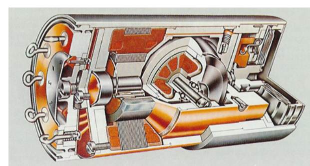
Spacecraft Sensors and Actuators

Space System Design, MAE 342, Princeton University
Robert Stengel

- Attitude Measurements
- Attitude Actuators
- Translational Measurements
- Mechanical Devices



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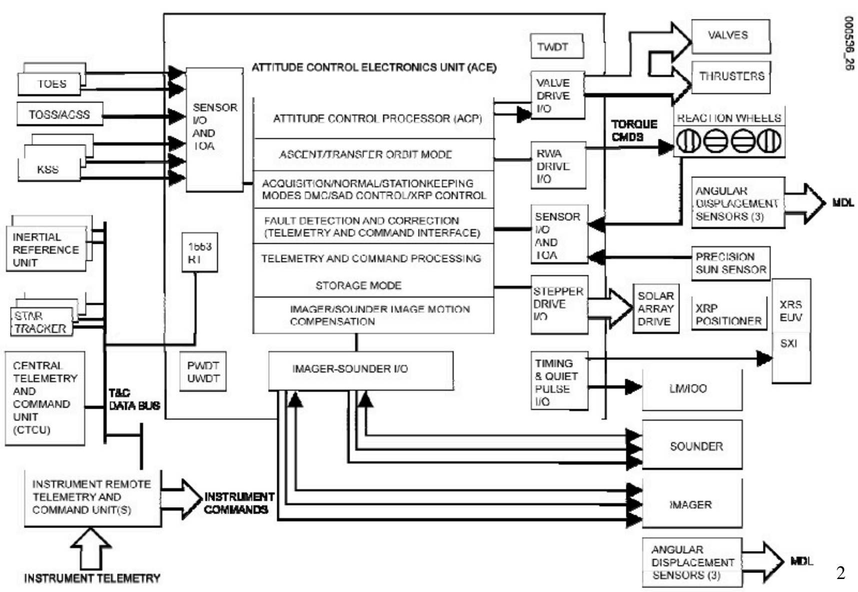
GOES Attitude Control Sub-System



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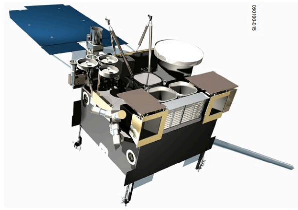
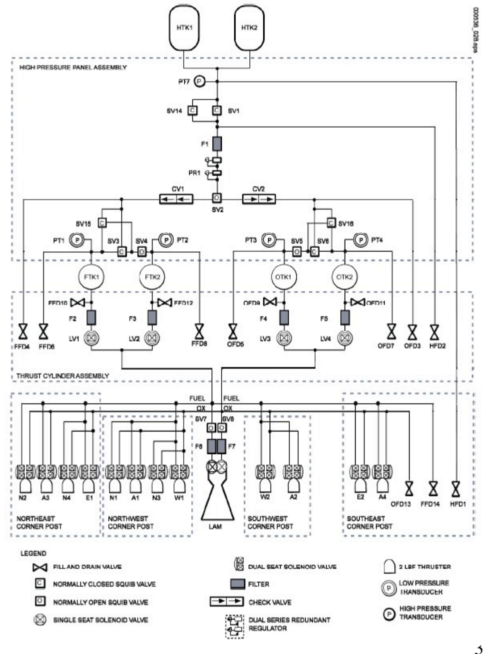
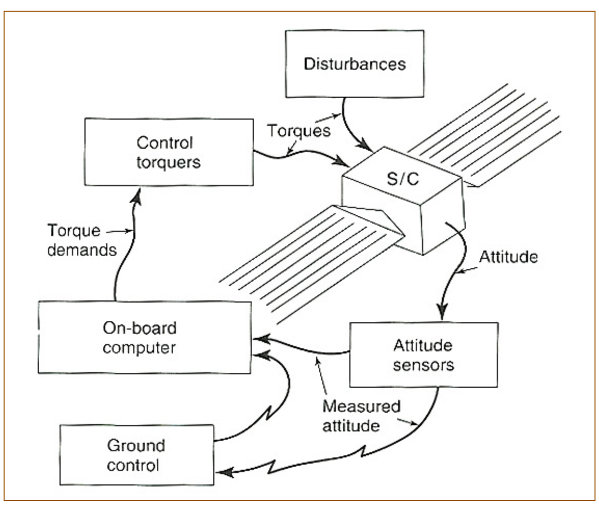


GOES Propulsion Sub-System

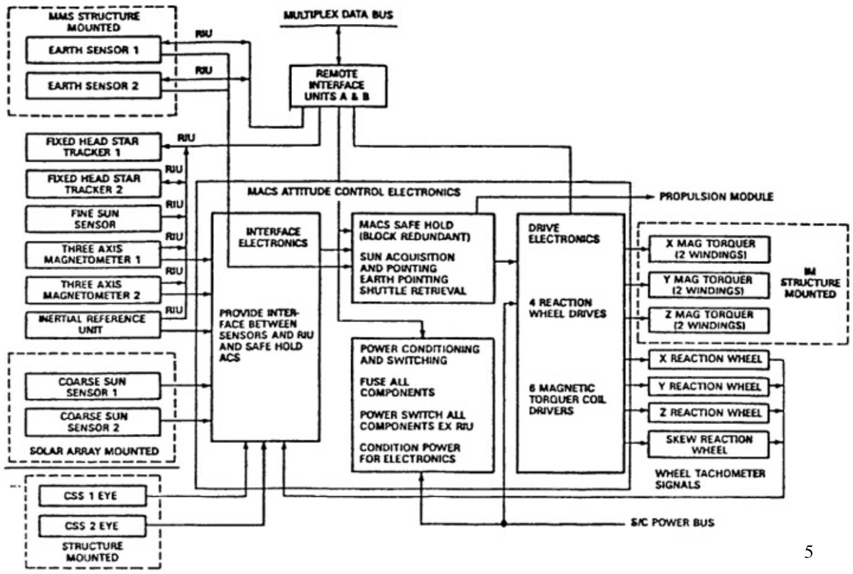
- Propellant tanks
- High-pressure control
- Valves
- Reaction control thrusters
- Main engine



Attitude Control System



UARS Attitude Control System



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Attitude Measurements

- Measurement of an angle or angular rate of the spacecraft with respect to a reference frame, e.g.,
  - Earth's magnetic field
    - Magnetometer
  - Direction to the sun
    - Sun sensor
  - Earth's shape
    - Earth horizon sensor
  - Inertial frame of the universe
    - Star sensor
    - Gyroscopes
- Mission requirements dictate spacecraft sensor configuration

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Potential Accuracies of Attitude Measurements

Reference object	Potential accuracy
Stars	1 arc second
Sun	1 arc minute
Earth (horizon)	6 arc minutes
RF beacon	1 arc minute
Magnetometer	30 arc minutes
Narstar Global Positioning System (GPS)	6 arc minutes

Note: This table gives only a guideline. The GPS estimate depends upon the 'baseline' used (see text).

