Attitude Determination and Attitude Control

- Placing the telescope in orbit is not the end of the story.
- It is necessary to point the telescope towards the selected targets, or to scan the selected sky area with the telescope.
- So the satellite attitude needs to be measured and controlled.
Attitude Control

- Is the control of the angular position and rotation of the spacecraft, either relative to the object that it is orbiting (Earth, Moon ..), or relative to the celestial sphere.

- The attitude control system (ACS) is composed of: **Attitude Sensors, Controller, Actuators.**

![Diagram of Attitude Control System]

- **Desired Attitude**
- **Controller** determines the desired torques, and send electrical commands.
- **Actuator** applies the desired torques.
- **Estimated Attitude** Estimates the current attitude.
- **Disturbance Torques** take the measurements.
- **S/C Dynamics**
- **Actual Attitude**
Yaw = Imbardata
Pitch = Beccheggio
Roll = Rollio

XY = piano dell’orbita
ACS: Gravity Gradient

Description:
Uses the change in gravity with altitude to create a torque when the principal axes are not aligned with the orbital reference frame. Long booms are usually extended to create the torque. The gravity gradient provides the restoring or stabilizing torque but does not damp the librational motion. Viscous dampers are added to dissipate the energy and damp out the librations. The gravity gradient torque can be a control torque but it can also be a disturbance torque if there are products of inertia. For example, LANDSAT had large products of inertia and the gravity gradient was the dominant disturbance torque.

Advantages:
Simple, reliable, cheap, long lifetime.

Disadvantages:
Poor pointing accuracy (5 deg), poor yaw control, thermal bending of boom causes oscillations, tendency to flip upside down.

(from D. Mortari)
Description:
The entire spacecraft spins, which provides inertial orientation. The spinning provides gyroscopic stiffness, and stability. The nutation damper damps out the nutation, but precession still exists. Spin is about the axis of maximum moment of inertia, that is usually, but not always, the orbit normal. Solar arrays are fixed to the body.

Advantages:
Simple, reliable, long lifetime.

Disadvantages:
Sensor collection is limited to scanning obtained by spin motion. High angular momentum results in poor maneuverability, i.e., reorientation of spin axis. Poor power efficiency, only half the solar cells are illuminated at any one time. Must spin about the axis of maximum moment of inertia.

(from D. Mortari)
Spinning Satellites Examples

- Spinning is used in satellites for astronomy when sky scanning is required.
- COBE, WMAP, Planck all spin at 1-10 rpm, so the telescopes (antennas) can scan the sky at a rate of deg/s.
- Complex scan patterns can be obtained by combining satellite spin and slow re-orientation manoeuvres (see COBE, WMAP, Planck)
Flat spin: in the absence of perturbations the spin axis orientation remains constant with respect to the inertial frame of distant stars – Not useful for astronomy.

Using the ACS and perturbations, the spin axis orientation can be continuously reoriented away from the earth center. This is useful for full-sky surveys (COBE)
Precession rate: 1 rph
22.5° half-angle

A-side line of sight

MAP at L₂

Spin rate: 0.464 rpm

1.5 x 10⁶ km

1.5 x 10⁸ km

North Ecliptic Pole

+90°

+45°

-45°

-90°

South Ecliptic Pole

MAP990031
A vehicle consisting of two primary components free to perform relative rotations about a common bearing axis is called a "dual- spin" vehicle, and the idea of stabilizing such a vehicle by spinning one part (the "rotor") while the other part (the "despun platform") rotates more slowly - or not at all - is called the dual-spin attitude stabilization concept.

This dual-spin configuration thus serves to create a spin stabilized satellite.


ACS: Dual Spin

Description:

The limitations of single spin satellites are partially overcome with dual spin satellites. With a dual spin satellite the payload, e.g. the antenna, is despun while the other portion of spacecraft spins to provide gyroscopic stability. Nutation is damped by nutation damper, located on either the spun or despun portion. Many of the geosynchronous communication satellites have been dual spin.

Advantages:
Despun payload allows Earth pointing payload. Can have spin about minimum moment of inertia axis. Reliable, long lifetime.

Disadvantages:
Poor power efficiency because solar cells are on spinning portion. High angular momentum results in poor maneuverability, i.e., reorientation of spin axis. Sensitive to mass imbalances.

