER GIMBAL AXIS. These terms ignore the relationship between the rocket and the surface of the earth and concentrate on the critical aspects affecting balance: when a part rotates about its inner gimbal axis, only the mass "inside" this axis affects the balance; when the part rotates about its outer gimbal axis then the mass of the inner gimbal is added to the moving mass.

We have discovered over the years that there is endless confusion regarding the definition of unbalance about gimbal axes. Part of this confusion stems from the fact that one person's pitch is another person's yaw and, in fact, in many large companies, different departments define the axes differently. In at least one instance, we have found that two different coordinate systems were used on a single gimbal. One was used for the body of the gimbal, and a second one was used to define the axes on a rotating telescope assembly mounted within the gimbal. Secondly, the assignment of positive and negative unbalance for each axis is arbitrary, so that again one department may define positive unbalance in one direction and another department in the same company may define positive in the opposite direction. Third, considerable confusion results from the fact that you can define unbalance about an axis or along an axis. Unbalance about a pitch axis is the same as unbalance along a yaw axis

Because of this confusion, Space Electronics has established a standard for the reporting of gimbal unbalance data. (See Figure 4.) The inner (moving) axis of the gimbal is called axis A. When the seeker or other gimbaled device rotates about the A axis, only the mass supported by this axis moves; there is no motion of the mass on the other axis. We have defined the positive direction as being toward the left as shown in the illustration, and as will be explained in the next section; the gimbaled test object is mounted in the balancing machine in this orientation. This axis A can be called "pitch", "yaw", "azimuth", or "elevation", depending upon the name assigned by the user. When we say that the unbalance is a positive value along axis A, then we mean that the mass of the inner axis is displaced upward along axis A (i.e. if the bearings of the seeker were perfectly frictionless, then the seeker would rotate about axis B so that the seeker faced up if it were accelerated forward).

We define axis B as the outer (fixed) rotational axis. When the gimbal rotates about this axis, both the mass associated with the inner and outer axes will move. We have defined axis B to be positive toward the right as shown in the illustration. When we say that the B axis unbalance is a certain positive value, then we mean that the mass of the gimbal is displaced along axis B toward the right. If axis A was called pitch, then axis B will be called yaw. If axis A was elevation, then axis B will be azimuth, etc.

We define axis C as unbalance in the forward direction. If the gimbal test object is a seeker, then axis C is the direction of flight and corresponds to the roll axis. Positive unbalance along this axis is toward the direction of flight (or the direction of the target, if the gimbaled device is a bombsight or other weapon aiming device). Often the test object is pictured so that we are looking directly at the front of the device. In this case, positive C unbalance is "out of the page".

Although this may seem quite clear right now, when you try to convey gimbal balance data to another person later on, you may later discover that there is considerable confusion regarding the definition of gimbal unbalance. If you are using a Space Electronics gimbal balance machine to measure gimbal unbalance, then the data will be presented as an unbalance along axes A, B, and C. Your company will undoubtedly use different terminology (although we wish they wouldn’t). To aid you in interpreting the printed results on the computer program, you should provided a data chart such as shown in Figure 4a to translate from Space Electronics' terminology to your company’s terminology.

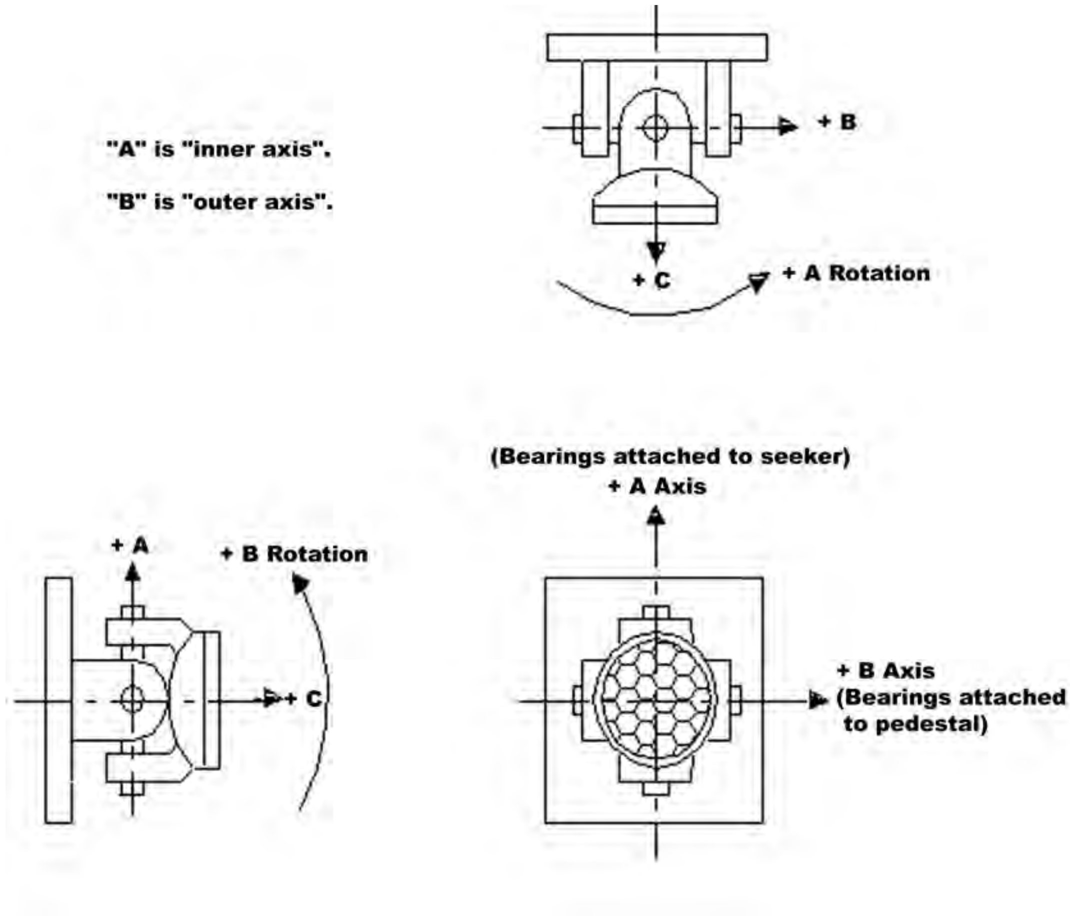



**Figure 4: Definition of gimbal axes (illustration uses "universal joint" type of gimbal)**

| Space Electronics' Terminology | User Terminology |
|---|---|
| Axis A | *Pitch* |
| Axis B | *Yaw* |
| Axis C | *Roll* |
| A Positive Polarity | *Reverse sign of Space Electronics data* |
| B Positive Polarity | *Same as Space Electronics data* |
| C Positive Polarity | *Same as Space Electronics data* |

**Figure 4a: Typical Translation Chart**

Note: The reason we chose A, B, and C as the symbols for unbalance data, rather than X, Y, and Z, was to avoid the confusion that occurs when our X corresponds to another person's Y. It's less confusing with A, B, and C, because you know immediately that this data is expressed in the Space Electronics standard coordinate system.

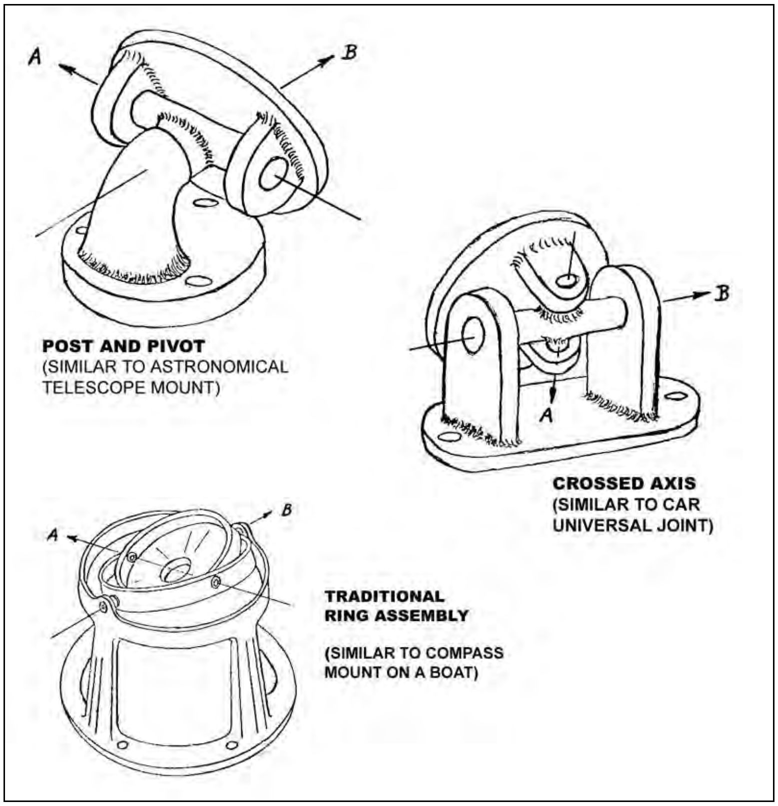



**Figure 5: "A" and "B" axes defined for different types of gimbals**

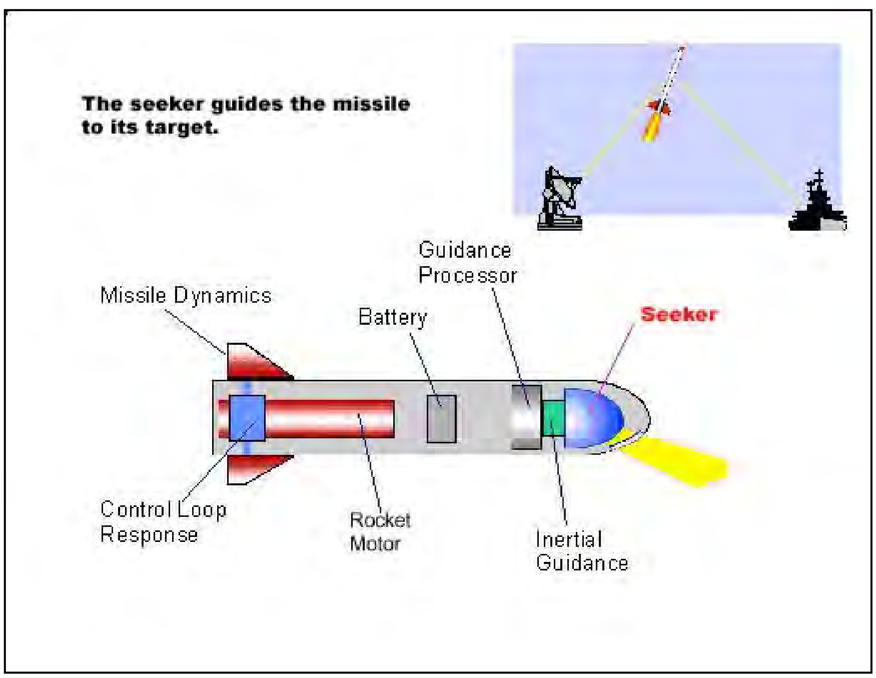
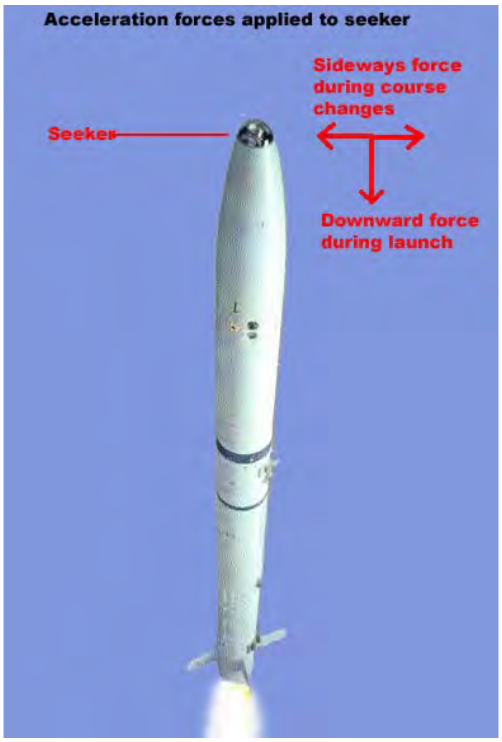


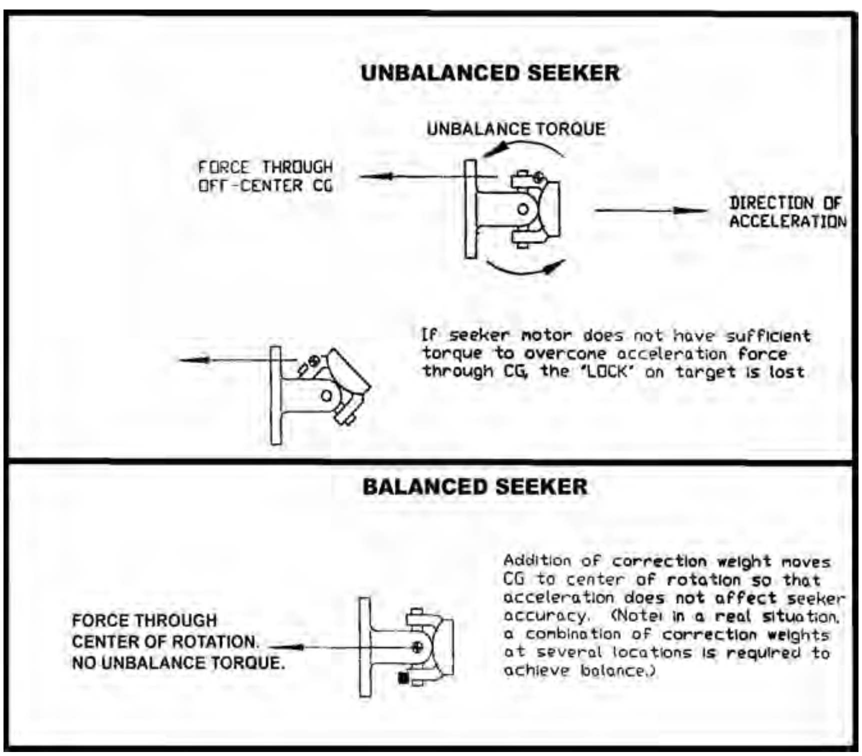

**Figure 6: Flight path is controlled by a seeker mounted in the nose of the missile.**

**Seekers -** Most rockets are guided by a seeker mounted in the nose of the rocket. This seeker must have at least two degrees of freedom, so that it can assume any orientation relative to the rocket. Torque motors turn the seeker; the seeker senses its target through infrared detectors, radar, pattern recognition of a visual image (such as a combination of stars or a profile of a tank), or other very sophisticated (and classified) technology. This seeker points at the destination and sends “error” signals to the rocket motors or steering fins to alter the course of the rocket. When the rocket is on course, both the seeker and the rocket are pointed in the same direction.