Fortescue

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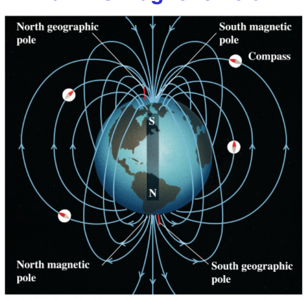
Magnetometer

- **Ionized gas magnetometer**
- **Flux gate magnetometer**
  - **Alternating current passed through one coil**
  - **Permalloy core alternately magnitized by electromagnetic field**
  - **Corresponding magnetic field sensed by second coil**
  - **Distortion of oscillating field is a measure of one component of the Earth's magnetic field**



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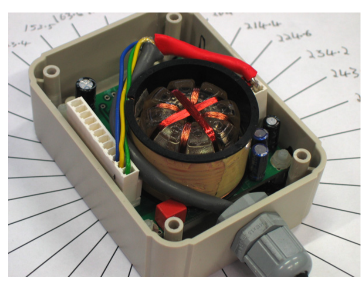

- **Three magnetometers required to determine direction of planet's magnetic field vector and magnitude of the field**
- **Two uses: exploratory measurements of unknown fields, and spacecraft attitude measurement for known fields**

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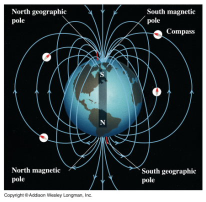

Body Orientation from Magnetometer

- Earth's magnetic field vector, $\mathbf{b}_I$, function of spacecraft position, (x, y, z)
- Body orientation vector, $\mathbf{b}_B$, related to $\mathbf{b}_I$ by
  - rotation matrix, $\mathbf{H}_B^I$, from inertial to body frame and
  - calibration rotation matrix, $\mathbf{S}$

$$\mathbf{b}_B = \mathbf{S}_{mag}\mathbf{b}_{mag}$$
$$\mathbf{b}_I = \mathbf{H}_B^I\left[\mathbf{b}_B(x,y,z) + \text{error}\right]$$
$$\mathbf{S}_{mag}(\varepsilon_1,\varepsilon_2,\varepsilon_3) = \text{calibration rotation matrix}$$
$$\mathbf{H}_B^I = \text{body to inertial rotation matrix}$$

- Estimation of yaw, ψ, pitch, θ, and roll, ϕ, angles requires additional information
  - Equation has 2 degrees of freedom, but there are 3 unknowns

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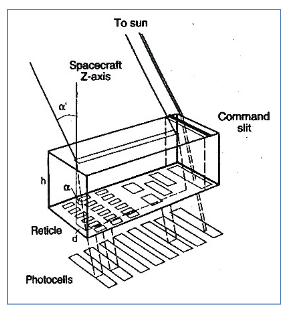
Single-Axis Sun Sensor

$$\tan\alpha = d / h$$
$$\sin\alpha' = n\sin\alpha \quad \text{(Snell's law)}$$
$$n = \text{index of refraction}$$



- Transparent block of material, known refractive index, n, coated with opaque material
- Slit etched in top, receptive areas on bottom
- Sun light passing through slit forms a line over photodetectors
- Distance from centerline determines angle, α
- With index of refraction, n, angle to sun, α, is determined
- Photodetectors provide coarse or fine outputs

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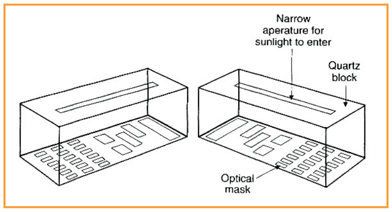
Dual-Axis Sun Sensors

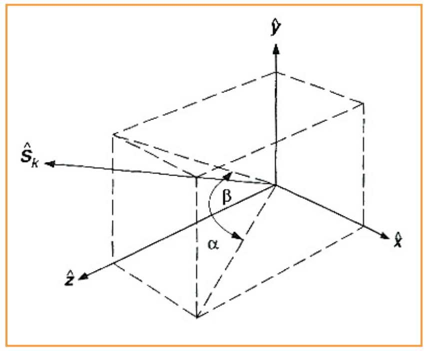
Orthogonal sun sensors determine direction (two angles) to the sun



$$\mathbf{s}_{Sun} = \frac{1}{\sqrt{1+\tan^2\alpha+\tan^2\beta}}\begin{bmatrix}\tan\alpha\\ \tan\beta\\ 1\end{bmatrix}$$

$$\mathbf{s}_B = \mathbf{S}_{Sun}\mathbf{s}_{Sun}$$

$$\mathbf{s}_I = \mathbf{H}_B^I\left(\mathbf{s}_B + \text{error}\right)$$



Two measurements, three unknowns

Three-axis attitude determination requires additional information

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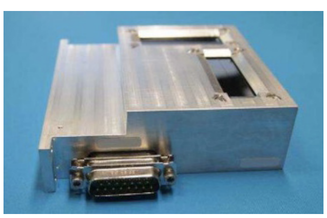
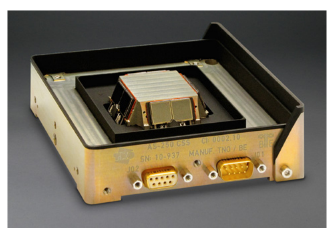
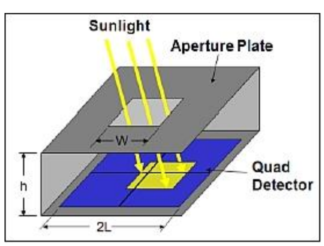
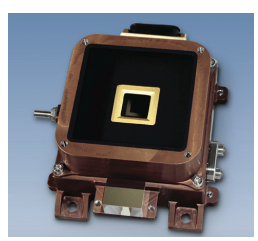
Dual-Axis Sun Sensors

