

## **HOW MASS PROPERTIES AFFECT SATELLITE ATTITUDE CONTROL**

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**Richard Boynton** is the former President of Space Electronics, Inc., Berlin, Connecticut, a company he founded in 1959. Space Electronics manufactures instruments to measure moment of inertia, center of gravity, and product of inertia. Many of these instruments were designed by Mr. Boynton. He currently is President of Middlefield Engineering, LLC, and is a director of Komodo Industries, Inc. 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 79 papers, including 39 papers presented at SAWE International Conferences and 3 papers presented at Regional Conferences. Four of Mr. Boynton's papers have won the L. R. "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, and is co-author of the Recommended Practice for Mass Properties Measurement (hopefully soon to be released).

Mr. Boynton has been a member of SAWE for over 40 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 a former member of the AIAA and the Society of Automotive Engineers, where he was the Secretary of the Balancing Subcommittee (which was 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).

## **Abstract**

The success of a satellite mission is highly dependent on the accuracy of the measurement of its mass properties before flight and the proper ballasting of the satellite to bring the mass properties within tight limits. Failure to properly control mass properties can result in the satellite tumbling end over end after launch, or quickly using up its thruster capacity in an attempt to point in the correct direction. Solar panels must continue to point toward the sun as the satellite orbits the earth. Telescopes must point earthward. Satellite attitude control systems generally consist of a closed loop of measurement and correction of the spacecraft's attitude such that it is constantly driven into its desired nominal orientation, effectively rejecting any disturbances imposed on the satellite, such as variations in the earth's magnetic field, non-spherical shape of the Earth, lunar and solar perturbations, drag of the residual atmosphere on the solar array, and solar radiation pressure, or by movement of mechanical parts within the satellite. This paper discusses the different means of attitude control: thrusters, momentum wheel, spin stabilization, gravity gradient stabilization, and magnetic field control, with emphasis on the relationship of mass properties to these control methods.

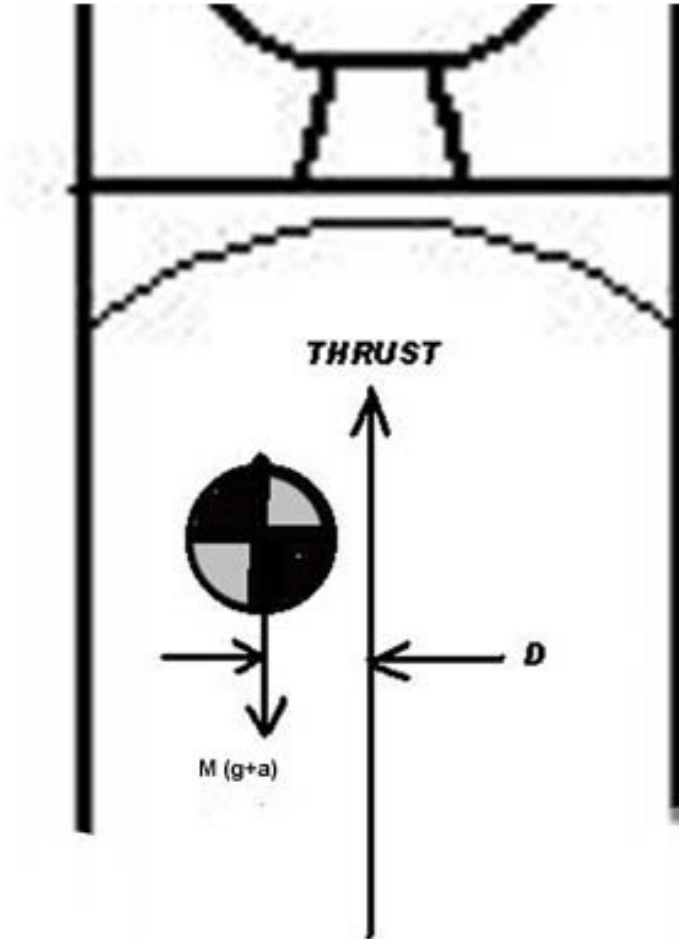
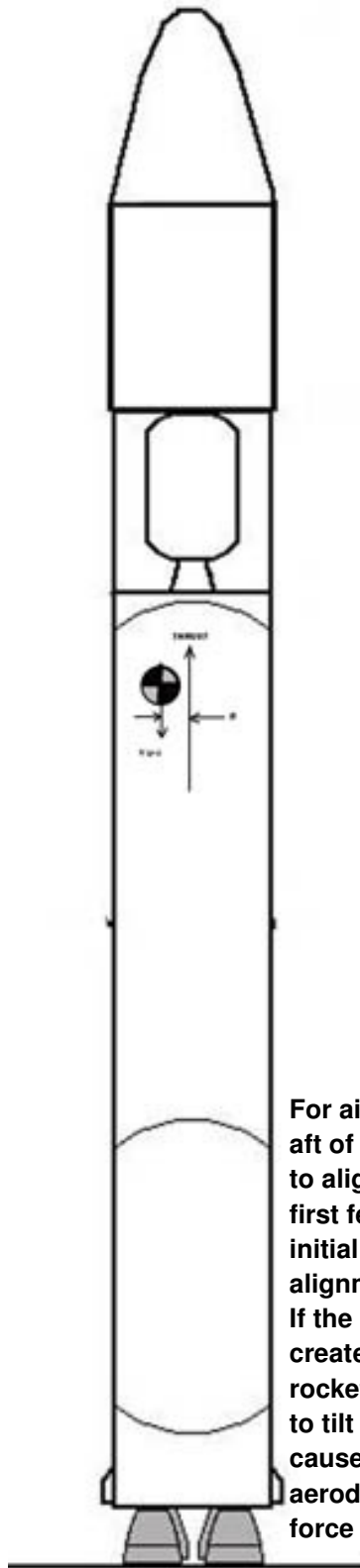
### **Satellite flight can be divided into 4 phases:**

1. Initial launch, using a two or three stage booster
2. Injection into the approximate desired orbit, using a "kick" motor on the satellite
3. Fine positioning to set the exact initial orbit or to correct for atmospheric drag, using small thrusters on the satellite
4. Attitude control to rotate the satellite about its CG so it points in the desired direction (many methods are discussed in this paper)