## 3 Why balance a seeker?




A rocket experiences acceleration in the forward direction during takeoff or change in forward speed. There are also accelerations along the two axes perpendicular to the longitudinal axis of the rocket when the rocket suddenly changes direction. If the CG of the seeker is not exactly on the center of rotation of the gimbal, then a torque equal to the mass of the seeker times the linear acceleration times the CG offset will be produced. The motors used to position the seeker are generally controlled by a closed-loop servo; this torque is counteracted by an increase in motor current to attempt to maintain the seeker position. This causes a positioning error, plus it uses valuable energy. In the extreme case, the rocket will fail its mission because the battery or other energy source will run out before the target is reached. On the other hand, if the gimbal is balanced to a very close tolerance, then the torque motors can be very small and the battery can be reduced in weight, improving the performance of the rocket. Now that accurate gimbal balance instruments are available, the trend has been toward tighter balance tolerances.



## 4 The Modern Gimbal Balance Machine

Space Electronics invented the gimbal balance machine in 1978. Our first instrument could only balance a seeker within a tolerance of 150g-cm. Although this was considered satisfactory for the hydraulically driven seekers of that era, it would be woefully inadequate for the high performance miniaturized torque motor driven seekers of today. Current state of the art gimbal balance machines now can achieve a balance sensitivity of 0.1 g-cm, and we are attempting to develop machines that are even more sensitive, in order to meet the tight tolerances of today's seekers and airborne telescopes.


**Figure 7: A state-of-the-art gimbal balance machine** **Space Electronics, Inc. Model GM904S2**

GIMBAL BALANCE MACHINES are highly sensitive, computerized, center of gravity measuring instruments used to achieve static balance of missile guidance seekers, airborne telescopes and tracking devices. A high degree of balance is needed so that acceleration of the missile will not apply excessive torque around any rotation axis of the gimbal. Space Electronics gimbal balance machines will balance a gimbal about each rotation axis within a tolerance as small as 0.1 gram-centimeter (0.0001 lb-in). The gimbal can be balanced in its completely assembled condition with wire bundle and fiber optic guide masses included.

Space Electronics is generally recognized as the inventor of the modern gimbal balance machine. Over 95% of all seekers worldwide are balanced on one of our instruments. We invented the concept of orienting the gimbal axes at 45° to the horizontal and measuring the change in horizontal CG position as the gimbal is rotated about its axes. Also, the concept of "permanently calibrated" moment sensing using a closed-loop servo to return the mechanism to its original state, and many of the conventions and standards used to define gimbal balance were originated at Space Electronics.

## 4.1 Theory of Operation of a gimbal balance machine

A gimbal balance machine is basically an extremely sensitive two-axis center of gravity instrument that has a limited full-scale range but is about 1000 times more sensitive than a conventional CG instrument. The unbalance of the gimbal is determined by measuring the change in CG location of the gimbal assembly when the inner mechanism (usually a seeker or telescope) is rotated to different positions. If the gimbal is balanced about its rotational center, then the CG of the gimbal assembly will remain fixed for all angular orientations of the seeker or telescope.

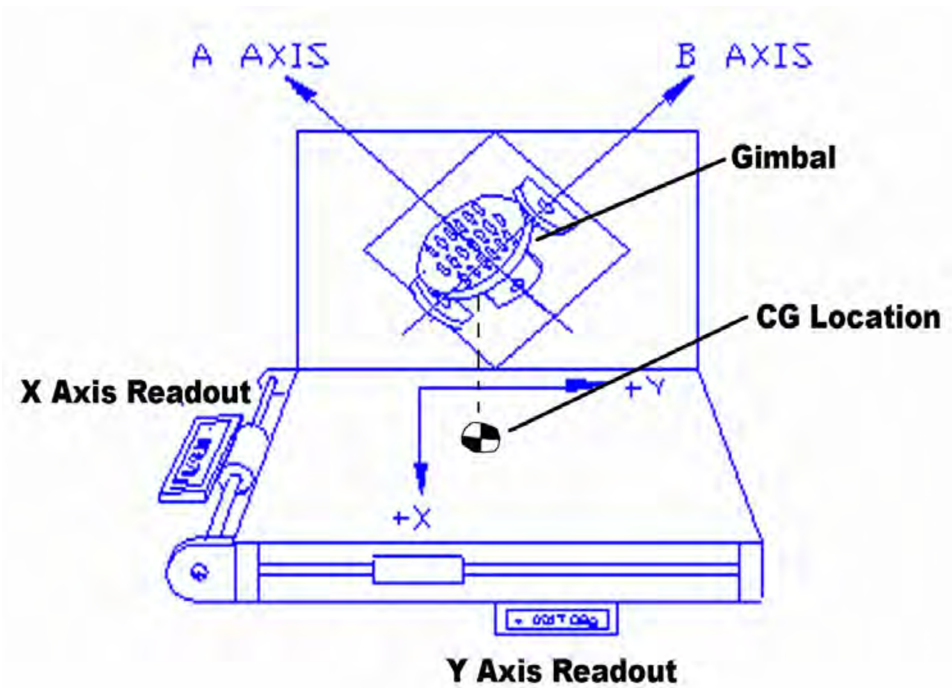



**Figure 8: A gimbal balance machine measures the CG change due to rotation of the gimbal about its own axis.**

## 4.2 The Space Electronics Method of Balancing a Two-Axis Gimbal

Gimbal unbalance measurement involves the following steps:

a. The seeker or other type of gimbal is mounted in the machine so that the gimbal base is against a vertical mounting plate and the two axes of the gimbal are oriented at 45° from the horizontal. (See figure 8).

b. The seeker is rotated about its own axes so that it faces directly forward,(i.e. both axes are at their midpoint of rotation). Tare weights on the instrument are adjusted so that the instrument reads approximately zero unbalance along both horizontal axes.

c. The seeker is then rotated to four different positions and the horizontal coordinates of the center of gravity measured at each position. Generally, these four positions are the maximum positive and negative excursions ABOUT the yaw axis and the positive and negative excursions ABOUT the pitch axis. Since the instrument measures both X and Y coordinates of horizontal center of gravity, this will result in a total of eight unbalance moment readings. If the seeker is exactly balanced about its rotational axes, then the CG of the total assembly will not change when the gimbal is rotated to its four different positions. If it is unbalanced, then the CG data will differ.

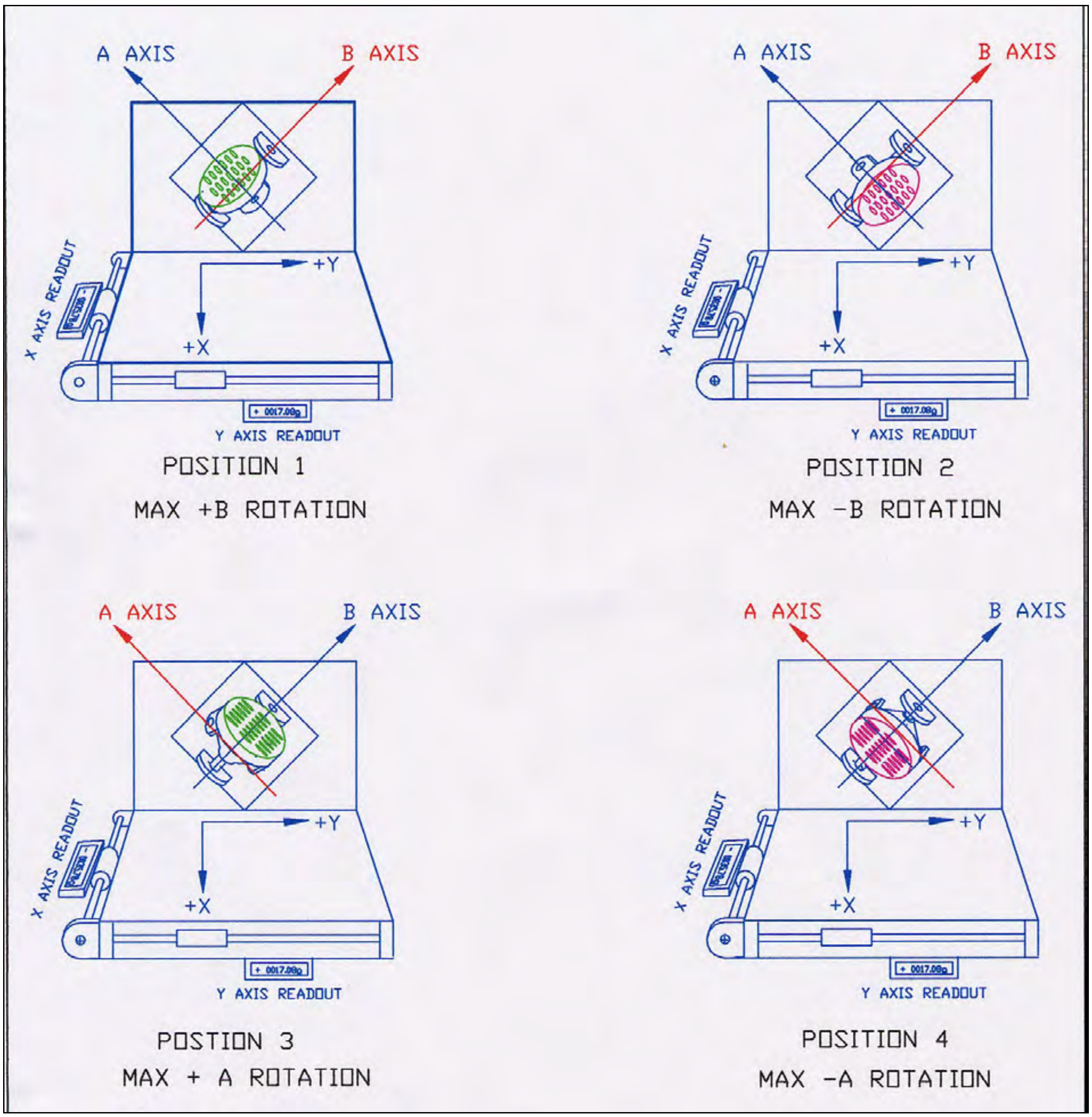
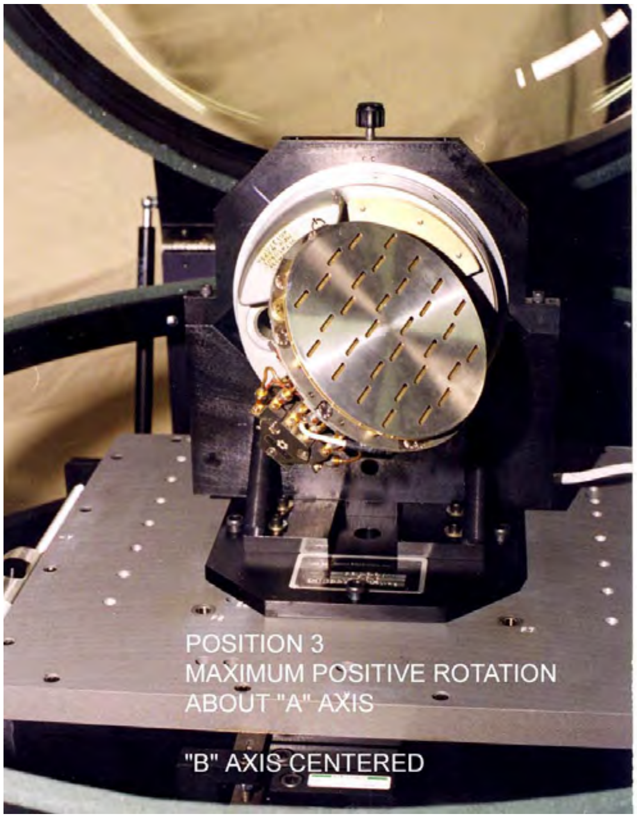
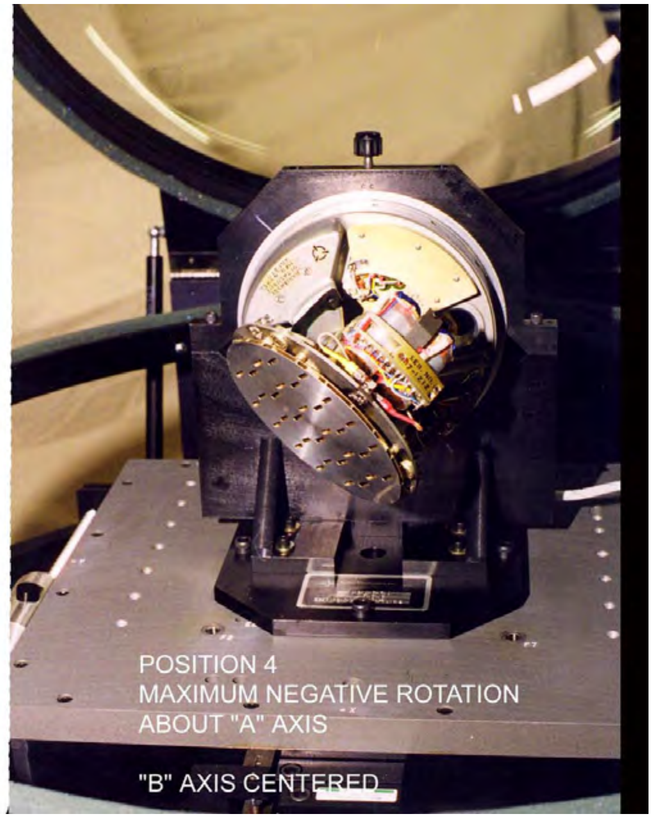



**Figure 9: Using the four standard measurement positions ensures that the coordinates of the data will be consistent for all measurements.**




d. Because of the 45° orientation, there is a unique relationship between the change in position of CG and the projection of its coordinates on the horizontal plane of the machine. This allows the machine's computer to analyze the data and compute the location and magnitude of the unbalance relative to the four coordinates of gimbal unbalance about the rotational center of the gimbal.

e. If the optional weight correction software has been purchased, then the computer calculates a solution to the unbalance problem and presents the test operator with a list of correction weights and their locations in order to achieve balance.