Dual single-axis detection **Four-quadrant detection**









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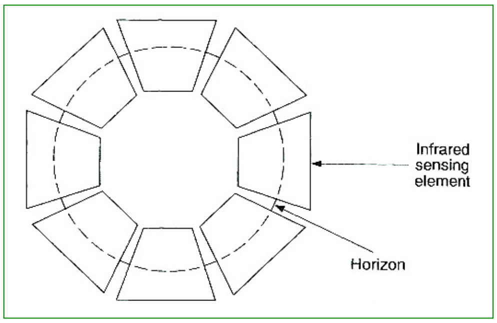
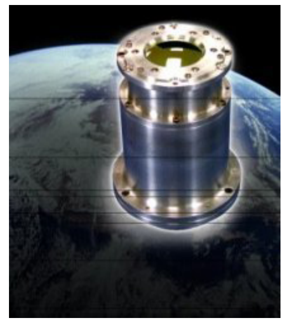
Static Earth Horizon Sensor

- Infrared sensing
- Field of view larger than the entire earth's edge (limb)
- Determines local vertical: provides orientation with respect to the nadir





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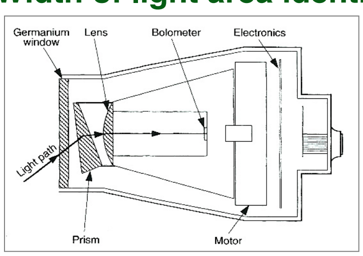
Scanning Earth Horizon Sensor

- <u>Spinning assembly</u> identifies light and dark IR areas
- Width of light area identifies width angle, η



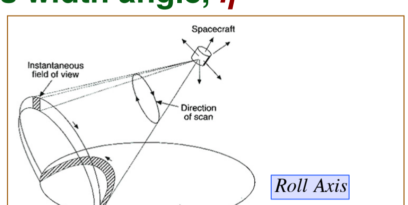


Figure 5.10 Scan cone geometry.

$\Omega = \omega_{scanner}\left(t_{LOS} - t_{AOS}\right)$: Width angle

$t_{LOS/AOS}$: Time of loss/acquisition of signal

$$\cos\rho = \cos\gamma\cos\eta + \sin\gamma\sin\eta\cos\left(\Omega/2\right)$$

ρ : Earth angular radius

γ : Half-cone angle

η: Scanner nadir angle

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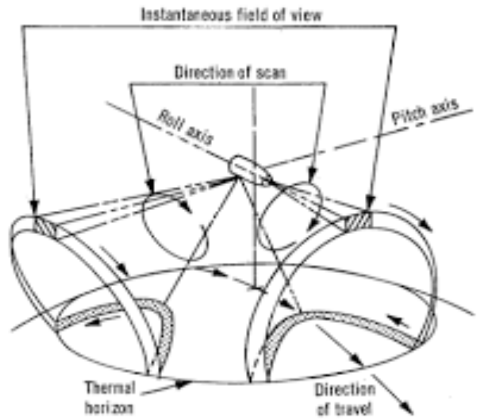
Dual Earth Horizon Sensor

Measures roll and pitch angles, more precise nadir angle



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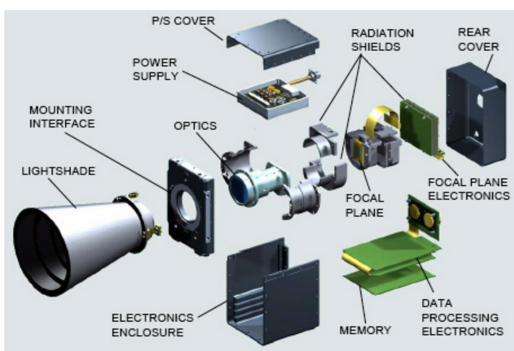
Star Tracker/Telescope

- **Coarse and fine fields field of view**
- **Star location catalog helps identify target**
- **Instrument base must have low angular velocity**
- ***(x, y)* location of star on focal plane determines angles to the star**



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Typical Spacecraft Sensor Suites

- Most precise measurements (e.g., scientific satellites, lunar/deep space probes)
  - star trackers
- Moderate accuracy requirements
  - coarse digital sun sensors
  - horizon sensors
  - magnetometers
- Spinning satellites
  - single-axis sun sensors
  - magnetometers
  - horizon sensors
- High-altitude (e.g., geosynchronous) satellites
  - optical sensors
  - gyroscopes

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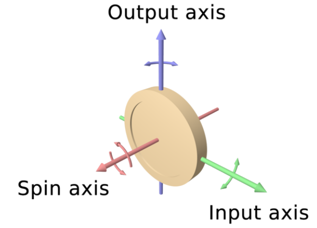
Mechanical Gyroscopes



- Body-axis moment equation

Angular momentum : $\mathbf{h}_B = \boldsymbol{I}_B \boldsymbol{\omega}_B$

$$\mathbf{M}_B = \dot{\mathbf{h}}_B + \tilde{\boldsymbol{\omega}}_B \mathbf{h}_B$$

$$\dot{\boldsymbol{\omega}}_B = \boldsymbol{I}_B^{-1}\left(M_B - \tilde{\boldsymbol{\omega}}_B \boldsymbol{I}_B \boldsymbol{\omega}_B\right)$$

- Assumptions
  - Constant nominal spin rate, ω_n, about z axis
  - $I_{xx} = I_{yy} << I_{zz}$
  - Small perturbations in ω_x and ω_y

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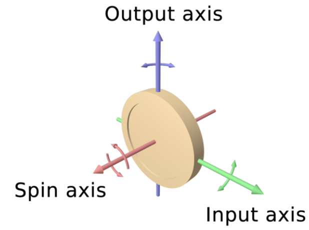
Gyroscope Equations of Motion