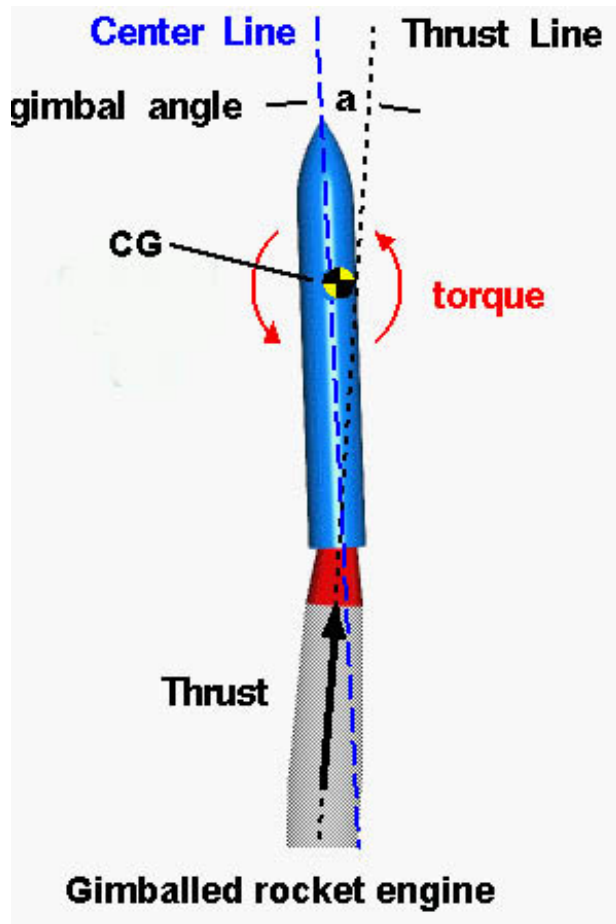
### **Initial Launch**

Mass properties play a key role in the first few seconds of rocket flight. At initial launch, there is no forward motion of the rocket and consequently no aerodynamic forces to stabilize the rocket motion. Alignment between the center of thrust and the center of gravity of the vehicle is critical to prevent large offset moments from being generated. If an engineer is used to dealing with flight vehicles that are inherently stable (such as aircraft), then the sensitivity of rocket flight to CG misalignment may come as a surprise. It is not uncommon for engineers to specify tight tolerance for rocket CG, such as +/- 0.002 inch. Unfortunately, many companies measure the rocket CG in a dry condition (i.e. without fuel). Since the weight of fuel can be as high as 85% of total vehicle weight, making a dry measurement can be almost meaningless unless you subsequently measure the same rocket after fueling. In my opinion, the only reliable way to

measure rocket CG is to locate the measuring equipment in the fueling area, and make the measurement (and perform ballasting if necessary) after the rocket has been filled with fuel.



For aircraft (and air-to-air missiles), the center of pressure of the airframe is aft of the center of gravity of the vehicle, so that aerodynamic forces tend to align the vehicle to the direction of flight. This is not the case for the first few seconds when a rocket is launched from earth, since there is no initial forward velocity to create aerodynamic forces. The aerodynamic alignment disappears again when the rocket leaves the denser atmosphere. If the rocket CG is offset from the center of thrust, then a torque will be created equal to the CG displacement  $D$  times  $M \cdot (g+a)$ . The gimballed rocket motor will rotate to align the thrust with the CG, causing the rocket to tilt relative the direction of flight. As the rocket builds up speed, this causes a drag. Subsequently tilting the rocket motor to align the rocket aerodynamically will reduce this drag but will waste a portion of the thrust force to correct for CG offset.



As fuel is consumed, the rocket CG changes dramatically. To minimize flight problems, the fuel tanks are nominally located exactly on the centerline of the vehicle, and the tanks contain pressurized bladders or baffles that minimize sloshing of the fuel and attempt to keep the mass of the fuel centered. However, if the fuel tank is not centered properly relative to thrust, as the fuel is consumed, the CG will shift along the yaw or pitch axis due to the increased importance of the mass of structure. The solution to this problem is to measure the rocket CG without fuel and then add the fuel. If the tanks are centered properly, the CG should not shift appreciably in a radial direction when fuel is added. CG will most likely move along the roll axis, but this is of a smaller consequence since the rocket does not use aerodynamic forces for stability, so that the

distance along the roll axis between the CG and the aerodynamic center of pressure is not a major factor.

It is easy to measure CG location relative to hard points on the rocket structure, using commercial equipment such as the instruments manufactured by Space Electronics, but often it is hard to accurately determine the relationship between CG and the center of thrust. What reference do you use for the thrust centerline? Is the center of thrust aligned with the dimensions of the rocket motor exit cone or is it canted slightly due to any number of complex factors within the engine? What about tolerance buildup between the mounting surface of the rocket on the center of gravity instrument and the location of the rocket motor nozzles? Thrust alignment is determined by mounting a similar rocket motor in a “thrust stand” that is instrumented with strain gage load cells and determining thrust alignment (as well as total thrust). Optical means can be used to determine alignment of the motor with the rocket structure. Photogrammetric techniques have been refined so that three axis positioning can be measured with a few thousandths of an inch.

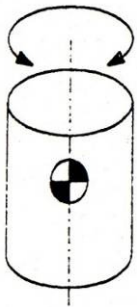
In the early days of satellite launches, it was not uncommon for a rocket to make a sharp turn shortly after leaving the launching pad and have to be destroyed. Other rockets would begin to “pinwheel” (tumble end over end) shortly after launch. I was hired as a consultant by a government agency in a foreign country after a rocket turned around and flew into the launching

pad, creating a 6 foot deep hole in the concrete and destroying the launch facility. One of the major causes of these failed flights was CG misalignment with the center of thrust. Another was the degree of balance of the gimbaled guidance system (see SAWE Paper No. 3320 *Static Balancing a Device with Two or More Degrees of Freedom –(The Key to Obtaining High Performance On Gimbaled Missile Seekers)*). Now there appears to be a much greater awareness of the importance of aligning rocket CG and of some of the pitfalls in the process.

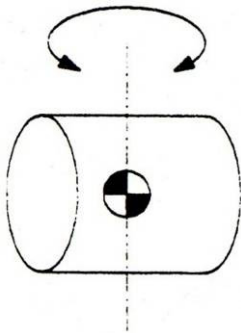
### Rocket moment of inertia

Although moment of inertia is less critical than center of gravity, it does have a significant effect on flight. At the instant of lift off, transverse (i.e. pitch or yaw) MOI is the only “force” resisting the tilting of the rocket. This is not a new concept—ancient tribesmen discovered thousands of years ago that a spear flies straighter if it is long and narrow. More recently engineers have assumed that they could calculate moment of inertia with sufficient accuracy that they didn’t need to measure it. I have seen reports that listed the expected MOI error as “less than 2%”. In fact these calculated MOI values were in error by more than 100%. The reason is that fluid makes up about 85% of the rocket mass, and the assumptions the mass properties engineers were using were erroneous. One school of thought assumed that the MOI of the fluid in the tanks was zero, since the fluid would remain stationery and the tank would move about it. The other school of thought assumed that the fluid should be treated as a solid. Neither of these assumptions is correct. As I have demonstrated in two SAWE papers on fluid dynamics, the effective MOI of the fluid depends on the shape of the tank and the presence or lack of baffles within the tank. {See SAWE PAPER No 2459 *The Moment of Inertia of Fluids*, and SAWE Paper No. 3006 *The Moment of Inertia of Fluids—Part 2.*}

Some of the conclusions of these papers are summarized below:



**1. Roll Moment of Inertia** The MOI of the fluid in a cylindrical tank is not zero about its centerline as is commonly supposed. For a simple right cylindrical tank with flat ends which are perpendicular to the centerline, it ranged from about 3% of the solid equivalent MOI for a fluid with the viscosity of water (or hydrazine) to 93% of the solid equivalent MOI for a fluid with the viscosity of gear oil. Since the mass of the fluid can be over 80% of the mass of the vehicle, this can be a significant contributor to the total MOI. In fact, the liquid can be the largest contributor to roll moment of inertia (as well as pitch and yaw MOI).