### 4.3 Gimbal Balance Fixtures

An adapter or "fixture" is required to support the gimbal rigidly with respect to the mounting surface of the gimbal balance machine. Any relative motion during measurement will be interpreted as an unbalance, so it is essential that the gimbal body not move more than about 20 millionths of an inch during the four measurement steps (the rotating part of the gimbal will, of course, move to each position).

The gimbal can be located pretty much anywhere relative to the machine, as long as it is rigidly mounted and its axes are oriented properly relative to the measurement axes of the machine. This is a point that is often misunderstood.

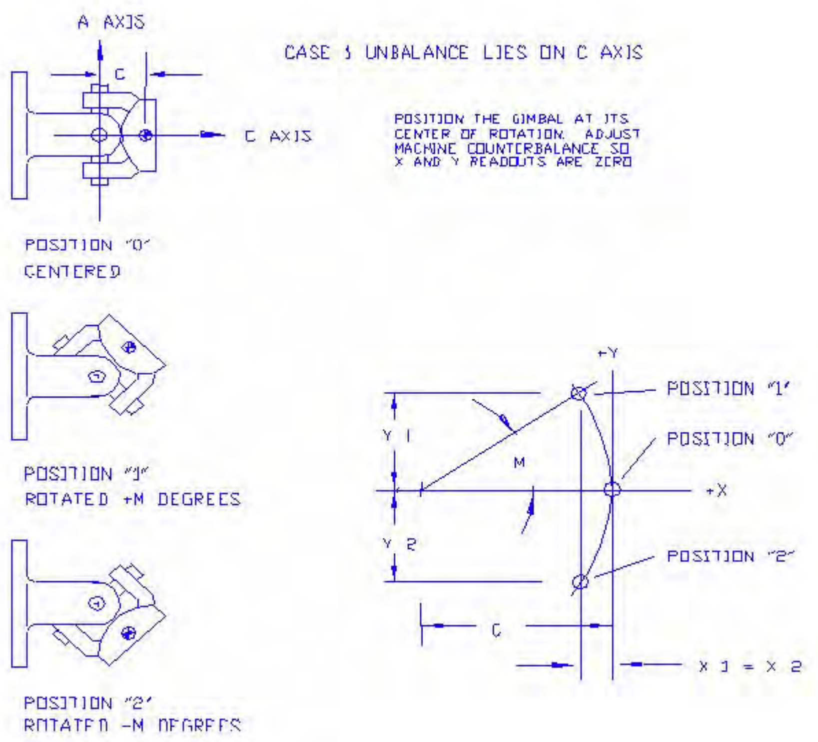
It is not necessary that the center of rotation of the gimbal be located directly above the center of the mounting surface of the gimbal balance machine. In fact, it often is not desirable that this be the case. The ideal location is one where the CG of the complete gimbal assembly AND

FIXTURE is close to the center of the machine, so that a minimum amount of counterbalance will be required to bring the moment readouts to their central position.

Since gimbal balance machines measure the change in CG due to rotation of the movable part of the gimbal about the rotational axes of the gimbal, fixturing accuracy requirements are minimal and do not affect accuracy of balance.

## 4.4 Measurement concept

The basic measurement concept that we use can best be understood by starting with a simplified example that does not exactly represent the Space Electronics method, and then showing the shortcomings of this method**.** Figure 10 illustrates the top view of a gimbal that has been fixtured in the instrument so that its rotational axis "B" is perpendicular to the measurement plane of the instrument. The gimbal axis A is locked at zero degrees. When the gimbal is rotated on this axis, the CG of the test object moves along a horizontal plane from one location on the Y axis of the gimbal balance machine to another. The magnitude of that change is a function of the displacement of the gimbal CG from the rotational axis and the magnitude of the angle of rotation. (In order to make it easier to visualize the movement of CG, we have shown the CG in an unrealistic location. In a real situation, the CG would be located close to the rotational center of the gimbal and would only move a few thousandths of an inch when the




gimbal is rotated).

**Figure 10: Case 1 - Gimbal oriented with "A" axis parallel to horizontal**

Using some simple trigonometry, we can calculate the unbalance vector of the test object. Note that the direction of the unbalance is at right angles to the change in measured CG. This is one of the most difficult concepts for first-time users of a gimbal balance machine to grasp. The C axis unbalance of the gimbal will result in a change in moment along the Y-axis of the machine when the gimbal is rotated to the two test positions. A or B axis unbalances of the gimbal produce a change along the X-axis of the machine. At first glance, this appears to be a typing error and we have accidentally reversed the axes. However, when you review the theory of gimbal balancing, it will become apparent that when the CG of the rotating part of the gimbal is displaced from the center of rotation, then the change in CG position falls along a line at right angles to the CG offset.

Also, note that the center of rotation of the gimbal does not have to be at any specific location relative to the measurement axes of the instrument, since we are determining the change in moment that results from a rotation of the gimbal. Adding a fixed weight to the base of the gimbal would change the location of total CG and thus alter the unbalance moment readings. However, the difference in moment when the gimbal was rotated about its axis would not be altered.

If the moment does not change when the gimbal is rotated, then the gimbal is balanced. A corollary to this observation is that linearity errors in the instrument will not ultimately affect the accuracy of balance; these errors may cause the first balance correction to not completely correct for unbalance of the gimbal, but ultimately when the moment does not change, then the gimbal is balanced (i.e. a 1% error in zero unbalance is still zero). What is critical is the *sensitivity* of the gimbal balance machine: its ability to repeatably detect small differences in CG.

Referring to figure 10, when the unbalanced gimbal is rotated “M” degrees about its (B) axis, the CG moves along the horizontal plane from position “0” to position “1”. The magnitude of the change in moment measured by the gimbal balance machine is proportional to both the unbalance of the gimbal and the angle through which the gimbal is rotated. A second measurement is made with the gimbal rotated to position “2”.

The magnitude and angle of the unbalance moment vector can then be calculated from these two X and Y CG readings. If the unbalance of the gimbal in this special case is directly on the C axis (i.e. no unbalance along A axis), and if the rotation angle in both the positive and negative direction is the same value (M), then

$$\mathbf{X_1 = X_2} \qquad \mathbf{Y_1 = Y_2}$$

$$\mathbf{C} = \frac{Y_1}{SinM} = \frac{Y_2}{Sin(-M)}$$

In the example in case 1, the rotation angle was the same for position 1 and 2. Averaging the two calculated values:

$$\mathbf{C} = \frac{Y_1}{2SinM} + \frac{Y_2}{2Sin(-M)} = \frac{Y_1 - Y_2}{2SinM}$$

A similar analysis can be performed to show that:

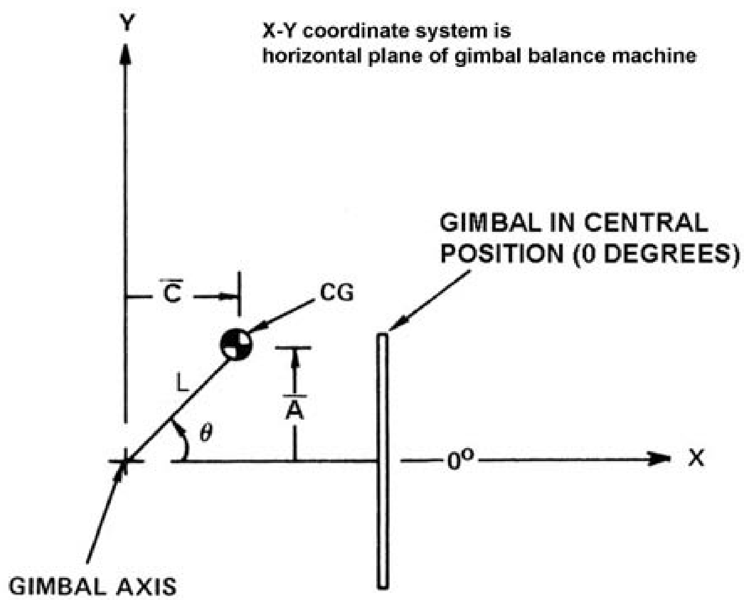
$$\mathbf{A} = \frac{X_1 - X_2}{2CosM}$$

for a CG offset directly on the A axis. In real life, the CG rarely falls on either axis. However, any real CG offset can be resolved into an A Axis and a C Axis component, and analyzed using the above formulas. The resultant unbalance is then:

$$\mathbf{U_{magnitude}} = \sqrt{A_2 + C_2}$$

$$\mathbf{U_{angle} = arctan}\left(\frac{A}{C}\right)$$

Note: The above mathematics applies to a single rotation axis (i.e. single degree of freedom).




**A general case for the single axis measurement (unbalance along both A and C axes**

Since the A-C plane of the gimbal and the X-Y plane of the gimbal balance machine are parallel (in this illustration), the CG of the gimbal projects straight down from the A-C plane to the X-Y plane. Its motion describes a circle with the center directly under the axis "B". All possible locations of gimbal CG are "visible" by the gimbal balance instrument (the reason for emphasizing this will be clear when we later consider the gimbal B-C plane, which is perpendicular to the X-Y plane in this example).

This orientation provides maximum sensitivity to measurement of unbalance in this A-C gimbal plane. However, as we will show later, it provides minimum sensitivity to unbalance in the B-C plane, and in fact, in certain cases, the instrument will not be able to detect unbalance at all in that plane.

The coordinates of the cg position are:

$$\bar{x} = \ell \cos \theta$$
$$\bar{y} = \ell \sin \theta$$

The line $\overline{AB}$ is perpendicular to $\overline{OC}$ so that:

$$\theta = \phi - \frac{\pi}{2}$$

Where $\phi$ can be found from the relationship:

$$\tan \phi = \frac{\Delta \bar{y}}{\Delta \bar{x}}$$

Thus the trigonometric functions of $\theta$ are:

$$\tan \theta = - \frac{\Delta \bar{x}}{\Delta \bar{y}}$$

$$\cos \theta = \frac{\Delta \bar{y}}{\left[\Delta \bar{x}^2 + \Delta \bar{y}^2\right]^{1/2}}$$

$$\sin \theta = \frac{- \Delta \bar{x}}{\left[\Delta \bar{x}^2 + \Delta \bar{y}^2\right]^{1/2}}$$

Substitution of Eqs. yields:

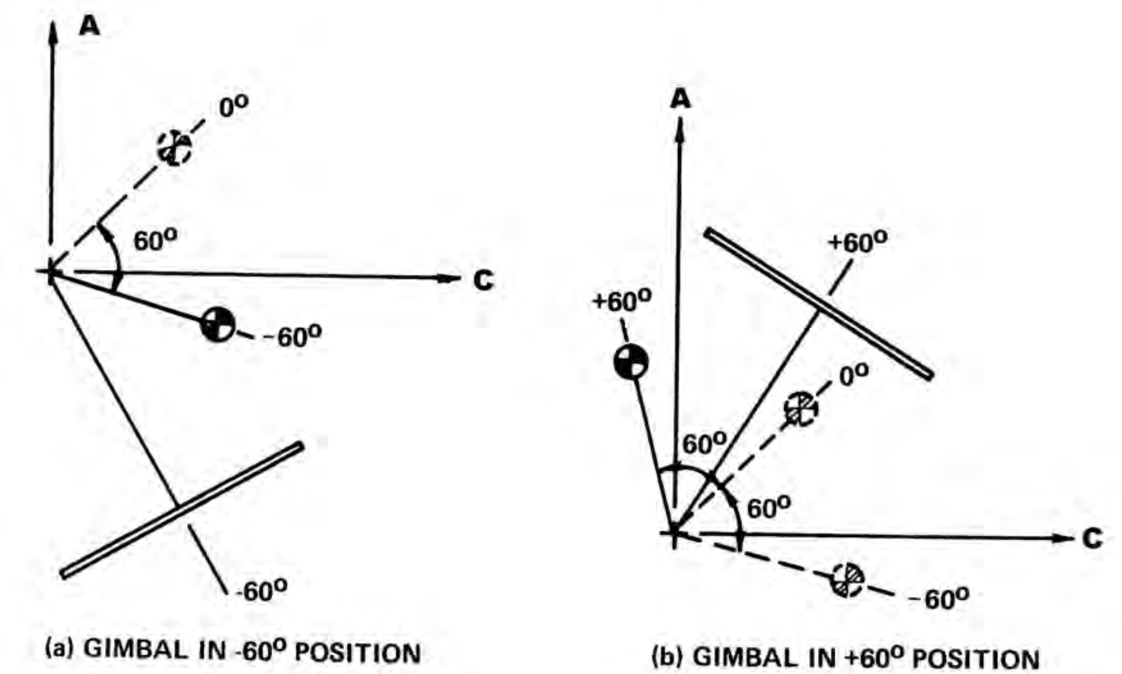
$$\bar{x} = \frac{\Delta \bar{y}}{\sqrt{3}}$$

$$\bar{y} = - \frac{\Delta \bar{x}}{\sqrt{3}}$$

Note that Eqs. are true for $\pm 60°$ rotation of the antenna. In general if the rotation is $\pm \alpha$ Eq. becomes:

$$\bar{x} = \frac{\Delta \bar{y}}{2 \sin \alpha}$$

$$\bar{y} = \frac{- \Delta \bar{x}}{2 \sin \alpha}$$



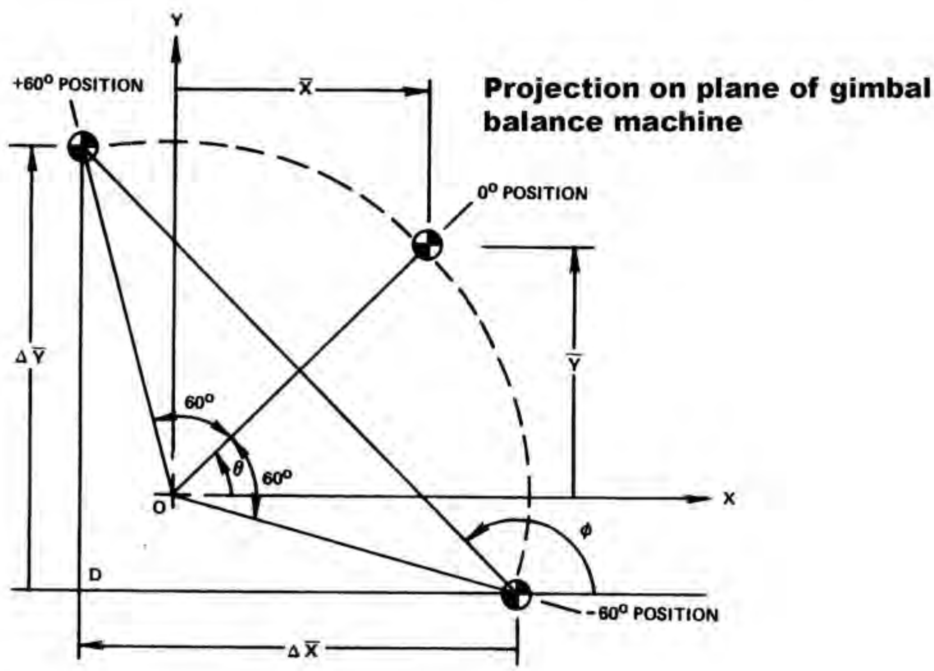




**Figure 11: Locus of unbalance projected onto X-Y plane of instrument**

**The problem with this orientation when measuring a two axis gimbal** Although the example above worked well for the A-C gimbal plane, it will not work for the B-C plane, since the projection of the gimbal CG on the instrument X-Y plane due to rotation about the A axis can be very small. In the extreme case, it is zero.