Linearized equations of angular rate change

$$\begin{bmatrix}\Delta\dot{\omega}_x\\ \Delta\dot{\omega}_y\\ 0\end{bmatrix} = \begin{bmatrix} I_{xx}&0&0\\0&I_{yy}&0\\0&0&I_{zz}\end{bmatrix}^{-1}\left[\begin{bmatrix}M_x\\M_y\\0\end{bmatrix} - \begin{pmatrix}0&-\omega_{z_o}&\Delta\omega_y\\ \omega_{z_o}&0&-\Delta\omega_x\\ -\Delta\omega_y&\Delta\omega_x&0\end{pmatrix}\begin{pmatrix}I_{xx}&0&0\\0&I_{yy}&0\\0&0&I_{zz}\end{pmatrix}\begin{pmatrix}\Delta\omega_x\\ \Delta\omega_y\\ \omega_{z_o}\end{pmatrix}\right]$$

$$\begin{bmatrix}\Delta\dot{\omega}_x\\ \Delta\dot{\omega}_y\\ 0\end{bmatrix} = \begin{bmatrix}\left[M_x-\omega_{z_o}\left(I_{zz}-I_{yy}\right)\Delta\omega_y\right]/I_{xx}\\ \left[M_y-\omega_{z_o}\left(I_{xx}-I_{zz}\right)\Delta\omega_x\right]/I_{yy}\\ 0\end{bmatrix}$$

or

$$\begin{bmatrix}\Delta\dot{\omega}_x\\ \Delta\dot{\omega}_y\end{bmatrix} = \begin{bmatrix}0 & \omega_{z_o}\left(I_{yy}-I_{zz}\right)/I_{xx}\\ \omega_{z_o}\left(I_{zz}-I_{xx}\right)/I_{yy} & 0\end{bmatrix}\begin{bmatrix}\Delta\omega_x\\ \Delta\omega_y\end{bmatrix} + \begin{bmatrix}M_x/I_{xx}\\ M_y/I_{yy}\end{bmatrix}$$

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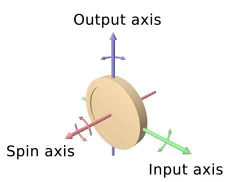

Gyroscope Natural Frequency

Laplace transform of dynamic equation

$$\begin{bmatrix} s & -\omega_{z_o}\left(I_{yy}-I_{zz}\right)/I_{xx}\\ -\omega_{z_o}\left(I_{zz}-I_{xx}\right)/I_{yy} & s\end{bmatrix}\begin{bmatrix}\Delta\omega_y(s)\\ \Delta\omega_y(s)\end{bmatrix} = \begin{bmatrix}M_x(s)/I_{xx}\\ M_y(s)/I_{yy}\end{bmatrix}$$

Characteristic equation

$$\Delta(s) = s^2 + \omega_{z_o}{}^2\left(\frac{I_{zz}}{I_{xx}}-1\right)^2 = 0$$

Natural frequency, ω_n, of small perturbations

$$\omega_n = \omega_{z_o}\left(\frac{I_{zz}}{I_{xx}}-1\right) \quad rad/\sec$$

Example

$$\omega_{z_o} = 36{,}000 \text{ rpm} = 3{,}770 \text{ rad/sec}$$

$$\text{Thin disk: } \frac{I_{zz}}{I_{xx}} = 2$$

$$\omega_n = 3{,}770 \text{ rad/sec} = 600 \text{ Hz}$$

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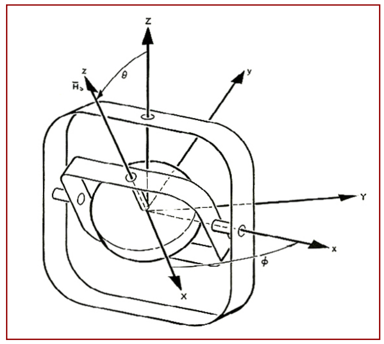
Two-Degree of Freedom Gyroscope



- Free gyro mounted on gimbaled platform
- Gyro "stores" reference direction in space
- Angle pickoffs on gimbal axes measure pitch and yaw angles
- Direction can be precessed by applying a torque

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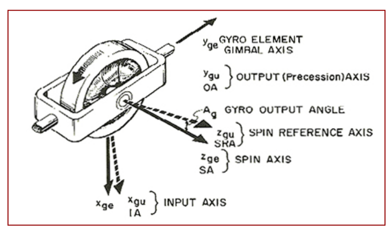
Single-Degree of Freedom Gyroscope



- Gyro axis, ζ, constrained to rotate with respect to the output axis, ***y***, only

$$\begin{bmatrix} \Delta\dot{\theta} \\ \Delta\dot{\omega}_y \end{bmatrix} = \begin{bmatrix} \Delta\omega_y \\ \left(h_{rotor}\Delta\omega_x + M_{y_{control}}\right)/I_{yy} \end{bmatrix}$$

- "Synchro" measures axis rotation, and "torquer" keeps $\Delta\psi$ small
- Torque applied is a measure of the input about the ***x*** axis

$$M_{y_{control}} = k_\theta\Delta\theta + k_\omega\Delta\omega_y + k_c\Delta u_c$$

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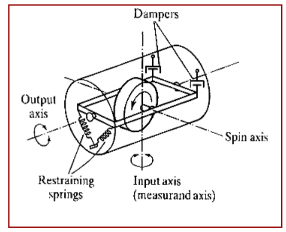
Rate and Integrating Gyroscopes



- **Large angle feedback produces a rate gyro**
  - **Analogous to a mechanical spring restraint**

$$\Delta\dot{\omega}_{y_{SS}} = 0 = \left(h_{rotor}\Delta\omega_{x_{SS}} + k_\theta \Delta\theta_{SS}\right) / I_{yy}$$

$$\Delta\theta_{SS} = -\frac{h_{rotor}}{k_\theta}\Delta\omega_{x_{SS}}$$

- **Large rate feedback produces an integrating gyro**
  - **Analogous to a mechanical damper restraint**

$$\Delta\dot{\omega}_{y_{SS}} = 0 = \left(h_{rotor}\Delta\omega_{x_{SS}} + k_\omega \Delta\omega_{y_{SS}}\right) / I_{yy}$$

$$\Delta\omega_{y_{SS}} = -\frac{h_{rotor}}{k_\omega}\Delta\omega_{x_{SS}}$$

$$\Delta\theta_{SS} = \Delta\phi_{SS}$$

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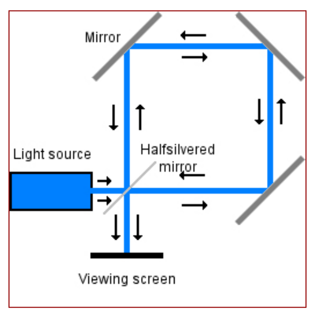
Optical Gyroscopes