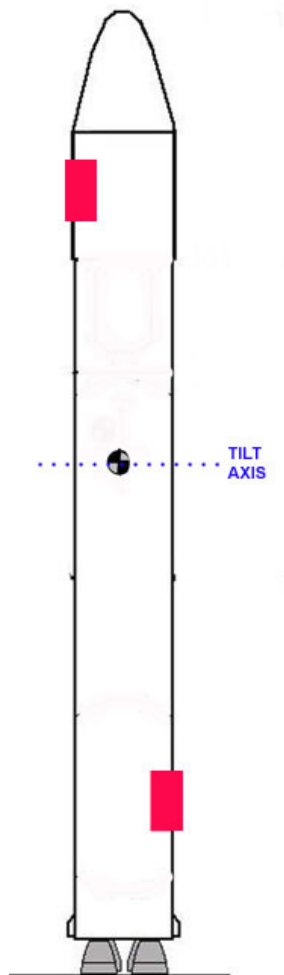
**2. Pitch and Yaw Moment of Inertia** The MOI of the fluid in a cylindrical tank about an axis perpendicular to its centerline typically ranges from 40% to 80% of the MOI which would result if the fluid were solid. The percentage of mass which should be used to calculate this effect depends on the aspect ratio.

3. **Viscosity** As the viscosity of the fluid increases, the fluid moment of inertia increases. This effect is most dramatic for the roll MOI about the centerline.

4. **Other effects of fluid** If a tank spins continuously in one direction, eventually all the fluid within the tank spins with the tank. For a given deceleration force acting on the spinning tank, an empty tank will slow down more quickly than a filled tank. In our tests, if the tank was not completely filled, its speed decreased and increased in an oscillatory fashion as it gradually slowed down. I would expect different results at zero g.

### Rocket Product of Inertia

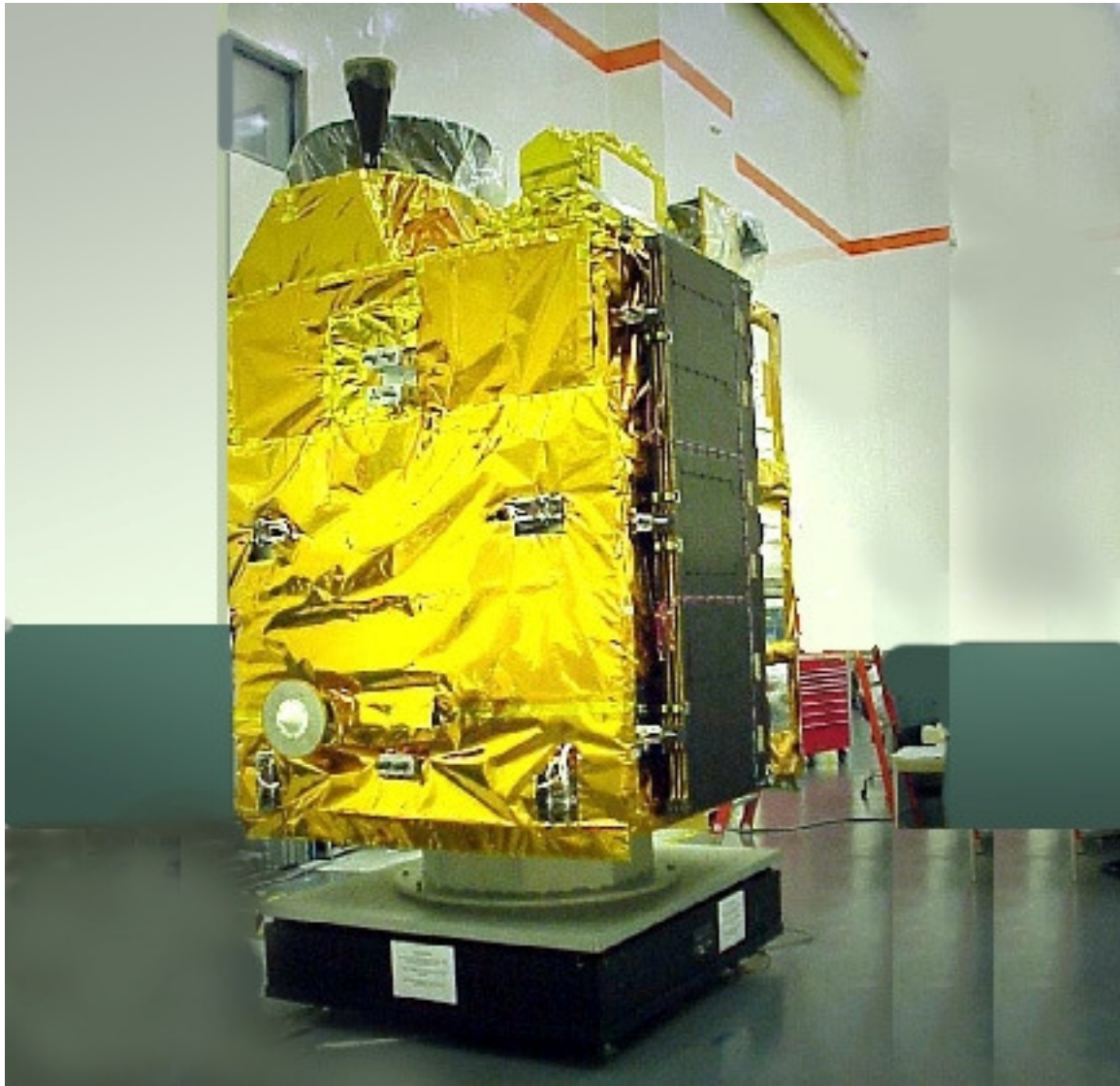
I frequently hear the comment that POI is not important for rockets that do not spin. It's true that the principal axis is not a critical issue in this case, but POI does have several effects.