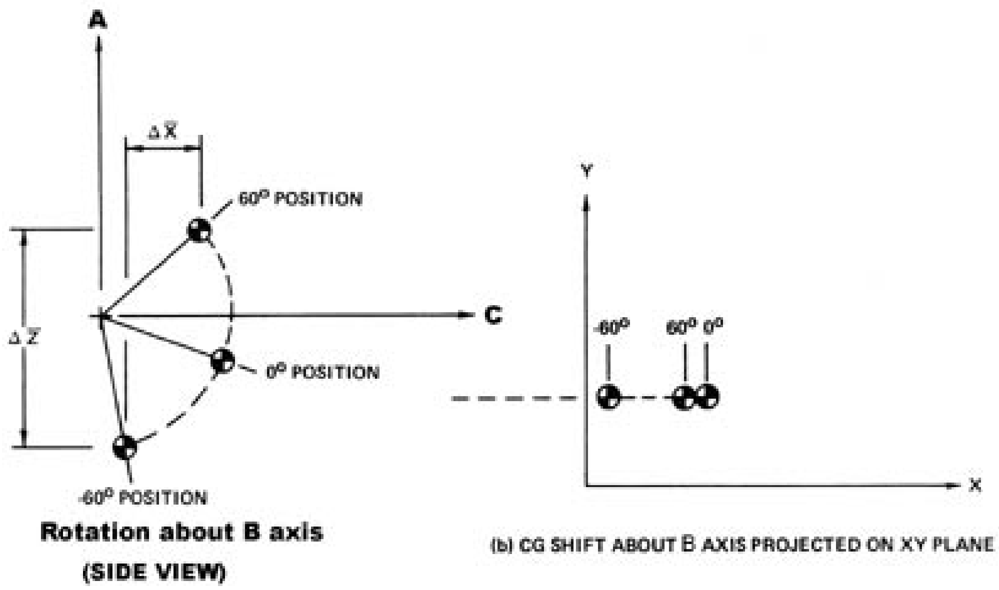



**Figure 12 Measurements of unbalance along B axis are indeterminate with this orientation.**

The illustration above shows what happens to the projection of the unbalance along the B axis. Rather than projecting at a circle on the X-Y plane of the instrument, they project as a straight line. Therefore, it is impossible to determine the magnitude by using two measurements, and three measurements yield very low sensitivity. The worst case is shown below. In this example, even though the gimbal has a large unbalance, the projected CG on the X-Y plane does not change at all.

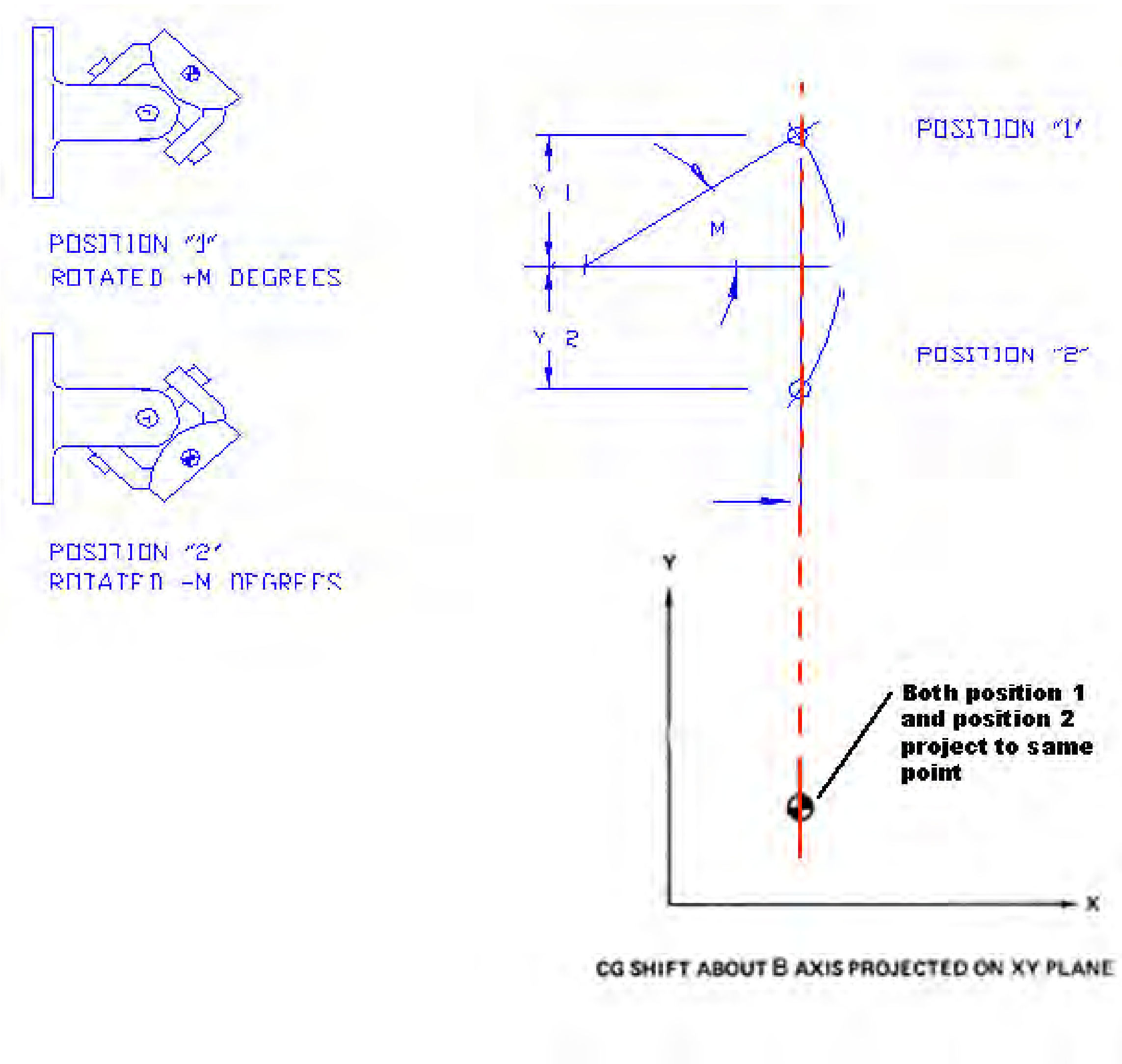



**Figure 13: Worst case: Unbalance is invisible in this orientation.**

If the gimbal is oriented so one axis is parallel to the instrument mounting plate, then the other axis cannot be measured in the same setup. This orientation makes it impossible to "see" the unbalance along the second (B) axis. For the second axis, the CG moves up and down as well as horizontally. For certain CG locations, the CG motion could be primarily vertical and the machine would not sense any change in horizontal moment for the two positions. In the first case, each position of the gimbal resulted in a unique X and Y moment; in the second case, the locus of CG measurement is a line; as the part is rotated, the CG will reach a maximum excursion and then retrace its path in the opposite direction along the same line.

## 4.5 Balancing a Two Axis Gimbal

There is a solution to this problem that avoids the need to re-fixture the part. If the part is fixtured with each axis oriented at 45° to the horizontal, then both axes are "visible". The locus of points for each axis becomes an ellipse.

Notes:
With this orientation, there are no blind spots or "invisible" unbalances. There is an unambiguous measurement of all four components of unbalance.
The unbalance can be fully measured in a single setup, greatly reducing measurement time.
This method, however, does reduce the sensitivity of the machine by 30% along the machine X axis, due to the 45-degree orientation. In the early days of gimbal balance, this was a concern. Recent increases in machine sensitivity have more than compensated for this loss.

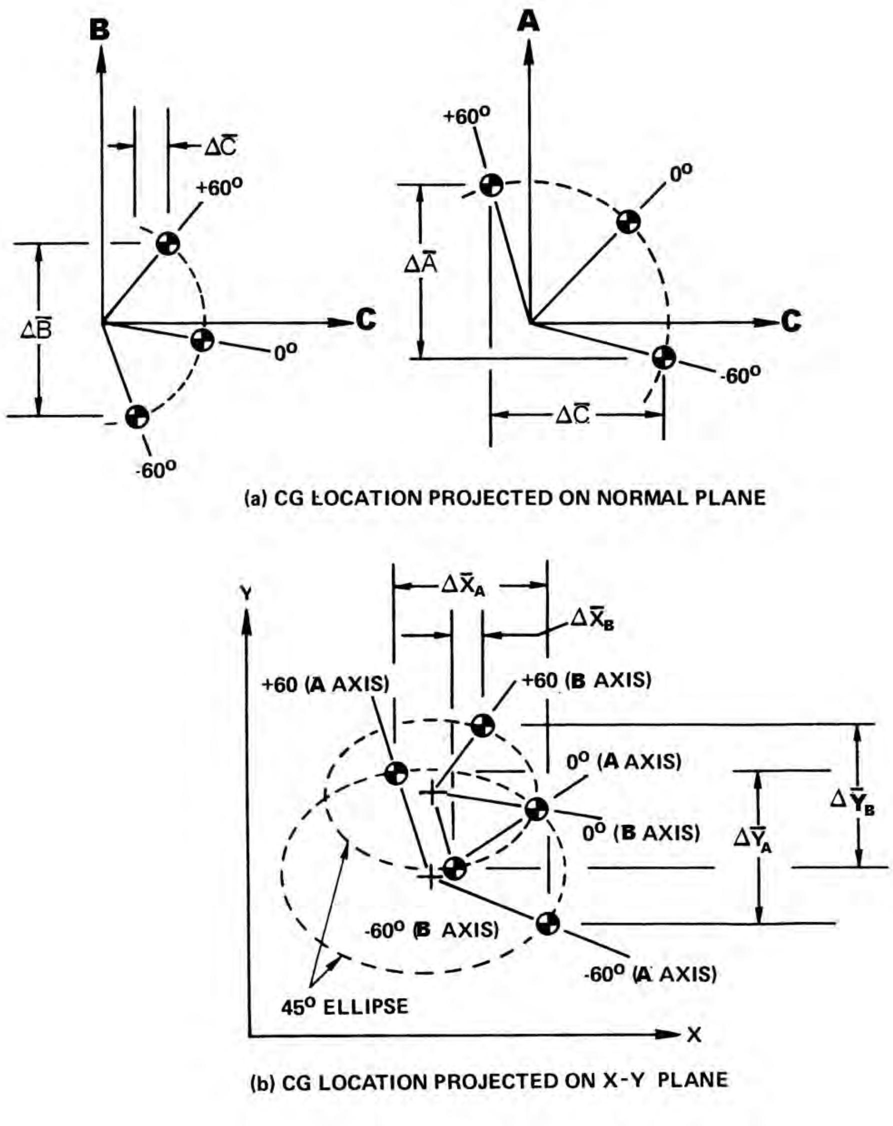



**Figure 14: 45-degree orientation results in elliptical projection onto instrument X-Y plane.**

Note that the centers of the two ellipses are not necessarily coincident.

4.6 Calculating Gimbal Unbalance

The following equations define the relationship between machine X_Y measurements and the A,B, and C center of gravity magnitudes along the gimbal axes:

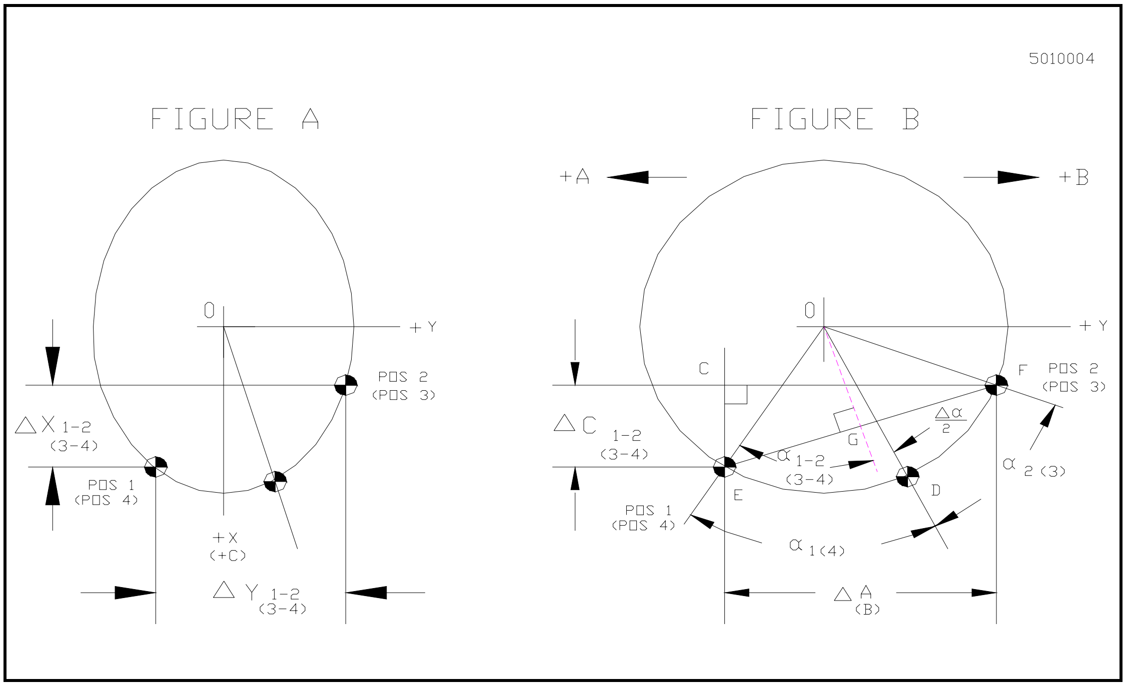



**Figure 15 (A and B): Projection of unbalance on X-Y plane for 2-axis gimbal mounted at 45 degrees from the horizontal**

DATA AS MEASURED AND AS USED FOR CALCULATIONS

Figure 15A shows the elliptical path of the seeker CG when rotated about an axis that is inclined $45^o$ to the horizontal. The X dimensions are accurate but the Y dimensions are foreshortened by a factor of .707, the sin of $45^o$. The notes at each CG symbol indicate the CG location when in measurement positions 1 and 2 (notes without parentheses) when rotated about axis B and in measurement positions 3 and 4 (notes with parentheses) when rotated about axis A. The first step in the calculation procedure is to determine delta X and Delta Y as measured, then divide the delta Y by sin$45^o$ to effectively project the data onto a plane parallel to the plane of motion. This will give the data in terms of delta A (or B) and delta C. The calculations for each axis are identical except that the 'plus' directions of the A and B axes are reversed. In the diagram below, Figure 15B (from above) is shown with the equations used to calculate the unbalance when rotated about axis A, the inner gimbal axis. When the unbalances about both axes have been calculated, the overall unbalance is reported in the following form.