- **Sagnac interferometer measures rotational rate, Ω**
  - **Ω = 0, photons traveling in opposite directions complete the circuit in the same time**
  - **$\Omega \neq 0$, travel length and time are different**
- **On a circular path of radius R:**



$$t_{CCW} = \frac{2\pi R}{c}\left(1 - \frac{R\Omega}{c}\right); \quad t_{CW} = \frac{2\pi R}{c}\left(1 + \frac{R\Omega}{c}\right)$$

$$\Delta t = t_{CW} - t_{CCW} = \frac{4\pi R^2}{c^2}\Omega = \frac{4A}{c^2}\Omega$$

c : speed of light; R : radius; A : area

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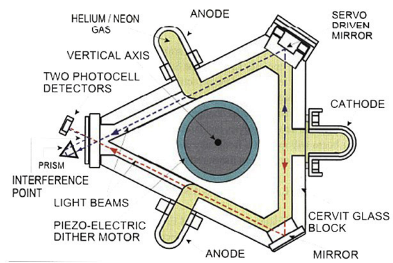
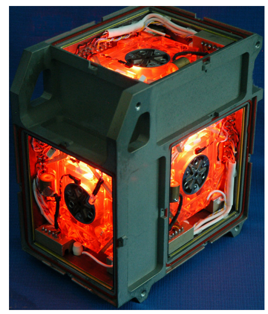
Ring Laser Gyro

- Laser in optical path creates photon resonance at wavelength, ***λ***
- Frequency change in cavity is proportional to angular rate
- Three RLGs needed to measure three angular rates



$$\Delta f = \frac{4A}{\lambda P}\Omega$$

P : perimeter length



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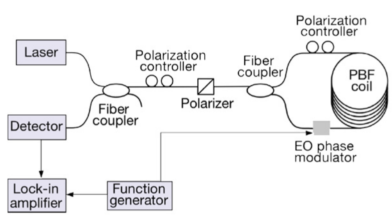
Fiber Optic Gyro



- Long fiber cable wrapped in circle
- Photon source and sensor external to fiber optics
- Length difference for opposite beams, ***ΔL***

A : included area

N : number of turns

- Phase difference proportional to angular rate

$$\Delta L = \frac{4AN}{c}\Omega$$

$$\Delta \varphi = \frac{8\pi AN}{\lambda c}\Omega$$

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Vibrating Piezoelectric Crystal Angular Rate Sensor

- "Tuning fork" principle
- 4 piezoelectric crystals
  - 2 active, oscillating out of phase with each other
  - 2 sensors, mounted perpendicular to the active crystals
- With zero rate along the long axis, sensors do not detect vibration
- Differential output of sensors is proportional to angular rate

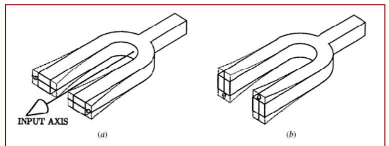
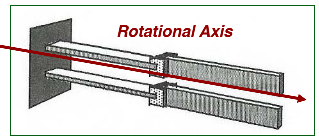
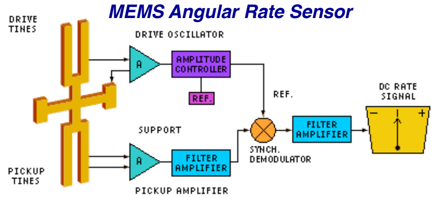


Fig. 9.11 Vibration modes of tuning fork gyroscope: (a) input mode; (b) output mode.



MEMS Angular Rate Sensor



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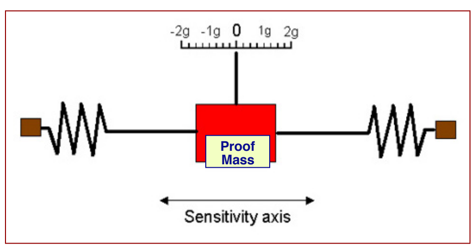
Spring Deflection Accelerometer



$$\Delta\ddot{x} = -k_s \Delta x / m$$

$$\Delta x = \frac{m}{k_s}\Delta\ddot{x}$$

- Deflection is proportional to acceleration
- Damping required to reduce oscillation

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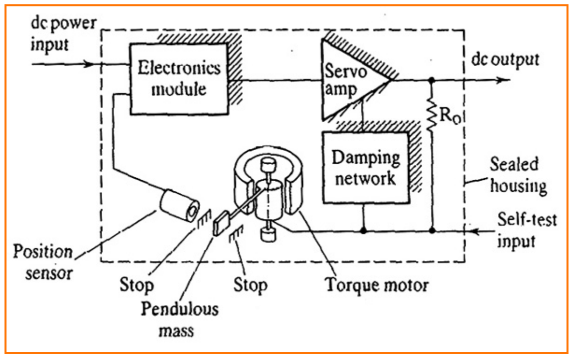
Force Rebalance Accelerometer

$$f = ma$$



$$\Delta\ddot{x} = f_x/m = \left(-k_d\Delta\dot{x} - k_s\Delta x\right)/m$$

Voltage required to re-center the proof mass becomes the measure of acceleration

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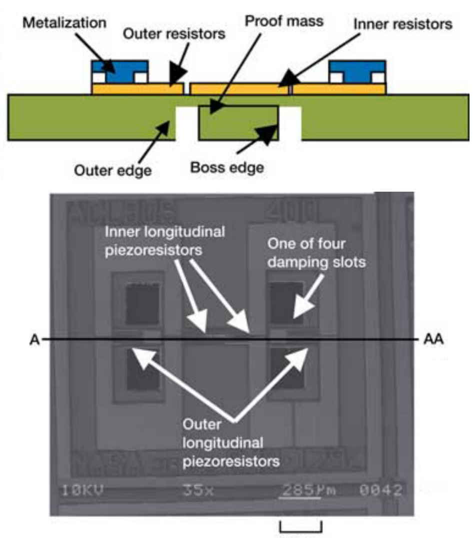
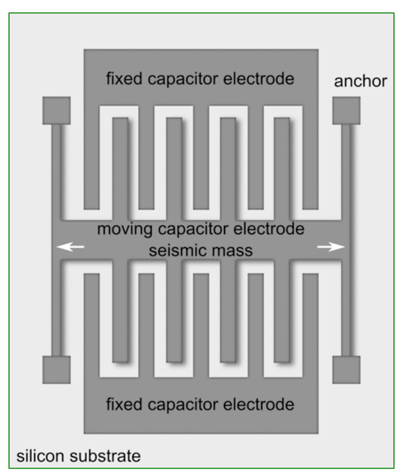
MicroElectroMechanical System (MEMS) Accelerometer