(from D. Mortari)
ACS: Momentum Bias

**Description:** The momentum bias satellite is a variation of the dual spin concept that overcomes some of the problems of the dual spin. With the momentum bias spacecraft the gyroscopic stability is provided by a *rapidly spinning momentum wheel* rather than the bus. The payload and bus are despun or rotating at orbital rate. The momentum wheel provides control about the spin (pitch) axis and some combination of nutation damper, magnetic torquing, or propellant provide control about the yaw and roll axes. Use of propellant is avoided whenever possible. Magnetic or propellant are used for momentum damping.

**Advantages:** Better pointing accuracy, better power efficiency due to despun solar arrays. Still relatively cheap and not complex which means less weight than three axis systems. When the pointing requirements are not stringent, i.e., > 0.5 deg, the momentum bias ACS is usually the desired approach. The momentum bias approach with magnetic torquers is the dominant type of ACS in LEO.

**Disadvantages:** Usually poor yaw control. Gyroscopic stiffness results in poor maneuverability. Poorer reliability and lifetime. Due to its lower cost and complexity and relatively accurate pointing capability this has been the most popular type of ACS.

(from D. Mortari)
• Typically a spacecraft will have several momentum wheels oriented along orthogonal axes.
• To change its rotation along those axes it will increase or decrease the spin of the momentum wheels in the opposite direction. When the spacecraft achieves its desired orientation, it can then halt its rotation by braking the momentum wheels by the same amount.
• Momentum wheels are usually spun by electric motors. Both spin-up and braking are controlled electronically by computer controls.
• The strength of the materials of a momentum wheel establishes a speed at which the wheel would come apart, and therefore how much angular momentum it can store.
• Since the momentum wheel is a small fraction of the spacecraft's total inertia, easily-measurable changes in its speed provide very precise changes in angle.
Example:

- In the CNES ACS:
- Three magnetic-bearing reaction wheels apply a torque on the satellite to rotate it about one of its three axes.
- Two magnetic torquers interact with the Earth's magnetic field to generate torques and thus control the speed of rotation of the reaction wheels.
- Thrusters complete the system.
ACS: Three Axis

Description:

All three axes are independently controlled by mass expulsion, reaction wheels (RWs) or control moment gyros (CMGs). Usually RWs or CMGs are used for control and propellant (sometimes magnetic torquing) is used for momentum dumping.

Advantages:

Pointing accuracy, maneuverability and adaptability to changing mission requirements.

Disadvantages:

Cost, weight, complexity and lifetime.

(from D. Mortari)
## ACS methods:

<table>
<thead>
<tr>
<th>Passive</th>
<th>Semi-passive</th>
<th>Active</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravity gradient</td>
<td>Momentum bias with magnetics</td>
<td>Propellant</td>
</tr>
<tr>
<td>Spinner with nutation damper</td>
<td>Reaction wheels with magnetics for momentum dumping</td>
<td>Reaction wheels with propellant for momentum dumping</td>
</tr>
<tr>
<td>Dual spinner with nutation damper</td>
<td>CMGs with magnetics for momentum dumping</td>
<td>CMGs with propellant for momentum dumping</td>
</tr>
</tbody>
</table>

(from D. Mortari)
<table>
<thead>
<tr>
<th>Type</th>
<th>Pointing Options</th>
<th>Maneuverability</th>
<th>Accuracy</th>
<th>Lifetime Limits</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Passive</strong></td>
<td>• Gravity gradient</td>
<td>• Earth local vertical only</td>
<td>• Minor adjustments with thrusters</td>
<td>• Very limited</td>
</tr>
<tr>
<td></td>
<td>• Gravity gradient &amp; momentum bias wheel</td>
<td>• Earth local vertical only</td>
<td>• Minor adjustments with thrusters</td>
<td>• Very limited</td>
</tr>
<tr>
<td><strong>Spinners</strong></td>
<td>• Pure spinner</td>
<td>• Inertially fixed any direction</td>
<td>• Large ( _V ) along spin axis, minor adjust in other two axes with thrusters</td>
<td>• High propellant usage to move stiff momentum vector</td>
</tr>
<tr>
<td></td>
<td>• Dual spin</td>
<td>• Limited only by articulation on despun platform</td>
<td>• Large ( _V ) along spin axis, minor adjust in other two axes with thrusters</td>
<td>• Despun platform constrained by its own geometry</td>
</tr>
<tr>
<td><strong>3-axis stabilized</strong></td>
<td>• Zero momentum (3 wheels &amp; thrusters)</td>
<td>• No constraints</td>
<td>• Any direction, any level depending on size of thruster and main engine</td>
<td>• No constraints (1)</td>
</tr>
<tr>
<td></td>
<td>• Bias momentum (1 wheel &amp; roll thrusters)</td>
<td>• Best suited for local vertical pointing</td>
<td>• Same as zero momentum with full set of thrusters; otherwise, not suited to translation</td>
<td>• Momentum vector of the bias wheel prefers to stay normal to orbit plane, constraining yaw maneuver</td>
</tr>
</tbody>
</table>