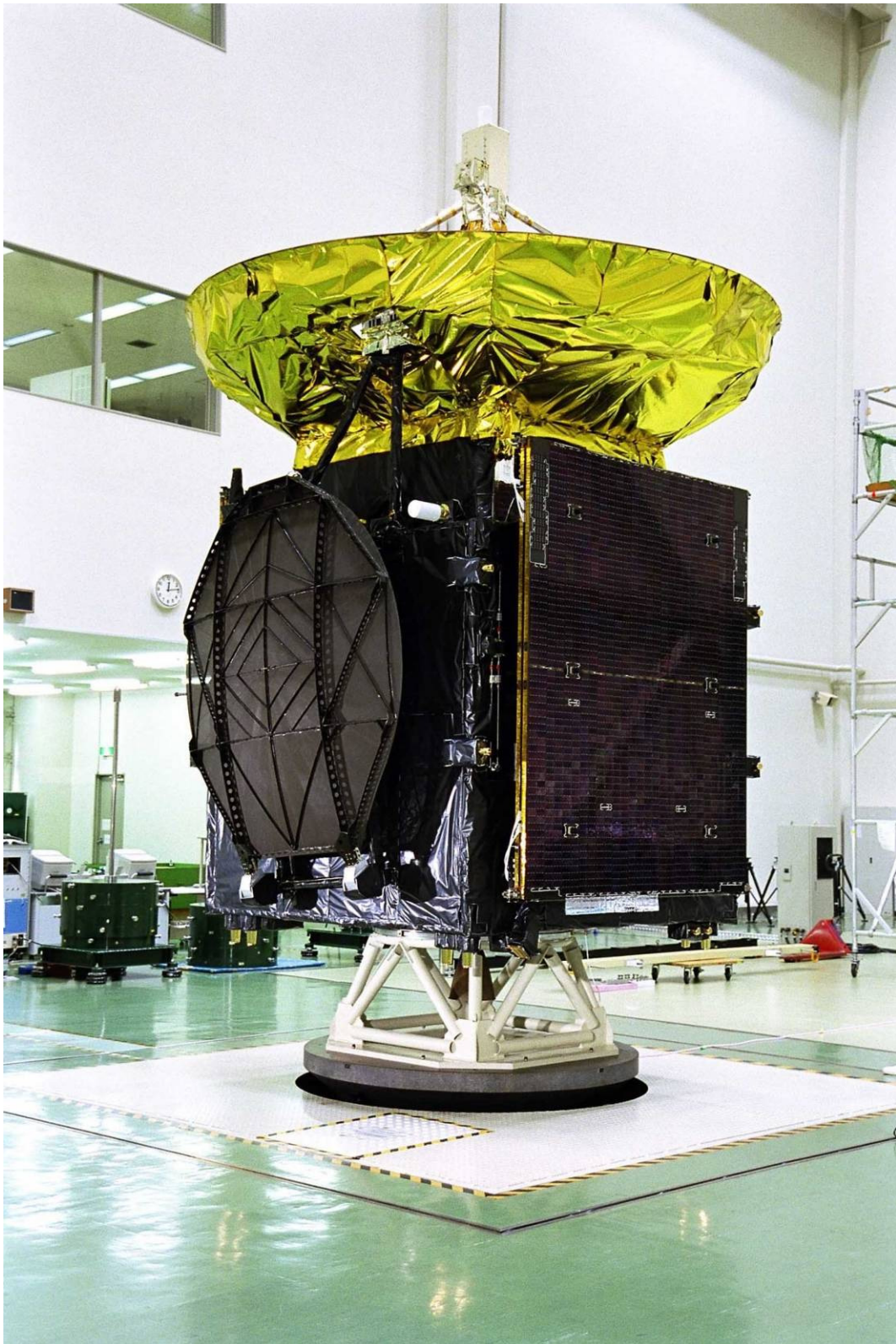
Consider the rocket shown along the left margin of this page. The red weights have been added to simulate a product of inertia unbalance. Since they are equal in mass and located equidistant from the CG, the CG position remains unchanged. However, when the rocket tilts about its CG to change the direction of flight, a couple is created, causing the rocket to rotate. The rocket will want to rotate about its principal axis, resulting in a coning of the rocket and increased drag.

Spin stabilized rockets will tilt to align with the minor axis along the length of the rocket. This results in an “angle of inclination”. Given a certain product of inertia, the amount of tilt (“A” degrees) is related to the moment of inertia difference between the major and minor axes by the following formula, where  $P_{xy}$ ,  $I_{yy}$ , and  $I_{xx}$  are in the same units.

$$A = \frac{1}{2} \arctan\left[\frac{2P_{xy}}{I_{yy}-I_{xx}}\right]$$



**Measuring weight and center of gravity of a satellite on a Space Electronics WCG Series machine**



**Measuring moment of inertia and center of gravity of a satellite on a Space Electronics instrument (the instrument is mounted in a pit under the floor to give maximum height capability and to simplify loading the satellite on the instrument)**

## Second stage

Most satellite launches require at least two stages. When the first stage runs out of fuel, explosive bolts release the second stage, which then ignites. Second stage motors may use a different technology than the first stage. Because of the greatly reduced mass, this second stage should have a lower thrust to prevent excessive g load on the satellite. Since the second stage is not flying in a dense atmosphere, it does not have to have an aerodynamic shape, and there is little concern that protruding objects will be damaged by windage forces.

The second stage will have enough fuel to put the satellite into orbit, but this may be a temporary orbit that has to be modified by the rocket motors in the satellite.

## Injection into the approximate desired orbit

Achieving orbit depends on two factors:

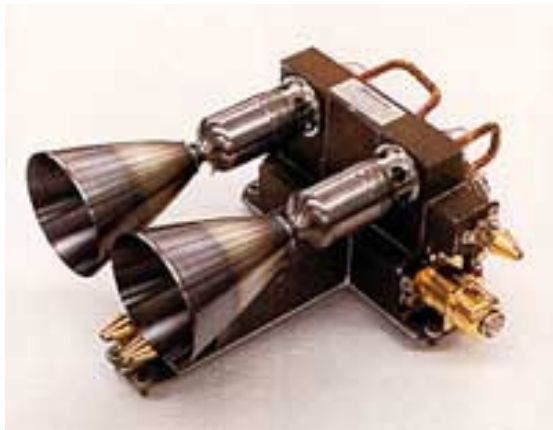
1. Reaching the desired altitude above the earth
2. Achieving the minimum velocity parallel to the earth to sustain orbit

The speed needed to orbit the earth depends on the altitude, according to Kepler's formula:

$$V = \sqrt{g * R^2 / (R + h)}$$

where **V** is the velocity for a circular orbit, **g** is the surface gravitational constant of the Earth (32.2 ft/sec<sup>2</sup>), **R** is the mean Earth radius (3963 miles), and **h** is the height of the orbit in miles

The higher the altitude, the lower the required velocity parallel to the earth. For example, to orbit the earth at an altitude of 100 miles, a velocity of 17,478 MPH is required. A geostationary orbit at an altitude of 22,236 miles requires a velocity of only 6877 MPH. At this height above the earth, the satellite orbits the earth once in 23hrs 56 minutes 4 seconds--the same rotational period as the earth, so the satellite constantly remains overhead of a fixed point on earth. (For you non-astronomers, the rotational period of the earth is not 24 hours. The extra 3 minutes and 56 seconds on an earth based clock compensates for the rotation of the earth about the sun, so that the sun is always directly overhead at noon.)