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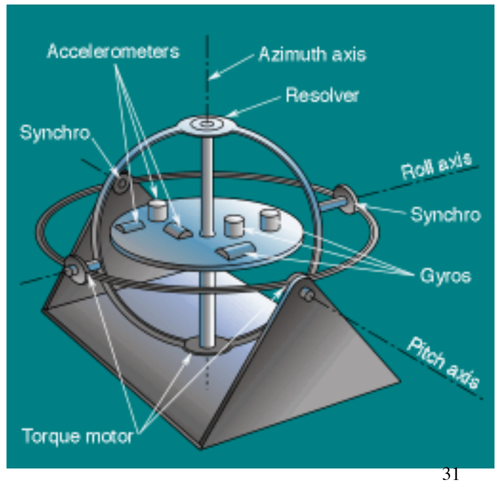
$$\begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix} \Rightarrow \begin{bmatrix} v_x \\ v_y \\ v_z \end{bmatrix} \Rightarrow \begin{bmatrix} x \\ y \\ z \end{bmatrix}$$

$$\begin{bmatrix} \omega_x \\ \omega_y \\ \omega_z \end{bmatrix} \Rightarrow \begin{bmatrix} \phi \\ \theta \\ \psi \end{bmatrix}$$

Inertial Measurement Units

- 3 accelerometers
- 3 rate or rate-integrating gyroscopes
- Platform orientation "fixed" in space
- Vehicle rotates about the platform
- Need for high precision instruments
- Drift due to errors and constants of integration
- Platform re-oriented with external data (e.g., GPS)

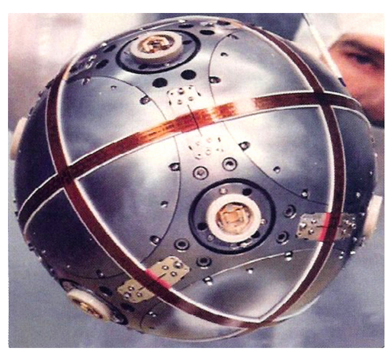
Gimbaled Physical Platform



Gimbal-less Physical Platform

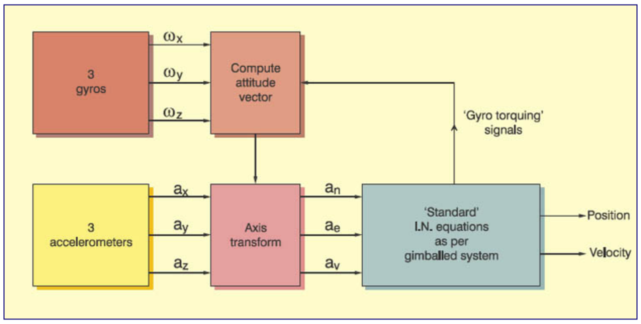
- Air bearing floats platform in lieu of gimbals
- Peacekeeper IMU*
- Reduced errors due to fluidic suspension
- Instruments subjected to low dynamic range, allowing high precision

Servo-driven reference frame



*IEEE Control Systems Magazine, 2/08

Strapdown Inertial Measurement Units



- Rate gyros and accelerometers rotate with vehicle
- High dynamic range of instruments is required
- Inertial reference frame is computed rather than physical
- Use of direction cosine matrix and quaternions for attitude reference

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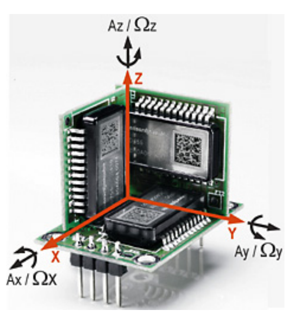
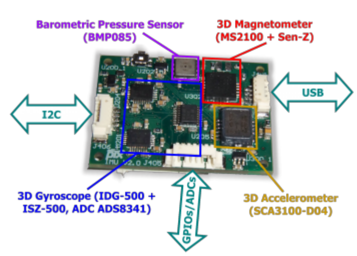
MicroElectroMechanical (MEMS) Strapdown Inertial Measurement Units

- Less accurate than precision physical platform
- High drift rates
- Acceptable short-term accuracy
- Can be integrated with magnetometer and pressure sensor, updated with GPS





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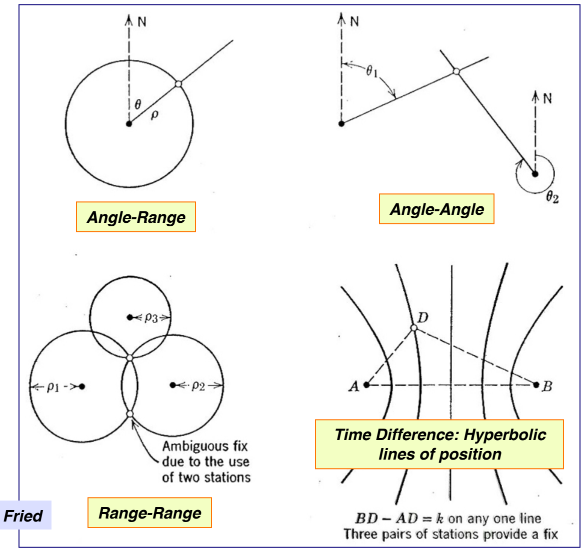
Position Fixing for Navigation
(2-D Examples)

Lines of Position: Lines, Circles, and Hyperbolae



Kayton & Fried

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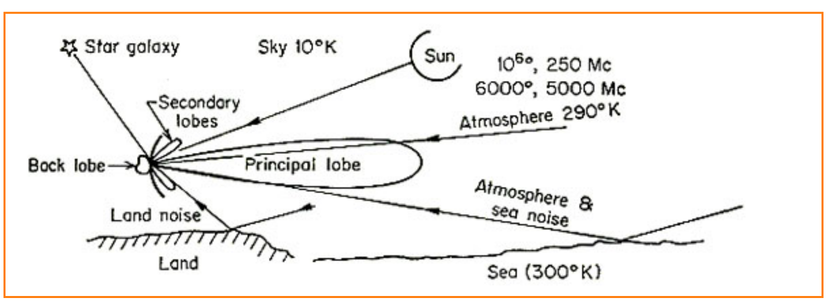
Pulse Radar

- **Pulse radar measures range by sending a pulse and measuring time to receive return**
- **Elevation and azimuth angles measured from tracking antenna angles**

$$R = c\Delta t = c\left(t_{receive} - t_{transmit}\right)$$



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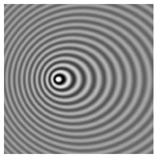
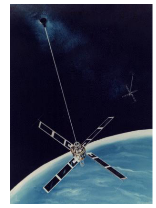