(1) High rates with thrusters or control moment gyros; low rate, accurate control with reaction wheels.
Actuators

Actuators are usually broken into four classes: mass expulsion, momentum exchange, environmental and dissipative. An ACS may have actuators from any or all the classes.

<table>
<thead>
<tr>
<th>Mass Expulsion</th>
<th>Momentum Exc.</th>
<th>Environmental</th>
<th>Dissipative</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reaction wheel</td>
<td>Gravity gradient</td>
<td></td>
<td>Nutation damper</td>
</tr>
<tr>
<td>Momentum wheel</td>
<td>Magnetic</td>
<td></td>
<td>GG viscous damper</td>
</tr>
<tr>
<td>CMG</td>
<td>Aerodynamic</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

There are two types of magnetic torquers. Those used for momentum dumping or control in momentum bias systems, and the eddy current dampers used in gravity gradient systems.

Range of torques available from some of these actuators (From Chobotov)

<table>
<thead>
<tr>
<th>Actuator Type</th>
<th>Torque Range (N-m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reaction Control (RCS)</td>
<td>10^{-2} -10</td>
</tr>
<tr>
<td>Magnetic Torquer</td>
<td>10^{-2} -10^{-1}</td>
</tr>
<tr>
<td>Gravity Gradient</td>
<td>10^{-6} - 10^{-3}</td>
</tr>
<tr>
<td>Aerodynamic</td>
<td>10^{-5} - 10^{-3}</td>
</tr>
<tr>
<td>Reaction Wheel</td>
<td>10^{-1} - 1</td>
</tr>
<tr>
<td>Control Moment Gyro</td>
<td>10^{-2} - 10^{3}</td>
</tr>
</tbody>
</table>

From this table we see that RWs and CMGs are used when precision pointing and/or high torque is required. Satellites that perform rapid attitude maneuvers or have articulating payloads which create large disturbance torques require CMGs.
The types of sensors used for attitude determination are:

1. horizon sensors (or conical Earth scanners),
2. sun sensors,
3. star sensors,
4. magnetometers,
5. inertial reference units (Inertia Measurement Unit or attitude reference units ARU), and
6. GPS receivers.

Horizon sensors measure pitch and roll to an accuracy of about 0.1-0.5 deg. An accuracy less than 0.05 deg can be achieved by extensive calibration and accounting for the equatorial bulge. Sun and star sensors provide directions. An horizon sensor does not provide yaw information (for momentum bias systems it is not necessary to measure yaw). One wide-FOV or two narrow-FOV star sensors are needed to provide attitude. Since the star sensors cannot provide continuous attitude measurements an IMU/ARU is needed to provide the attitude between measurements. IMUs suffer from drift and biases and need frequent updates which are provided by the star sensors. Magnetometers measure Earth's magnetic. Accuracies no better than 1 deg can be obtained. The GPS receivers are used in an interferometer mode to determine attitude. Accuracies as good as 0.01 deg are expected using GPS.
Sun Sensors

Most common because they are light weight, not expensive, limited power required and because they provide an accuracy which is acceptable for most of the missions.

Sun is the principal source of energy (exemption: interplanetary spacecraft). Solar flux goes as $1/r^2$.

Sun (in the Inertial Reference Frame) is evaluated by using interpolating functions (armonic series expansion) which least square fit the Sun positions recorded in the star atlas.

They are used to synchronize command with spin period, and they are used to protect star sensors.

At 1AU the sun may be considered as a point (0.267 deg.).