### **Establishing the final exact orbit**

Generally the result of launch is that the orbit is elliptical rather than the desired circular orbit. An additional step is then required to “kick” the craft into a circular orbit. By firing a rocket motor when the orbit is at the **apogee** of its orbit (its most distant point from Earth), and applying thrust in the direction of the flight path, the **perigee** (lowest point from Earth) moves further out. The result is a more circular orbit. Small “vernier” rocket motors called thrusters can then be used to precisely position the satellite. These attitude control rocket motors for satellites and space probes are often very small, an inch or so in diameter, and mounted in clusters that point in several directions.

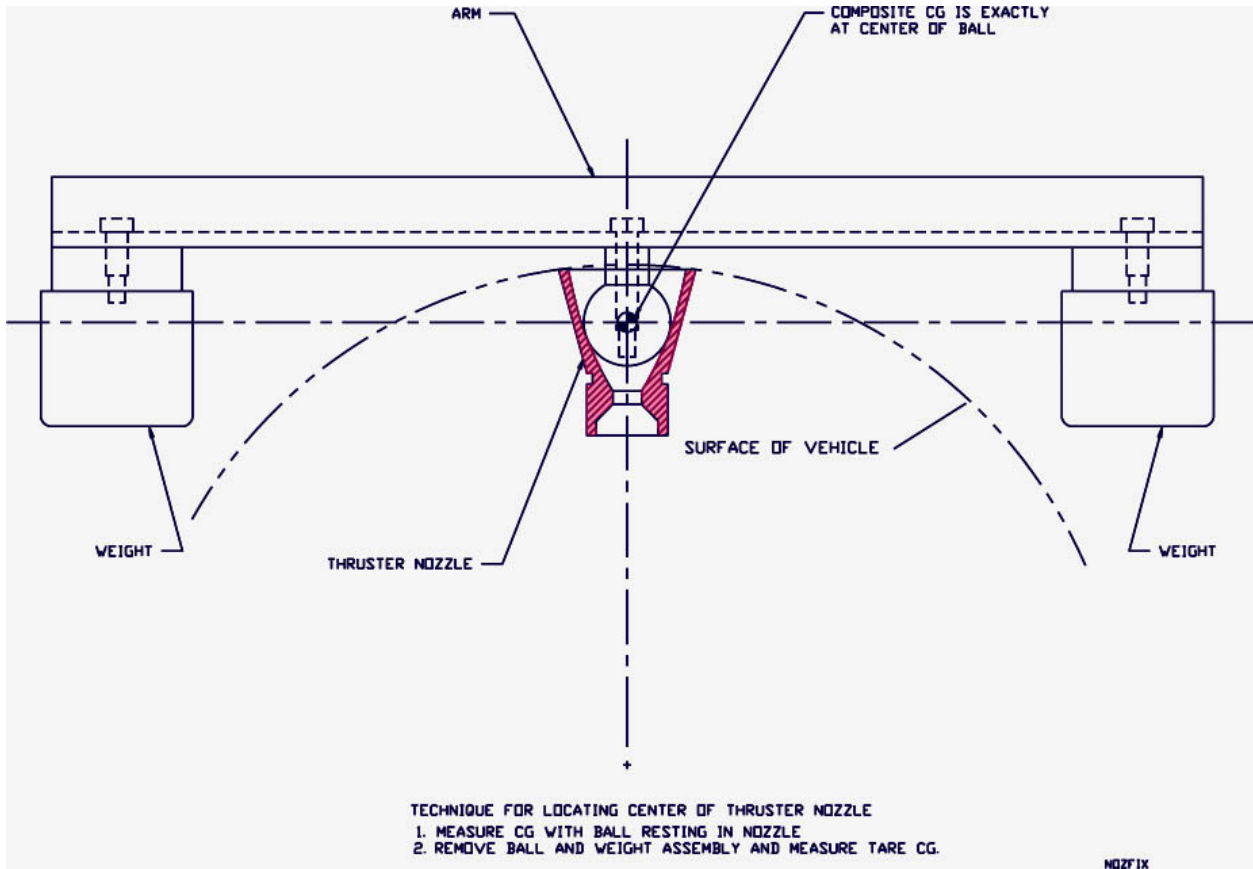
### **Importance of aligning thruster center of thrust with satellite CG**

If a thruster is to be used to translate the position of a satellite, then it is essential that it act directly through the CG of the satellite. Otherwise the satellite will spin rather than move in a straight line. It is often difficult to establish the relationship between the nozzle centerline and the CG measurement of the satellite. A novel method is described below, using a special test weight that is inserted directly into the nozzle cone.

The "Boynton Method" used to measure CG to thrust centerline directly is:

! Determine the center of thrust of the steering rocket motor. This may not be exactly in the center of the nozzle, particularly if the rocket motor body is at right angles to the nozzle. This quantity can be determined by mounting a motor on a rocket thrust stand such as those manufactured by Space Electronics. The rocket motor is then fired and the thrust misalignment is measured

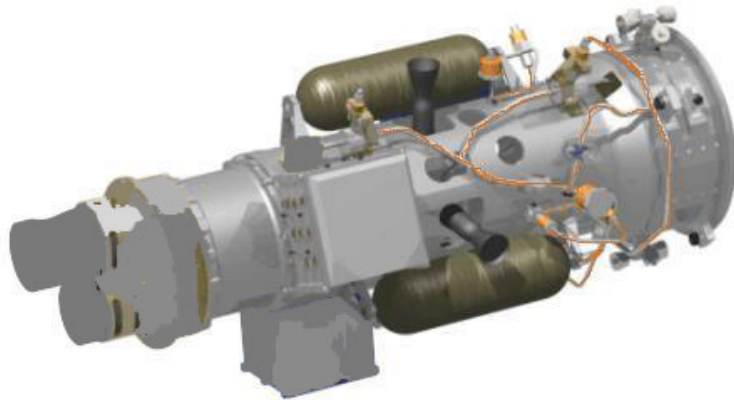
! Construct a precision calibration weight which fits precisely in the nozzle of the thruster and whose CG is at the nominal center of thrust of this type of motor.



! Measure the CG of the satellite with this weight in place. Remove this weight and make a second measurement. Then remove the satellite from its test fixture and measure the tare CG. By subtracting the tare measurement from the measurements of the satellite, the CG position of the satellite can be determined. By subtracting the measurement of the satellite from the measurement with both satellite and calibration weight, the CG position of the precision weight can be determined. If the CG of the satellite is in the same location as the CG of the weight, then the thrust is aligned with satellite CG. If they are different, then this difference is the thrust misalignment error. This method takes into account all the many dimensional errors that can exist in the mounting structure of the thruster. It measures what you want to know directly.