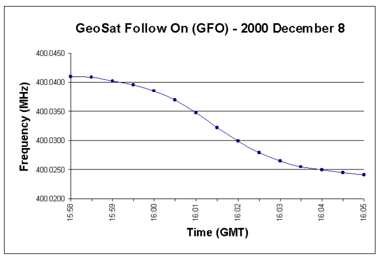
Doppler Effect (wave source moving to the left)

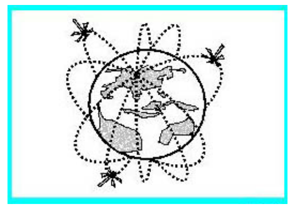
Doppler Radar

Doppler Effect Demo



- Doppler radar measures velocity along line of sight
- *Transit* satellite constellation (5 satellites, minimum)
  - navigation signals to 200-m accuracy
  - point of closest approach determined by inflection in Doppler curve (received signal frequency vs. time)
  - *http://en.wikipedia.org/wiki/Transit_(satellite)*





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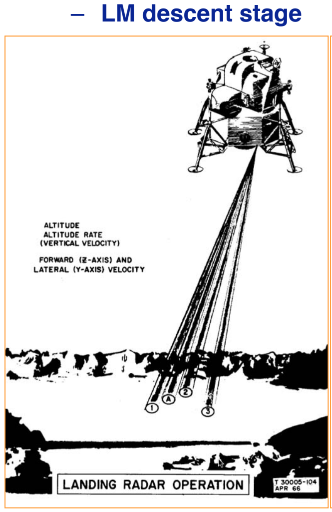
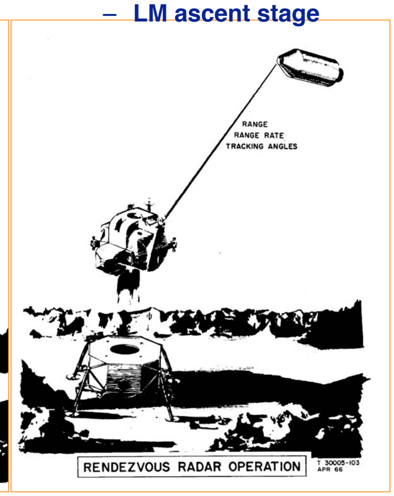
Apollo Lunar Module Radars

- Landing radar
  - 3-beam Doppler
  - radar altimeter
  - LM descent stage
- Rendezvous radar
  - continuous-wave tracking radar
  - LM ascent stage





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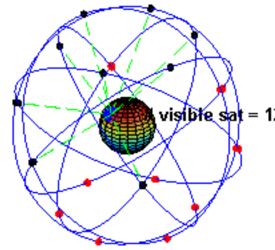
Global Positioning System



- Six orbital planes with four satellites each
  - Altitude: 20,200 km (10,900 nm)
  - Inclination : 55 deg
  - Constellation planes separated by 60 deg
- Each satellite contains an atomic clock and broadcasts a 30-sec message at 50 bps
  - Ephemeris
  - ID
  - Clock data
  - Details of satellite signal at http://en.wikipedia.org/wiki/Gps
- http://www.youtube.com/watch?v=v_6yeGcpoyE

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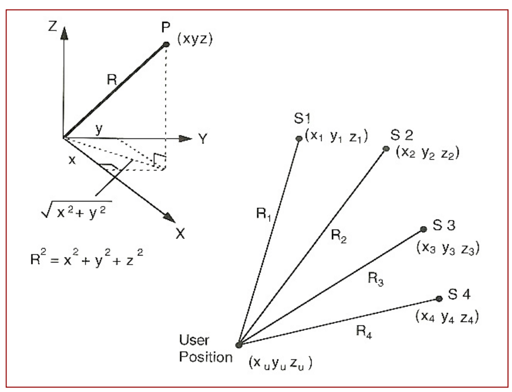
Position Fixing from 4 GPS Satellites

- Pseudorange estimated from speed of light and time required to receive signal



$$R_{1_p} = c\Delta t_1 \qquad R_{3_p} = c\Delta t_3$$

$$R_{2_p} = c\Delta t_2 \qquad R_{4_p} = c\Delta t_4$$

User clock inaccuracy produces error, $C_u = c\Delta t$

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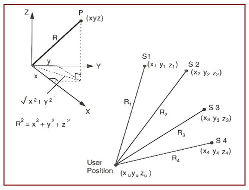

Position Fixing from Four GPS Satellites

$$R_1 = \sqrt{(x_1 - x_u)^2 + (y_1 - y_u)^2 + (z_1 - z_u)^2} = R_{1_p} + C_u$$
$$R_2 = \sqrt{(x_2 - x_u)^2 + (y_2 - y_u)^2 + (z_2 - z_u)^2} = R_{2_p} + C_u$$
$$R_3 = \sqrt{(x_3 - x_u)^2 + (y_3 - y_u)^2 + (z_3 - z_u)^2} = R_{3_p} + C_u$$
$$R_4 = \sqrt{(x_4 - x_u)^2 + (y_4 - y_u)^2 + (z_4 - z_u)^2} = R_{4_p} + C_u$$

- **Four equations and four unknowns (*x_u, y_u, z_u, C_u*)**
- **Accuracy improved using data from more than 4 satellites**

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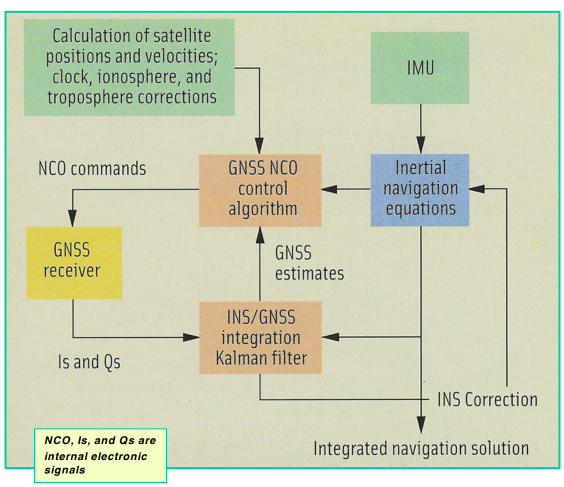
Integrated Inertial Navigation/GPS System