For GEO there is the parallax error (0.03 deg as max values).
Presence Sun Sensors

Presence sun sensors provide the sun crossing time only, or the sun presence within the sensor FOV. Used to synchronize pulsed command (spin-up, spin-down) to manoeuvre, and to turn on/off onboard experiments and instrumentation.
Presence Sun Sensors

Based on the Snell refraction law.

\[ n \sin \theta = \sin \theta' \]

\[ n \sin \gamma = 1 \]
Analogic Sun Sensors

\[ I(\vartheta) = I(0)d^T n = I(0) \cos \vartheta \]
Digital Sun Sensors

Command: sun presence

Measurement (4 parts):
1) ATA,
2) Sign bit,
3) Code bits,
4) Interpolating bits.
Digital Sun sensor

[Diagram of a digital sun sensor with various components labeled: Grid slits, Photocells, Measurement component entrance slit, Slab of index of refraction, Reticle slit pattern, Fine bits for interpolation, Gray code bits, ATA, Sign bit (MSB).]
Binary code

Gray code

Sun angle

LSB  Binary code  Sign (MSB)  LSB  Gray code  Sign (MSB)
# Binary and Gray code

The gain of the Gray code consists of the fact that the bit string, which represents the angle measure, changes one bit only at each digital step.

<table>
<thead>
<tr>
<th>Decimal</th>
<th>Binary</th>
<th>Gray</th>
<th>Decimal</th>
<th>Binary</th>
<th>Gray</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>11</td>
<td>1011</td>
<td>1110</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>12</td>
<td>1100</td>
<td>1010</td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td>11</td>
<td>13</td>
<td>1101</td>
<td>1011</td>
</tr>
<tr>
<td>3</td>
<td>11</td>
<td>10</td>
<td>14</td>
<td>1110</td>
<td>1001</td>
</tr>
<tr>
<td>4</td>
<td>100</td>
<td>110</td>
<td>15</td>
<td>1111</td>
<td>1000</td>
</tr>
<tr>
<td>5</td>
<td>101</td>
<td>111</td>
<td>16</td>
<td>10000</td>
<td>11000</td>
</tr>
<tr>
<td>6</td>
<td>110</td>
<td>101</td>
<td>17</td>
<td>10001</td>
<td>11001</td>
</tr>
<tr>
<td>7</td>
<td>111</td>
<td>100</td>
<td>18</td>
<td>10010</td>
<td>11011</td>
</tr>
<tr>
<td>8</td>
<td>1000</td>
<td>1100</td>
<td>19</td>
<td>10011</td>
<td>11010</td>
</tr>
<tr>
<td>9</td>
<td>1001</td>
<td>1101</td>
<td>20</td>
<td>10100</td>
<td>11110</td>
</tr>
<tr>
<td>10</td>
<td>1010</td>
<td>1111</td>
<td>21</td>
<td>10101</td>
<td>11111</td>
</tr>
</tbody>
</table>
Double Digital Sun Sensor

Photocells
Earth horizon sensor

Best range: 14μ-16μ of CO₂
(less high altitude clouds contr.)

Relative radiance
400 (IR) and 30,000 (visible)
Earth horizon sensor

Measure two crossing times $t_1$ and $t_2$

With angular speed $\omega$, the measured angle is $\varphi = \omega(t_2 - t_1)$

Two measured angles, $\varphi_1$ and $\varphi_2$, allow to evaluate the Nadir direction.

(a) Output from a body-mounted horizon sensor with a sun reference pulse

(b) Output from a wheel-mounted horizon sensor with a magnetic pickoff reference pulse
Moon horizon sensor

Moon temperature range: 
–240 deg to +30 deg

Hot Moon

Cold Moon

Hot horizon position

Cold horizon position

Hot area for cold Moon

Hot area for hot Moon

Relative radiance

Moon center distance
Earth/Sun sensors for spinning S/C

Meridian slit

Inclined slit

Satellite equator

Displacement angle (deg)
Star sensor for spinning S/C

Optical axis

Elevation slit

Azimuth slit
The Archeops Star Sensor

- Archeops was a telescope on a spinning balloon payload, designed to map a significant fraction of the CMB sky with a microwave telescope.
A fast star sensor for balloon payloads

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(Received 13 January 2003; accepted 30 June 2003)

We developed a system to reconstruct the attitude of balloon borne spinning experiments, where high accuracy (about 1') and high rotation speed (up to tens of degrees per second) are required. It is based on a stellar sensor, and gathers together hardware simplicity, cheap components, high resolution, and sensitivity. It is composed of an optical mirror (diameter 40 cm), an array of 46 fast and sensitive photodiodes, and low noise readout electronics. It was designed for the Archeops experiment, a balloon borne millimetric telescope whose goal is to generate high resolution maps of large regions of the sky, to study the temperature anisotropies of the cosmic background radiation.