In order for this method to work, it is necessary for the nozzle weight to be much larger than the opening in the nozzle. We have made these weights with a tooling ball which fits in the nozzle, attached to extension arms to support the weights. The total structure is adjusted so its CG is precisely at the center of the ball. In this way, the weight can be placed in any orientation

relative to the nozzle. {This process is described in more detail in SAWE Paper No. 2174 “*Measuring the Mass Properties of the Brilliant Pebbles Satellite*” by Richard Boynton.}



### **Fuel in tanks and pipes**

In this illustration, the fuel tanks and the piping are significantly offset from the centerline of the vehicle. To evaluate the effect of fuel mass, it is recommended that the satellite CG and MOI (and in some cases POI) be measured with the satellite dry and then again with both the tanks and the fuel lines

filled with fuel. This will provide data for the change in mass properties as fuel is consumed in flight. If the design is ideal, the CG will not shift significantly when fuel is used up (the MOI will always decrease). Fuel mass is a major factor affecting mass properties for many satellites and cannot be ignored.

### **Attitude Control**

The previous discussion has been concerned with position control -- placing the satellite into the desired nominal orbit. Attitude control concerns the angular orientation of the satellite.

For orbiting satellites, generally the position accuracy required is not particularly high, and in fact the satellite will gradually drift from its position due to the small drag from the very thin atmosphere, solar wind against the solar panels, etc. Weekly or monthly boosts may be required from thrusters on the satellite to restore its position. The Hubble Telescope drops back toward the earth by about 150 feet a day, but has no booster, because the resulting gas would surround the telescope and might coat the mirror with a thin film, blurring the image. If the Space Shuttle doesn't push it back into orbit when it makes its planned repair trip, then the Hubble Telescope will burn up in the atmosphere sometime between 2010 and 2030.

In contrast with position control, attitude control requirements can be extraordinarily high. For example, the Hubble Telescope requires a pointing accuracy of 0.007 arc second (2 millionths of a degree)—equivalent to the width of a human hair at a distance of one mile, or getting a hole in one when driving a golf ball from the east coast of the USA to the west coast.

**Forces disturbing a satellite's attitude** Even though a satellite in orbit is flying in an almost pure vacuum, there are some subtle forces acting on it that disturb its position over time. Any magnetic objects in the satellite are attracted to the earth's magnetic field, which varies as the

satellite orbits the earth. Gravitation attraction also varies, since the earth is not a perfectly round sphere. These effects are particularly important for lower altitude orbits (i.e. 200-400 miles) where many spy satellites are located. The Hubble Telescope is also located at a low orbit so it can be serviced by the Space Shuttle. Another disturbance in low earth orbit is the residual atmosphere dragging on the solar panels.

At a high orbit, such as the geostationary orbit at 22,236 miles, these effects are smaller. However, solar wind acting on the solar panels and mass position changes within the satellite itself due to rotation of antennas or telescopes can disturb the attitude of the spacecraft.

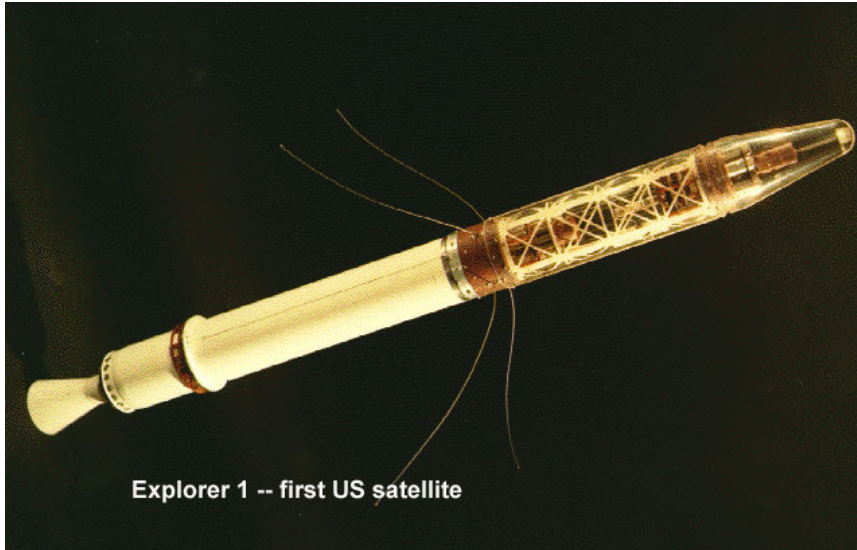
**Reasons for needing attitude control** Most satellites point either a telescope or an antenna toward earth. As the satellite makes its way around the earth, it must rotate to continue to face the earth. Furthermore, if the satellite uses solar power, it must turn its solar panels so they continuously face the sun. Unless some method is employed to control attitude, the rotation of the mass of the solar panels will produce an opposing rotation of the satellite.

The following sections describe different methods of attitude control. Many satellites use more than one of these methods.

**Passive Attitude Control** Most current satellites use closed-loop servomechanisms to maintain pointing angle. However, in the early days of the space program, two open loop methods were used to control attitude: spin stabilization and gravity gradient stabilization. There is a renewed interest in some of these methods.

**Gravity Gradient Stabilization** is the simplest of all methods. Basically it consists of providing a long thin structure that is large enough so that the force of gravity is significantly larger at the end closest to the earth, so that the spacecraft then spontaneously orients itself so that the axis of minimum MOI points toward the gravitational center of the earth. No fuel or apparatus is required. This stabilization technique works well for the earth's moon, since it is large and rigid. It has not worked well for artificial satellites, because there is essentially no damping in space and the satellite oscillates like a pendulum (the greater the ratio of minor to major MOI, the longer the period). One solution has been to attach a thin cable to the satellite and tether a mass toward the earth. A closed loop control mechanism can then vary the effective attachment point and damp the oscillations (but the major advantage of being passive is lost). The Chinese have been experimenting with adding an aerodynamic stabilizer for satellites in low earth orbit, where gravity gradient is higher and atmosphere is denser. Another method to overcome the oscillations is to add a viscous damper, a small can or tank of fluid mounted in the spacecraft, possibly with internal baffles to increase internal friction. Friction within the damper will gradually convert oscillation energy into heat dissipated within the viscous damper. As this system has two stable states, some way is required to flip the satellite and its tether end-for-end if needed.