Unbalance Results (TYPICAL PRINTOUT)
Along A about B (Ab) unbalance : 0.65 g-cm
Along C about B (Cb) unbalance : -1.32 g-cm
**Along B about A (Ba) unbalance : -0.34 g-cm**
Along C about A (Ca) unbalance : 1.01 g-cm
Total Unbalance About A (A) : 1.07 g-cm.
Total Unbalance About B (B): 1.47 g-cm.

**Figure 16: Equations & diagram to calculate unbalance about one axis**

Two measurements are made for each axis while the other is held at the zero angular orientation. The measurement positions usually are at the extremes of positive and negative rotation about each axis to maximize the change in CG location. In the example above, Positions 3 & 4, shown above, are used to calculate the unbalance when rotated about axis A, the inner gimbal assembly axis. The measurements are in moment units (i.e g-cm) so that all the quantities shown on the diagram are also in g-cm. This allows all calculations to be don in moment units and no component weights need be measured.

The diagram is constructed by locating points E and F based on the unbalance measurements C1, C2, B, & B2.
The chord length (L), is calculated from Delta B & C.
A line is then drawn perpendicular to the chord at its mid point. This line represents the mid line of the total rotation angle that is the sum of a1 and a2.
Lines are then constructed through points E or F to intersect the perpendicular at an angle equal to ½ the total rotation angle or (a3 + a4)/2 = a. The angles must be expressed as absolute values as shown in the diagram. The intersection is the center of the circle (O). The circle radius, which is the unbalance magnitude, is R. R can also be calculated as: R = (L/2)/(1/Sine a)
The location of the CG when the rotation angle is zero must also be determined. Geometrically, this can be done by constructing a line from the center of the circle at an angle a3 from line OF. Trigonometrically, this angle can also be determined by using angle delta a and angle b as shown in the equation:

CGang = 270 + b – delta a

The two unbalance vector components, C about A and B about A, are then calculated by respectively multiplying the unbalance vector magnitude by the sine and cosine of the unbalance vector angle.

## 5 How the Balancing Machine Works

As Figure 17 shows, the machine used to measure gimbal unbalance is itself a modified version of a concentric ring gimbal. Rather than use conventional bearings, the “rings” are pivoted using crossed web flexure assemblies. This eliminates friction errors, and provides a precision that is many times greater than the best precision bearing. This technique was originally developed for use in ultra-precision scales at the National Institute of Science and Technology (NIST). There is no relative motion, and thus no friction or wear in this type of pivot. Internal hysteresis in the nickel alloy webs is immeasurably small. The flexures act in the same manner as the knife edges on a beam balance scale—the pivot supports most of the weight of the gimbal and fixture; a low force transducer then measures the moment due to the displacement between the gimbal CG and the pivot axis. Prior to making a measurement, the tare weights are adjusted to correct the nominal CG to the center of the instrument, so that the moment transducers measure only the change in unbalance moment as the gimbal is rotated to its four positions about its own axis.

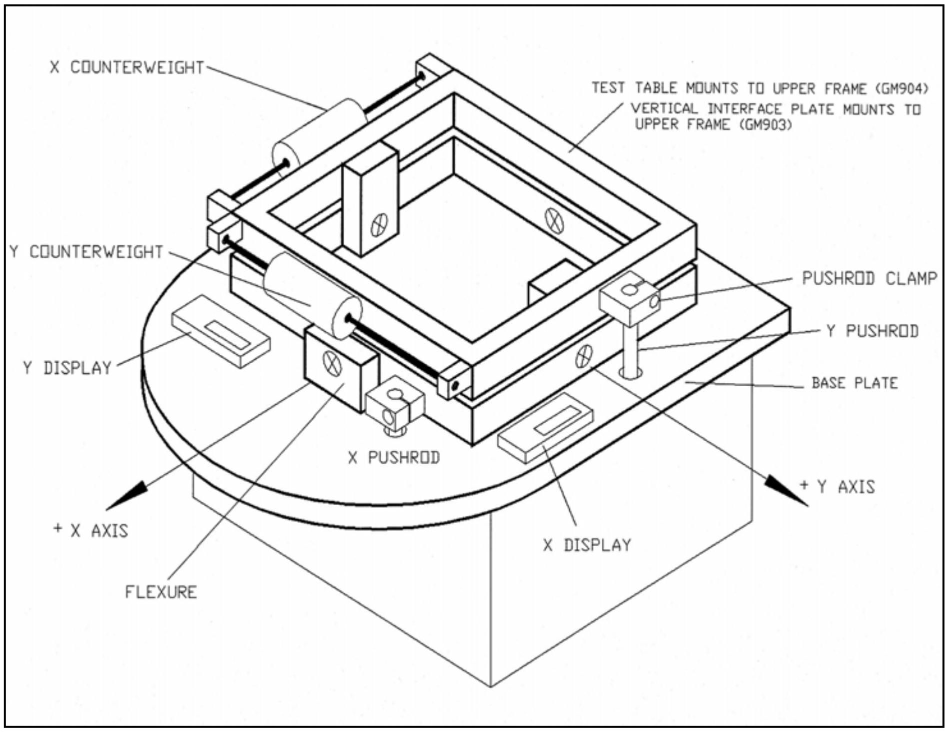
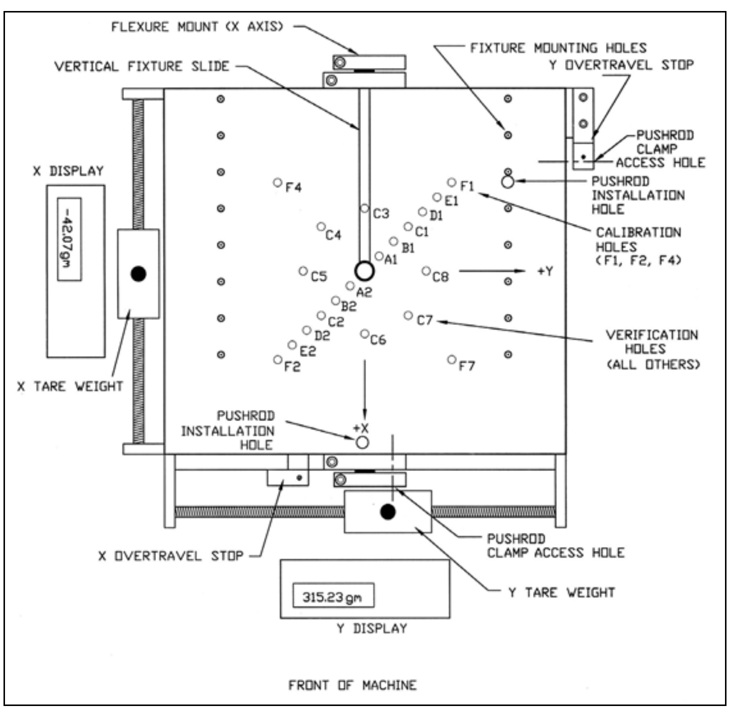



**Figure 17: Space Electronics Gimbal Balance Machine with mounting plate removed to show basic elements**

There are two pivot assemblies; each is connected to a transducer. One measures the X component of center of gravity, and the other measures the Y component. These transducers are use a force restoration technology similar to that used in Space Electronics mass properties machines and in our moment weight machines.



## 5.1 Force Restoration Transducers

This instrument uses two force restoration transducers. Each is capable of measuring force with an accuracy of at least 0.0005%. Unlike strain gage load cells, these transducers do not deflect and do not rely on the deformation of a piece of metal to determine force. Instead, an equal and opposite force is applied to counteract the force being measured.

When an object is placed on the weighing pan, the pan deflects downward. This pulls on the force link, causing the other end of the amplification beam to rise. This produces an output from the position sensor, causing the current in the electromagnet to increase until the amplification beam is back to its original position. A digital device determines the amount of current flowing through the electromagnet, which is proportional to weight. An internal computer translates the current magnitude into units of weight.

Since the position of the weighing pan and mechanical structure after the restoring force is applied is the same as the unloaded geometry, mechanical non-linearity is eliminated. The transducer is inherently linear, like the time honored balance beam scale. In contrast, a strain gage load cell relies on the deformation of the sensitive spring element to generate an output, a process that is inherently nonlinear.

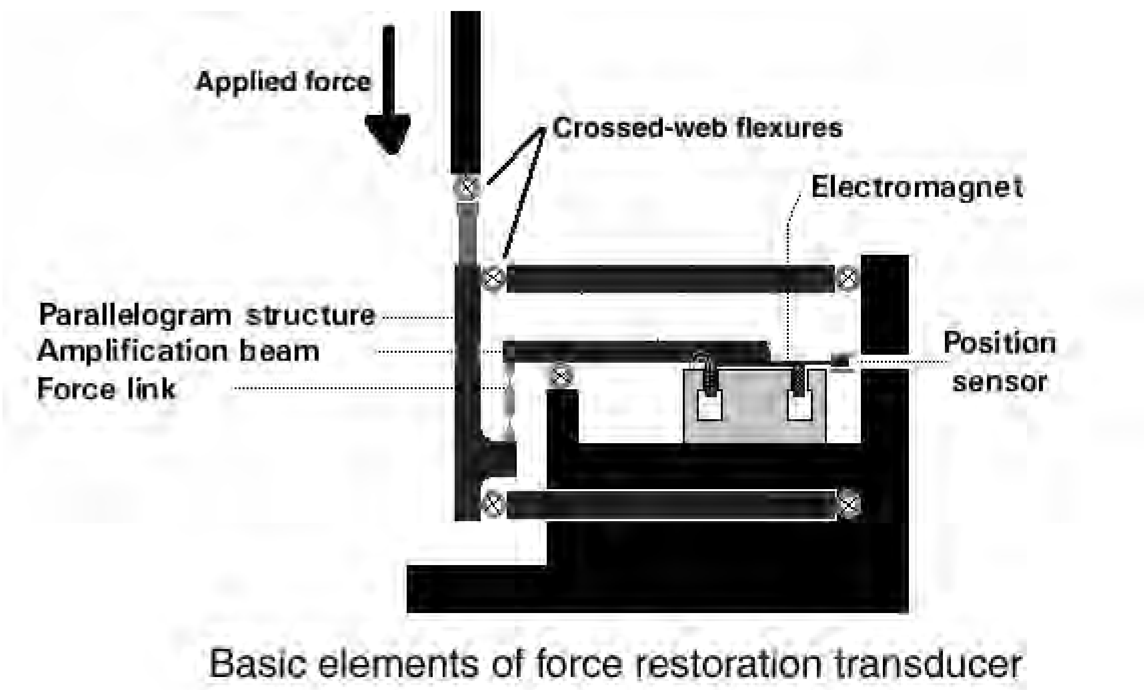



**Figure 18: The current in the electromagnet is increased through a closed-loop servo until the position sensor is centered. Force is then proportional to current applied.**

Another major advantage of this technology over strain gage load cells is that the output voltage of the transducer is in the order of 20 volts. Typical full-scale output voltage of a strain gage load cell is 20 millivolts – resulting in a factor of 1000 poorer signal to noise ratio than a force restoration transducer.

5.2 Vertical CG adjustment

A reason for balancing missile seeker gimbals is to minimize the moments introduced by extreme vibration and other external influences. This same concept holds true for the gimbal balance machine itself. If the total CG height of all moving elements including the fixture and seeker are not near the pivot center of the instrument, then errors can be introduced from floor vibration or changes in floor level due to lift truck traffic, etc. Although these effects are small, when you consider that the machine is capable of an accuracy of 1 part in 100,000, these effects are apparent in the readout and can limit sensitivity. For this reason, a vertical counterbalance is provided to adjust the CG height, thereby optimizing performance. The machine readout serves as an accurate indicator when adjusting CG height. A mechanism alters the level condition of the instrument. If the CG height is correct, then the readout will only change a small amount when the instrument is tilted.

# 6 Effect of gimbal rotation angle on ultimate balancing sensitivity

We define sensitivity to unbalance as the smallest unbalance moment that can be measured for a gimbal with a rotation angle of 45$^{o}$. If the gimbal rotation angle is smaller than this, sensitivity of measurement will be reduced. The table below illustrates this effect.

| **Rated Machine Sensitivity (g-cm)** | **Effective Gimbal Unbalance Sensitivity (g-cm) as a function of gimbal rotation angle** | | | |
|---|---|---|---|---|
| | **. 90$^{o}$** | **. 45$^{o}$** | **. 10$^{o}$** | **. 3$^{o}$** |
| 0.1 | 0.07 | 0.1 | 0.41 | 1.4 |
| 1.0 | 0.70 | 1.0 | 4.10 | 14.0 |
| 0.2 | 0.14 | 0.2 | 0.82 | 2.8 |
| 10.0 | 7.0 | 10.0 | 41.00 | 140.0 |

If possible, you should select a gimbal balance machine that is at least 5 times more sensitive than the balance tolerance for the gimbal. If your requirement is near the limit of the current state of the art, then this will not be possible, and you will have to reduce the allowable unbalance accordingly. For example, if you need unbalance to be less than 0.4 g-cm, and the best gimbal balance machine available has a sensitivity of 0.1 g-cm, then you will need to balance your gimbal to within 0.3 g-cm, to make an allowance for the uncertainty of the gimbal balance measurement.