FIG. 1. Telescope frame for the star sensor location of the various components and internal details of the photodiodes box.
Figura 3.1: Fotografia del sensore visto da davanti al telescopio. In primo piano si vede la scatola dei fotodiodi e dello stadio di preamplificazione posta direttamente davanti allo specchio, con i rivelatori nel fuoco. Si nota anche il sistema per fuoccheggiare l'apparato. La foto è stata scattata subito prima del volo di Trapani.

Archeops star sensor

FIG. 2. Star temperature distribution of the Hipparcos/Tycho catalog. The Red giant peak is clearly seen, providing the hope that most detected stars are redder than the sky.
15.14 – 26.59 UT, Sky Coverage = 29.8%
FIG. 6. Histogram of amplitudes of star candidates detected in the Kiruna flight (night).
FIG. 7. This graph shows the diode number vs time of large amplitude candidate stars as seen by the stellar sensor telescope and the star detector software. Bright stars trigger the star detector every turn (20 s). They are seen as “tracks” in this plot: as the sky moves in front of the balloon, the star triggers move from one photodiode to the next.
Archeops star sensor

The pointing solution was reconstructed with about 1' RMS, by means also of other sensors, like gyros.
Optical Gyroscopes

- Terry Pearson, How a gyroscope works, February 1997, www.gyros.freeserve.co.uk) in which two light waves traveling in opposite direction in the same closed loop and generated by the same source, undergo a phase shift proportional to the rotating speed of the closed loop with respect to the inertial frame. Both laser and fiber optic gyros replaced mechanical gyros
Star Trackers

Optics and Image Definition

Detector and Electronics

Optical Axis

Azimuth Axis

Elevation Axis

Narrow FOV

Angle Encoders and Servos

Electronics

Photomultiplier

Optical System

Grid

Baffle

Star
OLIMPO star camera

The camera is a Qimaging Retiga Exi CCD and the PC is a 266 Mhz Linux box. The system is provided by the CNR of Firenze (A. Boscaleri).

A PC-104 computer is mounted inside the star camera pressure vessel. The computer runs the software that processes the CCD images. The computer can also command the stepper motors for autofocus, and regulates the lens temperature.

The system sends the right ascension and declination of the center of the image to the flight computer, which will communicate with the TM and the data storage system.
Using a system similar to the BLAST one, Olimpo camera should be capable of providing a reconstructed pointing solution with an absolute accuracy < 5”. The system is sensitive to stars down to magnitudes ~ 9 in daytime float conditions.

It combines a 1 megapixel CCD with a 200 mm f/2 lens to image a 2° × 2.5° field of the sky. An internal computer controls the temperature, can adjusts the focus, and determines a real-time pointing solution at 1 Hz.

See M. Rex, E. Chapin et al., arXiv:astro-ph/0605039v1
ACS, sensors, data logging...

M. Rex, E. Chapin et al., arXiv:astro-ph/0605039v1
## CCD specifications

<table>
<thead>
<tr>
<th></th>
<th>ISC</th>
<th>OSC</th>
</tr>
</thead>
<tbody>
<tr>
<td>QImaging Camera</td>
<td>PMI 1401</td>
<td>Retiga EXi</td>
</tr>
<tr>
<td>CCD Sensor</td>
<td>Kodak KAF-1401</td>
<td>Sony ICX285</td>
</tr>
<tr>
<td>Light Sensitive Pixels</td>
<td>1312 × 1024</td>
<td>1360 × 1036</td>
</tr>
<tr>
<td>Pixel Size</td>
<td>6.8 μm × 6.8 μm</td>
<td>6.45 μm × 6.45 μm</td>
</tr>
<tr>
<td>Digital Output</td>
<td>14 bit</td>
<td>12 bit</td>
</tr>
<tr>
<td>Pixel Well Depth</td>
<td>45,000 e⁻</td>
<td>18,000 e⁻</td>
</tr>
<tr>
<td>Read Noise</td>
<td>20 e⁻</td>
<td>8 e⁻</td>
</tr>
</tbody>
</table>

Different choises can be made for CCD cameras, depending mostly on flight conditions (day or night) and scan strategy, which puts an upper limit to the integration time. Deeper well depths allow longer integration times (typically up to 200-300 ms), necessary with daylight. While having more bits per e⁻ means more sensitivity during the night, when lower integration time is allowed (about 20-30 ms).