**Spin Stabilization** is an ancient technology—hundreds of years ago gun manufacturers discovered that spiral grooves in a rifle barrel would cause the bullet to spin and improved the accuracy. The first American satellite—Explorer 1 in 1958—spun around its long axis. In



Explorer 1 -- first US satellite

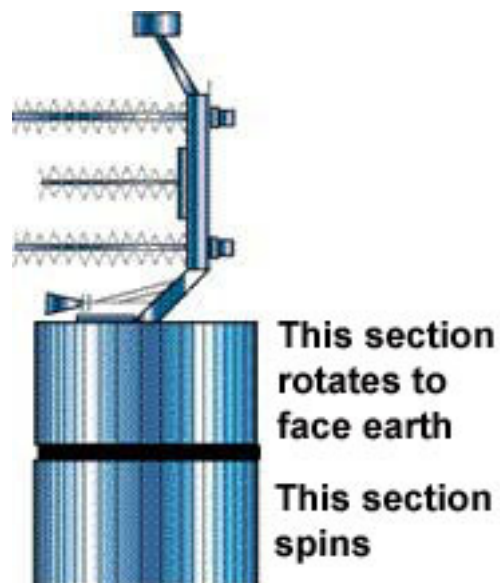
addition to defining its position, this spin was supposed to create centrifugal force to make the wire antennas extend out from the body of the spacecraft. Much to the surprise of JPL engineers, the spun object began to cone after launch and was soon tumbling end over end. What the engineers hadn't realized was that bullets obtain stabilization

because their center of pressure is aft of their CG. An object in space has no aerodynamic stabilization and will rotate about either its minor or major axis, but it favors the axis of major MOI because this axis results in minimum kinetic energy. We have a demonstration of this at our Mass Properties Seminars at Space Electronics. We rotate a yoke in a spin balance machine with a long cylinder pivoted at its CG. The cylinder is spun in a vertical orientation about its long axis. It maintains this position for a short time and then suddenly flops over into a horizontal orientation.

Spin stabilization is still used for certain types of spacecraft. The rules for this technique are:

1. Spin about the major principal axis, not the minor axis. This means that the satellite must be short and fat (not convenient for launch, since the rocket is long and thin).
2. Dynamically balance the spacecraft so that the product of inertia is small. The angle of inclination of the spacecraft is a function of the difference between the major and minor MOI. If you want to stabilize the vehicle and have it resistant to the effects of product unbalance, make the difference in moment of inertia as large as possible.

A variation on the spin stabilization technique is to use a two section satellite, connected by a bearing. One section spins to provide stability. The other is



stationary and adds to the axis MOI to make the spun axis into the principal axis with highest MOI. One feature of this design is that it fits conveniently into the outline of the launching rocket.

### **Active (Closed-loop) Attitude Control**

The techniques discussed previously provide enough attitude control to allow a broad band antenna to point toward the earth. However, they are not accurate enough for applications involving a telescope or a parabolic reflector. Closed loop control requires three elements: a sensor to determine the current attitude, a computer to determine the error between the desired and actual attitude, and a torque device commanded by the computer to change the attitude of the satellite.

Since this is a three dimensional problem, usually at least three sensors are required. These can be gyroscopes, a sun sensor, an earth horizon sensor, a moon sensor, a star tracker, etc. Obviously, sensors for astronomical instruments such as the Hubble Telescope have extraordinary accuracy, whereas as spy satellites that scan large areas without specific pointing can use less accurate devices.

The computer must be programmed to command the torque devices to correct the pointing error. Like all servomechanisms, overshoot and instability can be a problem. In order to anticipate any problems in orbit, Space Electronics has developed “space simulators” that float the satellite on a thin film of air, simulating the frictionless environment of space. These are discussed in SAWE Paper No. 2297. *Using a Spherical Air Bearing to Simulate Weightlessness* by Richard Boynton.

The torque devices can be small rocket motors (“thrusters”), magnetic devices that couple to the earth’s magnetic field, or momentum wheels that make use of Newton’s laws of conservation of momentum. These devices are discussed in the following sections.

**Attitude control using small thrusters** In the previous discussion of satellite position, I emphasized the importance of thruster alignment with the satellite CG. For attitude control, it is important that a thruster not be aligned with the satellite CG in order to create a turning moment. Micro-thrusters can be used to intentionally create a moment in order to realign the satellite or to unload a momentum wheel (see discussion of momentum wheels in later section). Typically an attitude control thruster supplies a few millisecond pulse of energy. The effect is like tapping the satellite with a small plastic hammer. A few seconds later, an opposing tap is given to stop the satellite in its new position. The simplest thruster type uses compressed gas such as nitrogen. This is not very efficient, since the specific impulse (exhaust velocity) is low compared to other methods, so that a relatively larger volume and mass is required. A more common type of attitude control thruster uses hydrazine as a fuel. The hydrazine is controlled by a solenoid

valve, which emits a millisecond pulse of hydrazine to a nozzle containing a catalyst. The hydrazine spontaneously ignites when it comes in contact with the catalyst.

Thruster control is essentially a digital process. The smaller the pulse, the finer the control can be. One serious drawback of this method is that it requires fuel to accomplish its goal. When the fuel runs out, the satellite has reached the end of its lifetime. This is not true of reaction wheels, which get their power from the sun (discussion of this technique follows).

Another drawback of thruster control is that the mass properties of the vehicle change as the fuel is consumed. If opposing thrusters are fired in pairs, CG shift can be minimized, and pure rotation results. If hydrazine is used as a fuel, the MOI of the vehicle is dependent on temperature, since the fuel becomes more viscous at low temperatures.

**Magnetic Stabilization** The earth's magnetic field can be used to steer a satellite. Long steel rods wound with fine wire form electromagnets that are used to pull the satellite toward the earth. The polarity can be reversed to push the satellite away. Since these are offset from the satellite CG, they cause the satellite to rotate.



**Magnetic Torquer**

### **Momentum Wheels**

This is one of the most elegant and accurate methods of attitude control. Momentum wheels take advantage of the laws of conservation of momentum. Changing the speed of a wheel causes the satellite to respond by turning in the opposite direction to the change. Since the momentum wheel has a very small MOI relative to the satellite, and its speed can be controlled with digital precision, extremely fine attitude control is possible.



**Momentum Wheel  
(speed up to 4000 RPM)**

In its best implementation four wheels are used. Three are mounted at right angles, so that each axis of the spacecraft can be controlled independently. The fourth is oriented so that it can be used to replace any of the other three in the event of failure. In this instance, there will be an interaction between axes, requiring more complex control.

If the speed of the wheel is increased in a particular direction, the satellite will rotate in the opposite direction. Conversely, decreasing the speed of the momentum wheel causes the satellite to rotate in the same direction as the momentum wheel. Absolute speed does not have an effect on satellite position; it is only the change in speed that matters. Theoretically the momentum wheel can be at a standstill and then be made to rotate in either direction. However, practical problems such as static friction and hysteresis favor operating the momentum wheel at a constant speed and then increasing or decreasing this speed but maintaining the same direction of rotation.