To calculate the rated machine sensitivity (S) required when given a balance tolerance (T), use the following formula:

$$S = 1.4(T)(F)SIN(a)$$

where **a** is the maximum rotation angle of the gimbal (measured from the midpoint of rotation) and F is the ratio between machine sensitivity and gimbal balance tolerance requirement (typically 0.2).

**EXAMPLE** If the gimbal must be balanced to a tolerance of 2 g-cm, a maximum of 20% of the allowed unbalance may be used up by the machine sensitivity limit, and the gimbal rotation angle is $25^o$, then
T = 2 g-cm, F = 0.2, **a** = $25^o$. The required gimbal balance machine sensitivity is:

$$S = 1.4 \times 2 \times 0.2 \times \sin 25^o = 0.24 \text{ g-cm}$$

Therefore, a machine with sensitivity better than 0.24 g-cm should be purchased (such as the Space Electronics Model GM904S2 with rated sensitivity of 2 g-cm).

## 7 Balancing the gimbal (applying "weight correction")

Weight correction is the process by which mass is added to the gimbal at specific locations to move the CG of the gimbal to the axis about which it rotates. While drilling or machining to remove weight is frequently used to balance rotating machinery, this method is not practical for gimbal assemblies. Instead, balancing is accomplished by adding or moving ballast weights.

The four unbalance components (Ca, Cb, Ab, and Ba) which are measured provide the data required to determine the amount and location of ballast to be mounted to reduce these unbalance components to zero. Ideally, there should be two locations on each axis at which ballast can be mounted. One would be on the axis such that a weight mounted at that location would move the CG in the positive direction along the axis and another to move the CG in the negative direction. This way, each of the four unbalance components can be corrected by simply mounting the appropriate weight at each of four locations. The correct weight is calculated by dividing the unbalance moment by the distance from the axis to the ballast location. In practice, this doesn't work. Some of the limitations are:
It is often impossible to have ballast locations directly on any axis. For example, it is rarely possible to have ballast locations directly on the +C axis because this is where the lens or antenna is mounted. For this reason, gimbals are often purposely designed to be forward (+C) heavy so ballast must always be added at the rear (-C).
The solution can seldom be done by calculation, because with discrete weight increments, there is no unique or perfect solution, so the best solution must be selected from all possible combinations through an iterative process.
Space is limited in a gimbal assembly, so in order to accommodate sufficient ballast weight, several locations are usually needed for each axis.
Item 2 introduces several additional problems.
More ballast locations required more computer time for iteration.
Off axis locations cause interactions; that is each weight affects more than one axis.
Unfortunately, weight correction is seldom high on the priority list of items to be considered early in the gimbal design. By the time a team of engineers considers the problem, it is often too late to implement the best solution.
Weight correction is a little understood topic, even in the circle of gimbal designers.

Most of these problems can be avoided or solved. There are several key considerations to obtaining good gimbal balance by providing good ballast locations.

NEVER mount small ballast weights in such a way that any large mass (gimbal component or large ballast weight) must be removed to mount the smaller weight. Parts NEVER go back together the same way twice and a large weight moved though even a few thousandths of an inch will generate a moment change that will exceed a tight gimbal balance tolerance.
Minimize the number of ballast locations. The total number of iterations is the number of weight increments at each location raised to the number of locations. For example, 5 locations with 10 weight increments each would require 10^5 or 100,000 iterations to check all possible combinations. By comparison, 10 locations with 5 weight increments each would require 5^10 or 9,765,625 iterations. The number of iterations required could very easily exceed the number that can be realistically processed. A ballpark assumption is that a customer will not tolerate more than 15 minutes of computing time to obtain a solution. If each iteration takes on the order of 0.1 milliseconds, then 15 x 60 10,000 = 9 million iterations is the limit. If 5 weight increments are required at each of 10 locations as above, this limit is exceeded. *Best results are obtained* when all possibilities are considered, rather than halting the analysis when tolerance is met.

The ballast locations must be of good "*quality"*. That is, they should be on or very near one axis to generate minimum effects on the other axes. In addition, the stacking directions (for washer type weights) should be parallel to the axis on which the ballast has the primary effect. The stack height must be taken into consideration when calculating the moment effect of a ballast stack. Minimize the number of weight increments at each location. Ideally, each weight should generate moments on the axis of primary effect on the order of ½ the unbalance tolerance. If combined with screw adjustments weights, the weight increments may be much larger. See further discussion of slider weights below. Good balance geometry can easily achieve unbalance reductions on the order of 95% when the initial unbalance is on the order of 100 times the gimbal balance machine sensitivity.

Use slider weights for fine adjustment. Relatively small weights on lead screws may be very effectively used for fine adjustment. These weights should be mounted on screws that are *parallel to each axis*. In this way, they provide infinite adjustment along one axis with no cross talk. In addition, there is no change in total gimbal weight. The moment change is simply the weight of the slider times the distance traveled. Once the gimbal is balanced close to tolerance, using a single pass iterative process, the residual unbalance on each axis can be corrected by a few turns of a screw. It is by far the most effective second pass.
Data stored in the computer for ballast location and increment of weight must be accurate. When balancing with weights and locations that are not accurate, residual unbalances after correction will be larger than predicted. A second iterative pass will not yield improvement if large stacks of weights must be reconfigured with equally inaccurate weights at the same inaccurate locations.

If on axis locations cannot be provided, provide ballast locations in pairs that are symmetrical about one axis. In this way, a pair can be used to affect only one axis while one of the two may be used to simultaneously correct unbalance on two axes.
For high production, adding/removing coarse adjustment weights may be a separate initial operation.

The drawing below shows a gimbal with 9 ballast locations. It is a somewhat unusual design because the B axis, which is typically called the Outer axis is actually inboard of the inner antenna structure. Notice however, that the inner antenna structure as well as the B axis shaft rotate about B while only the antenna structure rotates about the A axis. Only number 7 is on axis. The others can all be used in pairs to behave as a single on axis location, or individually to affect two axes simultaneously. If more than 6 weight increments at each location are needed, the number of iterations will exceed our 15 minute time limit. This configuration is actually better than most that are provided by our customers, but still would require some programming logic to make best use of the available locations.

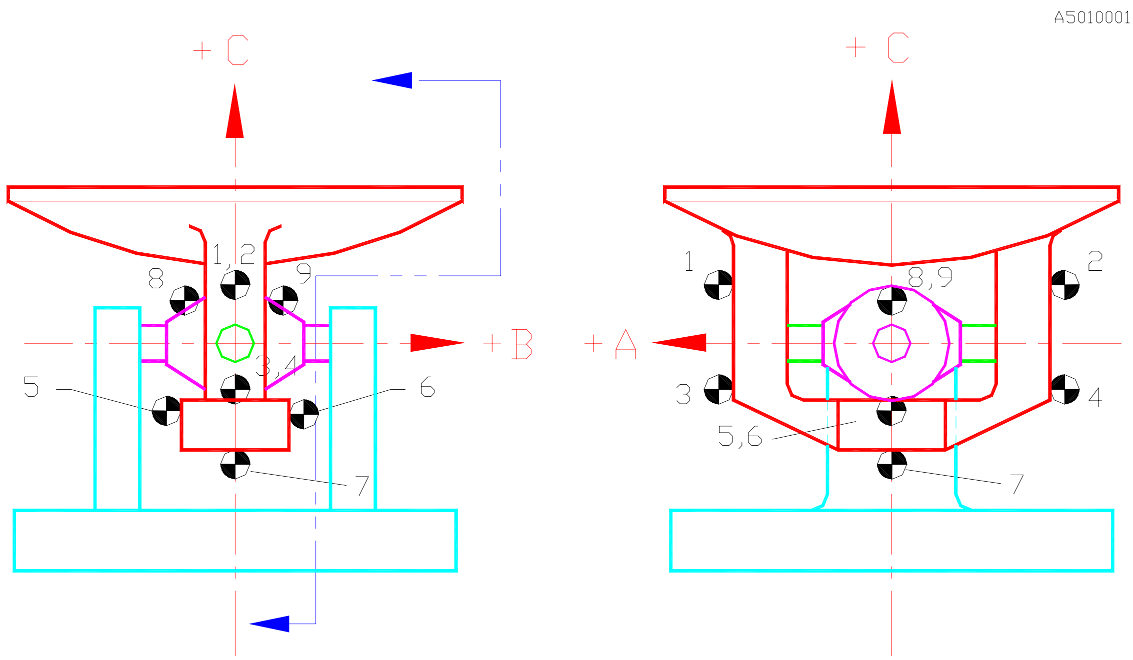



**Figure 19: Ballast Locations**

**What to do if there is no way to correct for a difference in the two values for unbalance "C"** If the difference between these two values is small relative to the three basic components of unbalance, in some instances, it can be ignored. {Some gimbaled test objects do not provide means for correction for this difference in unbalance so that it must be ignored.) In such cases, these two unbalance components are averaged when calculating the correction weights required for balance.}

## 7.1 Custom Weight Correction Software

The gimbal balance instrument calculates and prints the three-axis unbalance of any gimbal. However, this software does not advise the operator what to do to correct the unbalance, since this information is unique to each gimbal measured. It might be possible to add weights to the gimbal on a trial-and-error basis. However, since a correction to the inner gimbal mass causes a change in the unbalance of the outer gimbal axis, a simultaneous solution to the unbalance problem must generally be worked out mathematically (trial and error solutions can take hours to converge on the desired unbalance limit). If the instrument is to be used to its full potential, then custom weight correction software is highly recommended. This custom software calculates the best-fit solution to the balance problem and prints a list of correction weight part numbers and specific locations necessary to achieve balance. In order to write this software, we must be supplied detailed information on the number of available correction weights, their mass, and their location. We strongly recommend that the correction weights be located on or near individual axes of the gimbal. In this way, there is a minimum interaction (cross talk) between correction moments, resulting in two advantages:

The total mass of the correction weights required for balance is kept to a minimum, reducing flight weight.

The computer can quickly converge on a solution to the unbalance problem. If correction weights are not located near the gimbal axes, then it may not be possible to balance certain gimbals by adding correction weights, and part substitution or other methods may have to be used.

**Typical Gimbal Unbalance Report Generated by Computer**

**Unbalance along Axis A** ........................................ **7.31 g-cm**
**Unbalance along Axis C when rotating about Axis A** .................... **4.16 g-cm**
**RESULTANT OF ABOVE [A AXIS]** ........................................ **8.411 g-cm**
**UNBALANCE ALLOWED** ........................................ **4.0 g-cm**

**>> GIMBAL UNBALANCE EXCEEDS TOLERANCE <<**

**Unbalance along Axis B** ........................................ **2.131 g-cm**
**Unbalance along Axis C when rotating about Axis B** .................... **2.652 g-cm**
**RESULTANT OF ABOVE [B AXIS]** ........................................ **3.402 g-cm**
**UNBALANCE ALLOWED** ........................................ **4.0 g-cm**

**>> THIS AXIS WITHIN TOLERANCE <<**

**Typical Ballast Weight Report Generated by Computer**

**Add weights to locations shown**

| WEIGHT LOCATION | NUMBER OF WEIGHTS | WEIGHT PART NUMBER |
|---|---|---|
| 1 | 1 | 1736 AX |
| 3 | 2 | 1738 A |
| 4 | 1 | 1921 |
| 5 | 3 | 11621-3 |

To balance the gimbal, the operator mounts one 1736AX weight at location 1, two 1738A weights at location 3, etc. After mounting correction weights, the operator then re-measures the gimbal to verify that it is within unbalance tolerances.

## 7.2 Information Required to Create Data Table for Weight Correction Software

Exact coordinates of each balance weight location such as the following:

- Location Reference Point - This is the 3-axes reference point for this position. If weights are stacking, this is the center of the base surface with which the first weight in the stack makes contact when mounted. If the weights are set screws, this could be the center of the bottom of the hole or the center of the top flush opening of the hole.

- Stacking Direction - If weights are stackable, this is the direction that the stack height builds. For example, if the stack builds along +C, then +C is all that is needed. If the stack builds at an angle and affects two axes at once, then that relationship is needed, such as "stacks on C-A plane at 60 degrees relative to A and 40 degrees relative to B". If the weights are set screws, then this is the displacement vector the screw travels as it is screwed into the location. As with the stack, this can either be single-axis or multi-axis related information.

- Stack Height Limit or Depth - This is the total height that a stack of weights can achieve. Typically, a greater height will cause interferences with sensor views or physical objects on the gimbal. In the case of setscrews, this is the total depth of travel the setscrew is allowed.

- Mounting Hardware - Any hardware that is needed to mount the weight or weight stack to the gimbal. This can include single or multiple screw(s), with or without washers. Weight values for washers, screws, and weight as well as lengths for screws are all required.

Exact correction weight information such as the following

- Weight Types - The type of weight used may be set screws, washer weights, or even odd shaped weights such as C rings.

- Dimensions - Length, height, width are the dimensional information needed. For odd shaped weights CG location along all 3 axes relative to reference location point above is needed.

- Manufacturing Tolerances - This is needed in order to do an error analysis of projected correction effects when using these weights and positions.

# 8 Electrical Rotation of the Gimbal

The ideal means of rotating the gimbal is to power it electrically (using the optional flex strips which are available with the instrument). If the part is rotated electrically, then no external forces are applied to the gimbal and the change in CG location is entirely a function of the unbalance of the part. Furthermore, this ensures that the rotation angle is correct, and that it does not shift after the dome to the instrument is closed before taking a reading. This requires a "drive/read" electronic package to translate computer commands into the electrical signals necessary for gimbal rotation. Space Electronics can provide this as an option.

All gimbals use some form of motor device to drive each axis of the gimbal and some device for feedback to indicate the position of the axes. In flight the gimbal uses a closed loop guidance system to control the position of each axis to maintain targeting and tracking. On the ground during unbalance measurement, the gimbal's position can be controlled by various combinations of its flight hardware and other control hardware.

To position the axes, most gimbals use a torque motor to apply the rotation force necessary to move and hold the gimbal. For feedback older gimbals use potentiometers that return a voltage proportional to angle. Newer gimbals use resolvers to achieve much greater accuracies.