Scanning speed limits the integration time because, if too high, will result into a smearing of the star blobs through the pixels.

Da Nati et al. Mem. S.A.It. 2008
Magnetometers

They may be used at altitudes less than 1,000 Km, only.
(Earth magnetic field decreases with radius as $1/r^3$)

Small precision is associated with the fact that the EMF Models are not so accurate.

Biases not negligible
(residuals of magnetic fields caused by onboard circuits)

\[ V = \int E \, dl = \frac{d\Phi_B}{dt} \]
<table>
<thead>
<tr>
<th>Sensor</th>
<th>Typical Performance Range</th>
<th>Wt Range (kg)</th>
<th>Power (W)</th>
<th>Some Typical Suppliers</th>
</tr>
</thead>
</table>
| Inertial measurement unit (gyros & accelerometers) | Gyro drift rate = 0.003°/hr to 1°/hr accel.  
linearity = 1 to 5 x 10^{-6} g/g^2 over range of 20 to 60 g | 3 to 25       | 10 to 200 | Northrop, Bendix Kearfott, Honeywell, Hamilton Standard, Litton, Teledyne |
| Sun sensors                                 | Accuracy = 0.005° to 3°                                         | 0.5 to 2      | 0 to 3    | Adcole, TRW, Ball Bros                    |
| Star sensors (scanners & mappers)           | Attitude accuracy = 1 arc sec to 1 arc min                     | 3 to 7        | 5 to 20   | Ball Bros, Honeywell, Hughes              |
| Horizon sensors                             | Attitude accuracy = 0.1° to 1° = 0.1°                           | 2 to 5        | 5 to 10   | Barnes, Ithaco, Lockheed                  |
| • S canner                                  |                                                                 | 2.5 to 3.5    | 0.3 to 5  | Barnes, Lockheed, Quantic                 |
| • Fixed head (static)                       |                                                                 |               |           |                                           |
| Magnetometer                                | Attitude accuracy = 0.5 to 3° (may need second reference)     | 0.6 to 1.2    | < 1       | Schonstedt, Develco                      |
# Attitude Determination Systems

<table>
<thead>
<tr>
<th>Performance Deg. (3 sigma)</th>
<th>CES &amp; Magnetometer</th>
<th>CES &amp; Sun Sensor &amp; ARU</th>
<th>CES &amp; ARU (Gyro-compas.)</th>
<th>Star Tracker Plus ARU</th>
<th>GPS &amp; ARU (IFOG)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absolute pitch &amp; roll: 0.09</td>
<td>Absolute pitch &amp; roll: 0.09</td>
<td>Absolute pitch &amp; roll: 0.09</td>
<td>&lt; 0.01 all axes</td>
<td>&lt; 0.01 all axes</td>
<td>&lt; 0.01 all axes</td>
</tr>
<tr>
<td>Absolute yaw: 0.5</td>
<td>Absolute yaw: 0.03</td>
<td>Absolute yaw: 0.05</td>
<td>&lt; 0.01 all axes</td>
<td>&lt; 0.01 all axes</td>
<td>&lt; 0.01 all axes</td>
</tr>
<tr>
<td>Relative p&amp;c &lt; .05</td>
<td>Relative p&amp;c &lt; .05</td>
<td>Relative p&amp;c &lt; .05</td>
<td>&lt; 0.01 all axes</td>
<td>&lt; 0.01 all axes</td>
<td>&lt; 0.01 all axes</td>
</tr>
</tbody>
</table>

| Flight Proven | Yes | Yes (mech gyro) | No (RLG or (IFOG)) | Yes | No | No | No |

| Dev. Status | --- | --- | --- | Space qual needed | Dev. & space qual needed | Ground test experiment & dev., & space qual needed |

| Est. reliability | current 3-7 yrs. | current 3-7 yrs. | current 3-7 yrs. | worst 2-5 yrs. | third best | second best | best |

| Est. recurring cost | $300K-$400K | $400K-$500K plus ARU | $300K-$400K plus ARU | $1.6M-$2.7M | $1.35M-$2.2M | $900K-$1800K plus | $250K - $400K plus |

| Est. non-recurring cost | zero | ARU if needed | ARU if needed | zero | Minimal Since ongoing (MSX) | $3-5 mil | $3-7 mil for GPS, $3 mil for ARU |