The angular momentum of an object is the product of its moment of inertia and its angular velocity:

$$\mathbf{L} = \mathbf{I}\boldsymbol{\omega}$$

In the general case, these variables are vector quantities. However, since the reaction wheel control concept incorporates three reaction wheels which are mounted at right angles to each other to coincide with the three axes of roll, pitch, and yaw, we can consider each rotational motion separately as a linear variable. There are two angular momentums for each axis: the rotation of the spacecraft about a particular axis (such as roll), and the rotation of the corresponding momentum wheel aligned with that axis. The momentum wheel is driven by an electric motor, usually powered by solar panels. Its speed is controlled by a computer. The law of conservation of angular momentum is the rotational equivalent of Newton's second law. Applied to a satellite in space it states that there is no net momentum gain or loss unless acted on by an outside force. The satellite has a momentum due to its moment of inertia and speed, and the attached momentum wheel has a separate momentum due to its much smaller moment of inertia and much higher speed. Therefore,

$$\mathbf{I}_s * \boldsymbol{\omega}_{s1} + \mathbf{I}_m * \boldsymbol{\omega}_{m1} = \mathbf{I}_s * \boldsymbol{\omega}_{s2} + \mathbf{I}_m * \boldsymbol{\omega}_{m2}$$

where  $\mathbf{I}_s$  is the MOI of the total spacecraft (including the mass of the momentum wheel acting through the center of rotation),  $\mathbf{I}_m$  is the MOI of the rotating disc of the momentum wheel system,  $\omega_{s1}$  is the initial angular velocity of the satellite before correction,  $\omega_{m1}$  is the initial angular velocity of the momentum wheel before correction, and  $\omega_{s2}$  and  $\omega_{m2}$  are the corresponding angular velocities after correction.

If the satellite is rotating due to disturbing influences and you want to stop its rotation, then the momentum wheel can be used to absorb the momentum of the spacecraft platform to prevent it from rotating. In this case,  $\omega_{s2} = 0$ . The equation then becomes

$$I_s * \omega_{s1} + I_m * \omega_{m1} = I_m * \omega_{m2}$$

or

$$I_s * \omega_{s1} = I_m \{ \omega_{m2} - \omega_{m1} \}$$

Note that momentum wheels only cause rotation, not translation, and that this rotation is about the CG of the satellite.

This method works smoothly when corrections are alternately in opposite directions. However, when corrections must be made in the same direction, the wheel eventually reaches its maximum safe speed or approaches zero, at which point a “momentum dump” is required. This consists of slowing or speeding up the wheel and simultaneously employing some other means (such as thrusters or magnetic actuators) to counteract the effect of changing the speed of the momentum wheel.

Because of the extremely high speed, these wheels must be balanced to a high degree of precision to minimize vibration, which would blur a telescope’s image. These wheels are among the most likely devices in a satellite to fail, since they operate at such a high speed. Some of them use magnetic bearings, which are non-contacting. I’ve read that others use ball bearings whose balls are coated with diamond dust to minimize wear. Currently the Hubble telescope has several failed momentum wheels. Another satellite lost a key momentum wheel, but engineers were able to restore operation by revising the software to use magnetic actuators in combination with the remaining momentum wheels.

The rotational equivalent of Newton's Second Law is that the net torque acting on an object is equal to its moment of inertia times its angular acceleration.

$$\tau = I \alpha$$

where

$\tau$  is the net torque.

$I$  is the moment of inertia.

$\alpha$  is the angular acceleration.

Constant angular acceleration is equal to the change in angular velocity divided by the time it takes to change.

$$\alpha = \Delta \omega / \Delta t$$

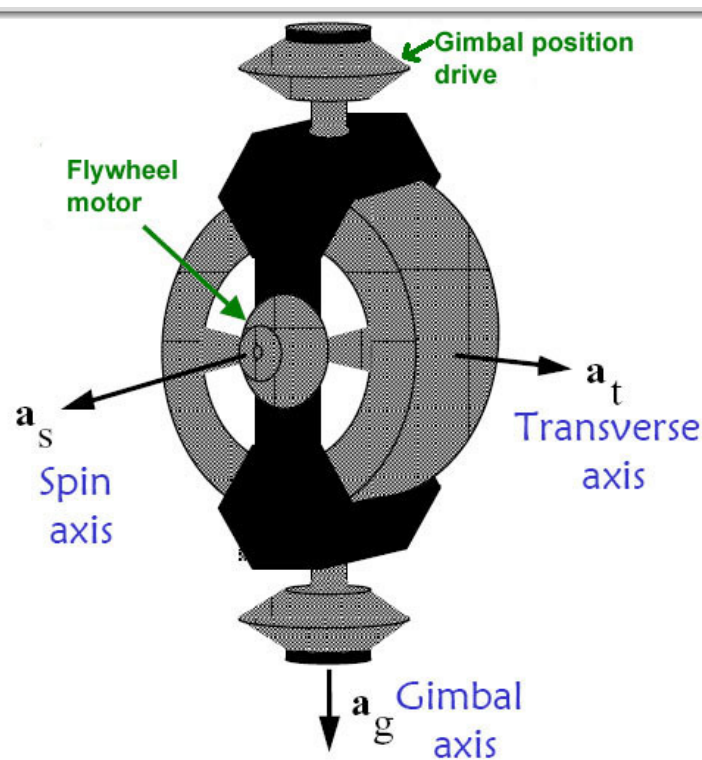
$\alpha$  is the angular acceleration

$\Delta \omega$  is the change in angular velocity

$\Delta t$  is the elapsed time.

### Control Moment Gyros (“CMG’s”)

If a high speed flywheel is mounted in a gimbaled assembly, then the angular position of the flywheel bearing can be altered, causing the satellite to turn relative to the flywheel, whose position is fixed in



space. This direct method has the advantage that the flywheel always turns at a constant speed, so that no “momentum dump” is required. The power efficiency is higher than momentum wheels. The disadvantage of this method is that precise motion of the gimbaled structure is hard to achieve. Backlash in the gimbal position drive gears, small aberrations in the gimbal bearings, and other mechanical limitation cause the gimbal position to jump unpredictably rather than move in a smooth manner. Furthermore, the mechanical structure is relatively heavy and is less reliable than other methods of attitude control. The Skylab, MIR, and International Space Station all use this concept for attitude control.

## Conclusions

This paper gives a general overview of some of the methods of controlling rocket and satellite position and attitude. Since the spacecraft is unrestrained in space, mass properties define its position and motion. Evaluation of mass properties is complicated by the presence of liquid fuel, whose effective MOI is related to the shape of the fuel tank, the presence or lack of baffles, the viscosity of the fuel, and the amount of fuel remaining. Fuel is carried to the thruster nozzles via piping that often is located near the circumference of the satellite, making the effect of fuel mass in the pipes more significant in affecting both MOI and CG. The dry weight of this piping is considerably less than when filled with fuel. There's no guarantee that the piping is symmetrical about the CG, so CG may shift when the pipes fill with fuel. Engineers are cautioned to measure rockets and satellites in a dry and wet condition, since fuel mass can be as high as 85% of total vehicle mass and can be the dominant contributor to MOI and CG location. Although mass property measurement adds another step to the fabrication process, the consequences of not making a measurement can be catastrophic—the spacecraft mission can fail, with the spacecraft endlessly tumbling end over end or not reaching its desired orbit, resulting in hundreds of millions of dollars lost, and the mission delayed for years.