Following are some examples of how the drive/read loop can be closed to control the gimbal's position.

1. One type of drive/read system uses the gimbal manufacturer's own closed loop control system to power the torque motors and read back the axes positions. In these systems a voltage or digital steering signals are sent from the gimbal balance station to the gimbal's drive read hardware. These signals are then used by the closed loop control to control the torque motors based on the axes positions feedback data (figure 20).

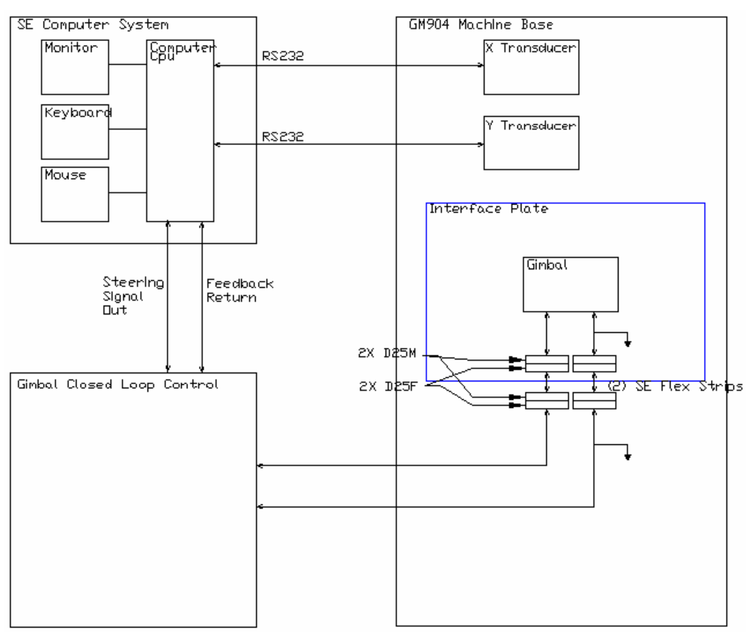



**Figure 20: Type 1 Drive/Read System**

2. Another type of drive system uses separate feedback devices and a separate amplifier system to replace the gimbal manufacturer's close loop control system. In this system the voltage or digital steering signals sent from the gimbal balance station go to an error/feedback circuit. This error/feedback circuit controls the power to the torque motors in the same way as the type 1 system (figure 21).

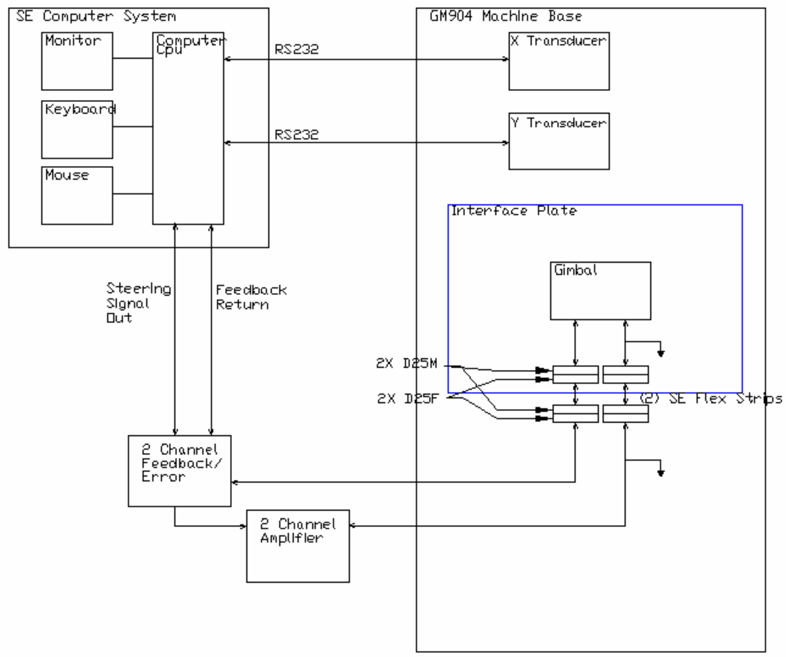



**Figure 21: Type 2 Drive/Read System**

# 9 Operating Environment

A gimbal balance instrument can be operated in just about any location. However, in order to achieve the guaranteed sensitivity, the machine must be located in an environment with the following characteristics.

1. The stability of the floor must be such that walking around the instrument or driving lift trucks or other vehicles nearby does not disturb the level condition of the instrument. This is often the limiting factor on sensitivity. As discussed previously, a major improvement can be made by adjust the CG height of the movable section of the gimbal balance machine so that its CG is coincident with the pivot axis of the machine.

2. Short term temperature stability should be at least +/-1$^{\circ}$ C and preferably should be +/-0.5$^{\circ}$ C over a 10-minute period. This does not require elaborate air conditioning systems. A simple shroud or inner room that restricts the motion of air in and out of the test area will accomplish this.

3. The test area should be free from drafts. Although the gimbal balance machine has a built-in dome enclosure, it is still possible that excessive air motion around the instrument can affect readings.

4. The 115 VAC line used to power the instrument must be free from electrical transients and must be more than 90 VAC and less than 130 VAC.

## 10 Precautions

**Avoid moving anything other than the rotating part of the gimbal** Since the gimbal balance instrument determines unbalance by noting the change in center of gravity which results when the part is rotated about its own axis, care must be taken to avoid disturbing any wires, fiber optic light guides or other elements of the gimbal itself when the gimbal is rotated, since the resulting change in CG will be interpreted as gimbal unbalance. . Therefore, extreme care should be used during the testing sequence to prevent extraneous changes in moment from occurring. This precaution is particularly important if the gimbal is rotated manually. In addition, any accidental disturbance of the machine tare weights that may occur between the four readings, or any movement of the gimbal in its fixture will also be erroneously interpreted as gimbal unbalance.

**Don't overload the machine** It is important not to overload the machine when the gimbal is rotated about its axis during the measurement sequence, since this may result in reduced sensitivity. We have seen instances where an inexperienced operator leaned on the gimbal while moving it from position 1 to position 2, etc.

**Make certain the rotation angle is correct** The software interprets the change in CG as the result of a specific angular rotation of the gimbal. If the intended angle is ±30 degrees, and the operator accidentally only rotates the gimbal by 25 degrees, then this will produce a 17% error in the measured unbalance. Furthermore, if the operator is rotating the A axis, then the B axis must be positioned exactly at 0 degrees.

**Make certain that the table defining the locations of the correction weights is correct** Errors in this table will reduce the reduction ratio for each iteration.

## 11 Obsolete Methods of Gimbal Balance

Before our gimbal balance instrument was developed, gimbal mounted seekers were balanced using three methods, as described below. None of these methods produced satisfactory results, and their use is now generally limited to old programs where the test procedures have been frozen by management or by the government and cannot be changed by the engineers in charge.

Add-Weights-Until-Everything-Is-Level Method If the seeker bearings had no friction, and there were no wires or other objects which caused a torque about the seeker axis, then it would be possible to balance the seeker by setting it on a bench and adding weights until the antenna or optical assembly assumed a level condition. If the CG of the seeker were above the pivot axis of the bearings (causing the seeker to flop to either side when unbalanced), then the seeker could be hung upside down and balanced by this method. Unfortunately, all seekers have considerable friction (the bearings have to be tight to minimize play) and all seekers have wires or fiber optic light guides that cause torque about the bearing axis, so this method can only be used to measure gross unbalance (such as might be caused if some part of the guidance system were missing.)

Knife Edge Method With this method, prior to assembly the seeker inner shaft was supported on knife-edges. Weights were added on a trial and error basis until the part was balanced on one axis. The outer gimbal ring was now added, and the assembly was supported on the shaft for the outer bearing. Weights were then added to balance this axis. Unfortunately, this unbalanced the first axis and the seeker had to be disassembled and rebalanced, etc., etc. This method could require as long as 3 days to balance one part. In addition to the tedious nature of this method, there was a fundamental problem: when the seeker was assembled after balancing, wires, fiber optic light guides, and other flexible moving objects were added; these unbalanced the part again, and there was no way to correct for this unbalance.

Shaker Method The seeker was assembled completely and then mounted on a shaker (vibration test exciter.) The error signal from the feedback potentiometers on the seeker was monitored while the seeker was moved up and down sinusoidally at various rates. Trial and error corrections were then made and the test repeated. This method overcame the objections of the knife-edge method in that the part could be balanced in the final assembled condition. However, it had several disadvantages:

3. The test equipment required was extremely expensive.
4. The gimbal was subject to extreme vibration, which could cause damage.
5. Often a gimbal would be destroyed when an electrical transient caused the shaker to give out a shock pulse.

The majority of gimbal balance machines in use today were manufactured by Space Electronics. The Space Electronics method overcomes problems inherent in other methods.

## 12 Thoughts about the design of your gimbal

**Limitations on final balance -** Gimbal design can significantly affect the ultimate ability to balance the gimbal. Good design will:

- minimize movement and size of wire/fiber optic bundles and provide secure tie down points
- minimize cross axis effects of balancing weight locations by incorporating ballast weight attachment points into the basic design
- minimize gaps in the balance weight moment table by providing weight increments which represent less than ½ of the balance tolerance for the gimbal
- minimize bearing tolerances (usually OK, since the performance of the seeker or telescope with depend on having tight tolerance bearings)

**Budgetary -** Tight balance tolerances increase the cost of balancing in two ways.

1. The initial cost of high sensitivity machines is greater than the cost of low sensitivity machines. Some of this cost may be offset by the greater unbalance reduction for each run.

2. The tighter the balance tolerance, the longer it will take to balance a gimbal. This results from several factors:

   a. Since coarse correction weights are not always their nominal mass and location, unbalance reduction is limited to a factor of 20 or less in a single run. If the required tolerance is less than 4 g-cm, then two runs are usually required.

   b. It is more time consuming to install a complex set of small correction weights than a few large weights.

   c. High sensitivity often requires longer measurement time in the balancing machine, to eliminate external environmental influences such as ground vibration.

## 13 Different Types of Gimbals we have Encountered

**Two-Axis Single Plane**
This type of gimbal has two axes about which the gimbal can rotate. The axes are perpendicular to each other and exist on a single plane that is perpendicular to a non-rotating 3rd axis. This is the simplest of gimbal types.

**Two-Axis with "Look Down Angle"**
This type of gimbal also has two perpendicular and co-planer axes about which the gimbal can rotate. However on this type of gimbal one of the axis (usually elevation) is canted down when the gimbal is driven and held at its 0 angle on each axis. This complicates the relationship to the flight-line axis (C axis) about the outer assembly axis (elevation axis) and the perpendicular axis (C axis) of the inner assembly axis (azimuth axis).

**Two-Axis Non-Single Plane**
This type of gimbal has two perpendicular axes but the axes are NOT on the same plane. On this gimbal, care must be taken when relating the common axis (C axis) since they are measured about origins that are offset from one another.

**Two-Axis + Sub-Assembly Single Plane**
This type of gimbal is the same as the "Two-Axis Single Plane" but with the addition of another mass assembly that rotates with one of the axes in the opposite direction. This adds a vector unbalance whose relationship to the primary axes being measured must be tracked to allow balancing of the primary axis. In order to do this, the sub-assemblies' vector unbalance, and its motion relationship to the primary axis must be determined.

**Two-Axis Roll-Axis Gimbal**

In this case, one of the pivot axes is coincident with (or parallel to) the flight-line axis. The gimbal must be positioned so that this "roll" axis is at 45 degrees to the horizontal plane. When fixtured properly, this becomes the simple case of a 2-Axis Single Plane gimbal.

**Gimbals with more than two degrees of freedom**

Some gimbal assemblies have a primary gimbal that allows for rough positioning, but has a slow response, and a second "piggy-back" gimbal that is light and has a fast response. The "LANTIRN" gimbal has 5 degrees of freedom, and is analogous to a human neck, head, and eyes. The "neck" provides three degrees of freedom (yaw, pitch, and roll axes) and is used to get a coarse position. The "eye" provides two degrees of freedom (yaw, pitch), and is used for rapid fine positioning.

## 14 Product of Inertia Unbalance

Until recently, product of inertia unbalance has been ignored by most engineers. However, the effect of a large POI can be quite significant in certain applications.

Weight correction configurations can be optimized for correcting unbalance and as well as POI. In placement of the correction positions, care should be taken to insure that they can be used to correct the unbalance and POI independently. In the following example, the inner assembly has a sizable forward unbalance (along C about A).

A (two piece) main counter weight is designed to mount on the back (Along -C) of the inner assembly (figure 22). This counter weight has been designed with correction weight positions that form 2 parallel rows of 4 parallel positions each, plus 2 holes bored parallel from one end of the counter weight to the other and perpendicular to the 4 holes. The first 8 positions are drilled parallel to the C axis while the second set of 2 holes are drilled parallel to the A axis, as shown in the illustration.

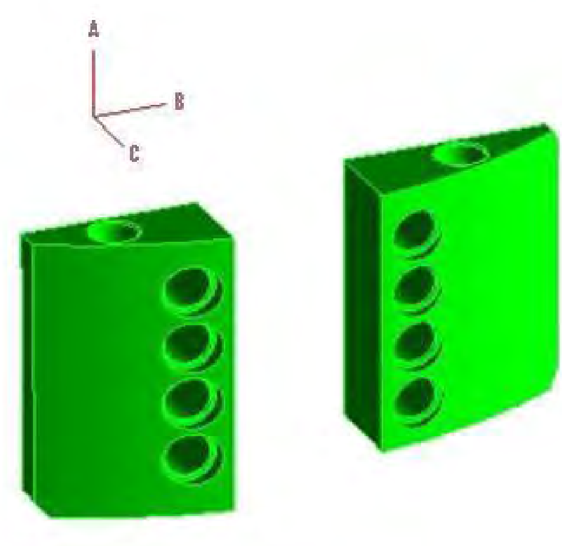



**Figure 20: Two Piece (Balanced) Counter Weight**

The main counter weight was designed so that a nominally balanced gimbal requires all six positions loaded with setscrews. The first four correction weights are mounted into the middle set of C adjustment holes, threaded to the middle depth. The last two correction weights are mounted, one in each A adjustment hole threaded to the mid point. See figure 23.

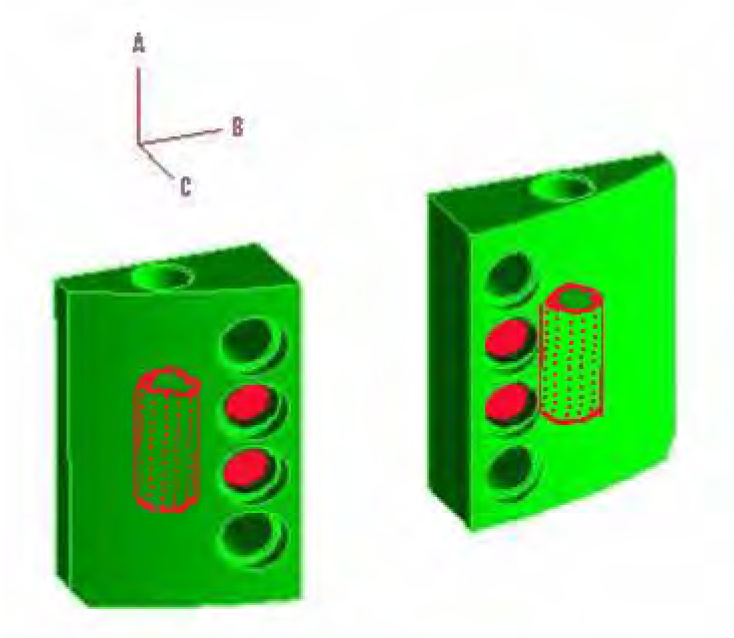



**Figure 21: Nominal Weight Configuration with screws inserted**

When the gimbal requires a negative C correction, the set screws can be removed (aft) or replaced with heavier set screws (see figure 24).

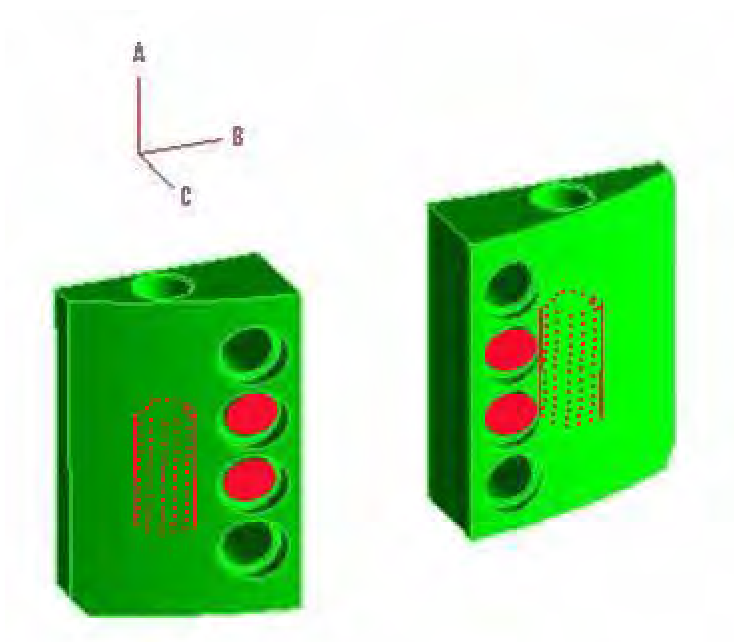



**Figure 22: Nominal Weight Correction Adjusted to Produce Negative C Correction**

In order to avoid changing the POI in the AC plane, two setscrews balanced along the A axis should be adjusted back or replaced so that the following POI equation remains zero.

AC Plane POI Change = (W1*A1*DeltaC1) + (W2*A2*DeltaC2)
Along C Change = (W1*DeltaC1) + (W2* DeltaC2)

Where W1 = Weight of upper set screw
A1 = Along A axis dimension of the upper set screw position
A2 = Along A axis dimension of the lower set screw position
A1 and A2 positions are equal but opposite distance from the B axis
DeltaC1 = Change in position depth of the upper weight
DeltaC2 = Change in position depth of the lower weight
DeltaC1 and DeltaC2 are equal

As the C dimensions change, the effects on the POI from the upper and lower weight cancel each other causing no change in the POI. Since the (along A) or (along B) unbalance remain unchanged, the AB plane POI remains also unchanged.

For a gimbal that is statically balanced, but the AC plane POI needs to be changed, two of the correction weights can be screwed in opposite directions to cause the Delta C for each weight to go in opposite polarities, causing the POI to increase or decrease in the equation above (figure 25).

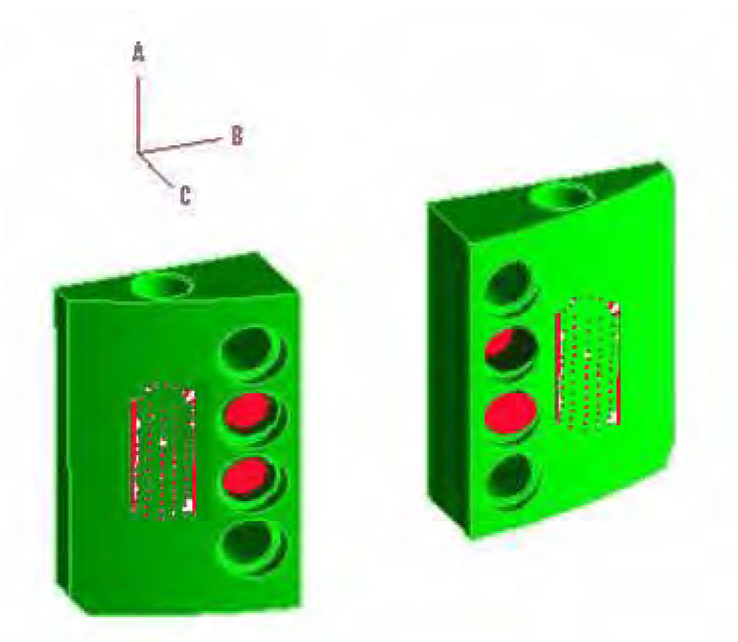



**Figure 23: Nominal Weight Correction Adjusted for AC Plane POI Affect**

Since they are changed in equal and opposite directions, the along C unbalance will remain unchanged. If more AC plane POI change is needed, the weights can be moved away from each other along A, increasing the effect on the AC plane POI when the Delta Cs are changed (figure 26).

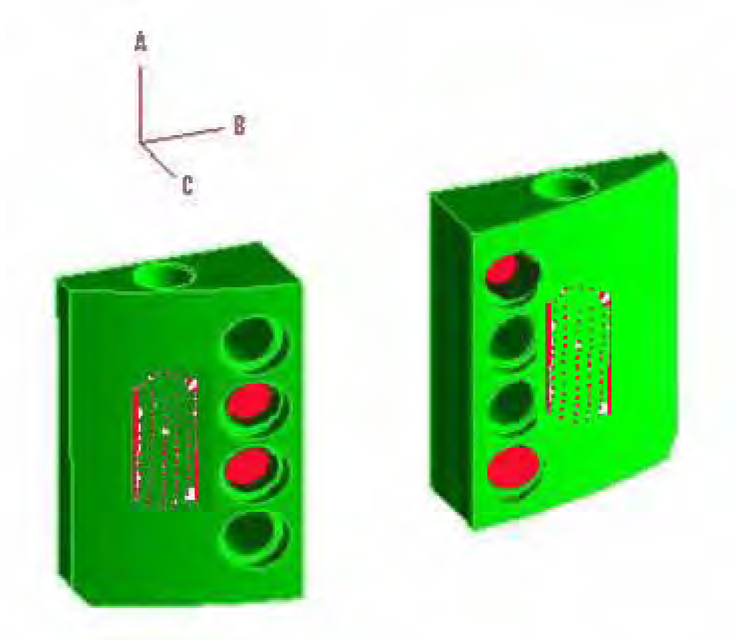



**Figure 24  Nominal Weight Correction Adjusted for Greater AC Plane POI Affect**

The two correction positions that are parallel to the A axis and are threaded from end to end can be used to correct for an along-A axis unbalance as well as correct the AB plane POI. By moving them up and down along A together they will adjust the along A axis unbalance (figure 27).

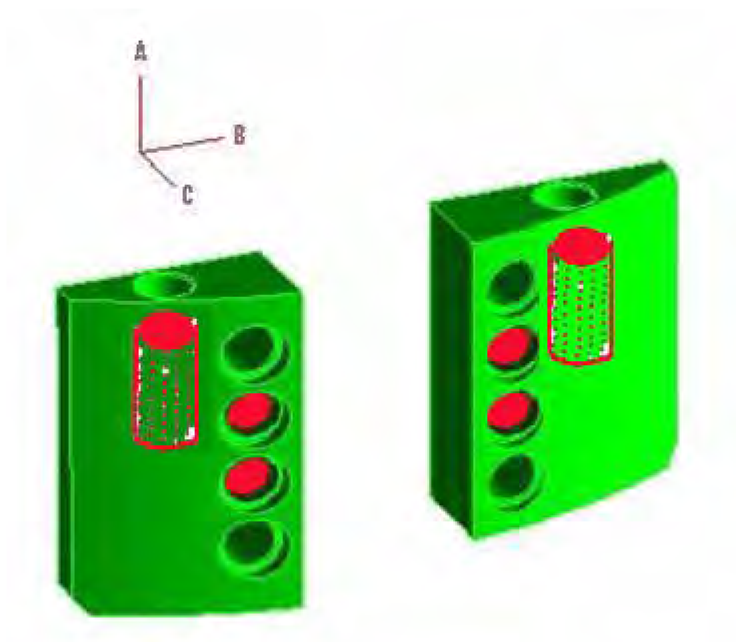



**Figure 25:  Nominal Weight Correction Adjusted for + A Effect**

By moving them up and down along A equal and opposite each other they will not change the along A axis unbalance but will change the AB plane POI (figure 28).

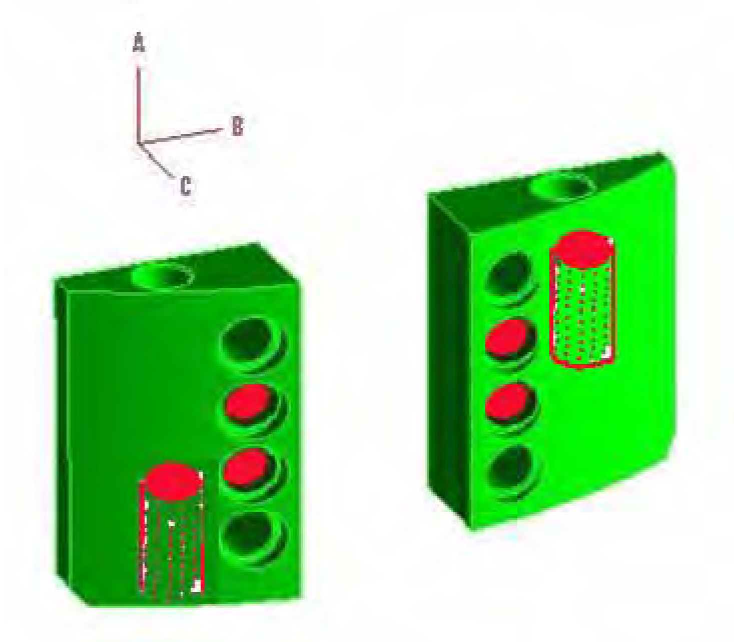



**Figure 26Nominal Weight Correction Adjusted for AB Plane POI Effect**

## 15 Conclusions

An instrument has been developed that measures the unbalance of gimbaled devices such as missile seekers and airborne telescopes with extraordinary accuracy. Balance sensitivity is better than 0.001% of full-scale moment. The instrument first measures the unbalance of the gimbaled device with sensitivity as high as 0.1 g-cm. Then the computer calculates the optimum ballast weights and the locations on the gimbal to balance the gimbal about its rotational axis.

This device has reduced the time to balance a seeker from days to less than one hour. Furthermore, the high performance has driven the industry. Missile seekers can now be made smaller and lighter, because the higher degree of balance obtainable with the Space Electronics instrument has reduced the torque requirements on the positioning motors.

This paper has attempted to present the mathematics and concepts required to balance devices with two or more degrees of freedom.

## About the Authors

**Richard Boynton** is President of Space Electronics, Inc., Berlin, Connecticut, a company he founded in 1959. Space Electronics, Inc. manufactures instruments to measure moment of inertia, center of gravity, and product of inertia. Mr. Boynton has designed many of the mass properties measuring instruments manufactured by Space Electronics. He has a B.E. degree in Electrical Engineering from Yale University and has completed graduate studies in Mechanical Engineering at Yale and MIT. He is the author or co-author of 73 papers, including 36 papers presented at SAWE International Conferences and 3 papers presented at Regional Conferences. Four of Mr. Boynton's papers have won the "Mike" Hackney Award for Best Technical Paper at the International Conference of the SAWE. He is the author of the SAWE Recommended Practice for Standard Coordinate Systems for Reporting the Mass Properties of Flight Vehicles. Mr. Boynton has been a member of SAWE for over 30 years and is currently Director of the Boston Chapter. In 1992 he was elected a Fellow and in 1998 was elected an Honorary Fellow of the SAWE. Mr. Boynton is also a member of the AIAA and the Society of Automotive Engineers, where he serves on the Balancing Subcommittee (which is currently involved with setting standards for jet engine balancing).

Mr. Boynton is a former professional folksinger. In addition, he is an artist, specializing in pen and ink drawing. He recently illustrated a book of poems entitled A Web of Longing and Desire (Published by Lamentation Mountain Press).

**Kurt Wiener** is Chief Engineer of Space Electronics, Inc. Mr. Wiener holds a B.S. in Mechanical Engineering from M.I.T. and a M.S. in Industrial Education from Central CT State College. He is a former Associate Professor of Mechanical Technology at Vermont Technical College. Mr. Wiener is the principal instructor for the Mass Properties Seminars that are presented twice a year at Space Electronics. He has co-authored 15 papers for SAWE conferences. He won the "Mike" Hackney Award for Best Technical Paper at the International Conference of the SAWE in 1998.

**Paul Kennedy** - is Operations Manager and Sales Manager of Space Electronics, Inc. Mr. Kennedy received his engineering education at the University of Connecticut. Paul joined Space Electronics in 1983. He is the main point-of-contact for technical and contractual issues between our customers and our staff.

**Brandon Rathbun** - is the Assistant Chief Engineer and Director of Software Development of Space Electronics. Mr. Rathbun received his engineering education at Porter & Chester Institute. He is responsible for standard and custom software for all instruments manufactured at Space Electronics.