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Angular Attitude Actuators

Internal Devices

Momentum/reaction wheels
Control moment gyroscope
Nutation dampers

External Devices

Magnetic coils
Thrusters
Solar radiation pressure

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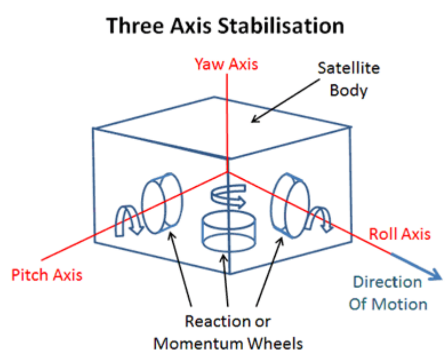
Momentum/Reaction Wheels

Flywheels on motor shafts

Reaction wheel *rpm* is varied to trade angular momentum with spacecraft for control

Three orthogonal wheels vary all components of angular momentum
Fourth wheel at oblique angle would provide redundancy



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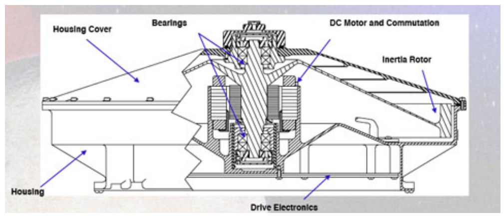
Momentum/ Reaction Wheels

- **Momentum wheel** operates at high *rpm* and provide spin stability (~dual-spin spacecraft) plus control torques



- **Reaction wheel** *rpm* is low, varied to trade angular momentum with the spacecraft for control
  - Three orthogonal wheels vary all components of angular momentum
  - Fourth wheel at oblique angle provides redundancy

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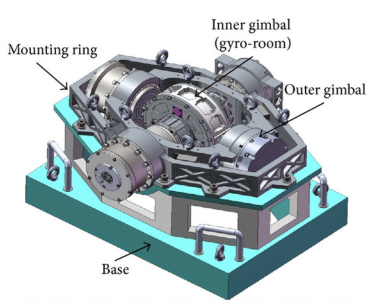
Control Moment Gyroscope

Gyros operate at *constant rpm*

Small torque on input axis produces large torque on output axis, modifying spacecraft momentum

One or two degrees of freedom



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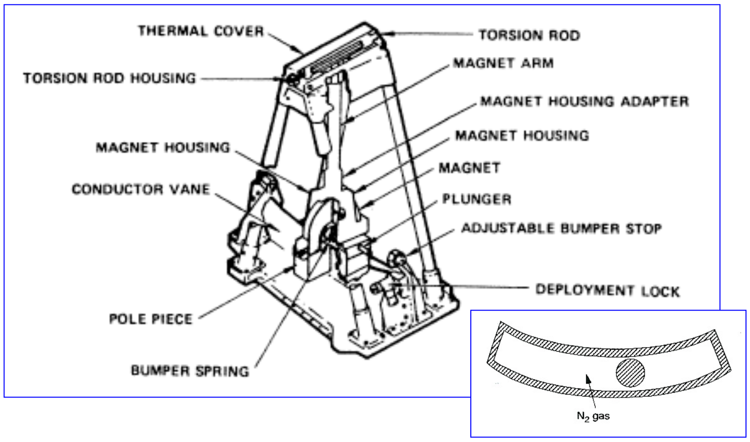
Nutation Dampers

- **Nutation dampers dissipate angular energy**
  - **Eddy current on a conducting pendulum in a magnetic field**
  - **Mass moving in a gas or viscous fluid**



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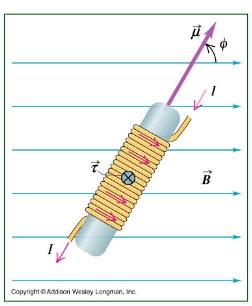
Magnetic Torquers

$$\mathbf{m} = N\,I\,A\left(\mathbf{i} \times \mathbf{B}\right)$$

- **Current flowing through a loop generates a magnetic torque through interaction with the Earth's magnetic field**

N : *number of loops*
I : *current*
A : *included area of loops*
i : *unit vector along coil axis*
B : *local flux density*



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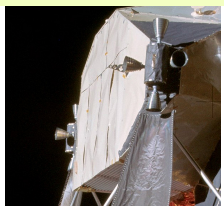
Reaction Control Thrusters

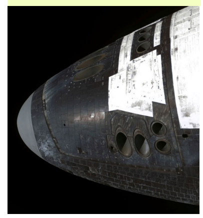
- Direct control of angular rate
- Unloading momentum wheels or control-moment gyros
- Reaction control thrusters are typically on-off devices using
  - Cold gas
  - Hypergolic propellants
  - Catalytic propellant
  - Ion/plasma rockets

- Issues
  - Specific impulse
  - Propellant mass
  - Expendability

Apollo Lunar Module RCS



Space Shuttle RCS



- Thrusters commanded in pairs for *pure couple*

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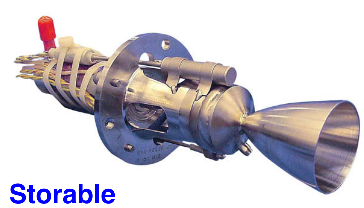
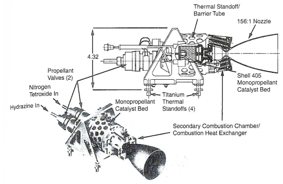
Reaction Control Thrusters

Cold Gas Thruster
(used with inert gas)

Monopropellant Hydrazine Thruster



Hypergolic, Storable Bipropellant Thruster



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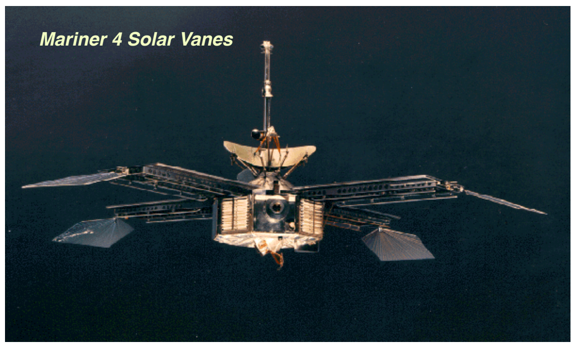
Solar Radiation Pressure Control Panels

Solar radiation pressure

Vanes deflected differentially

Analogous to aerodynamic control surfaces

Long moment arm from center of mass



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Sensors and Actuators for Spacecraft Mechanisms

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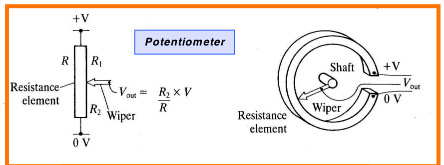
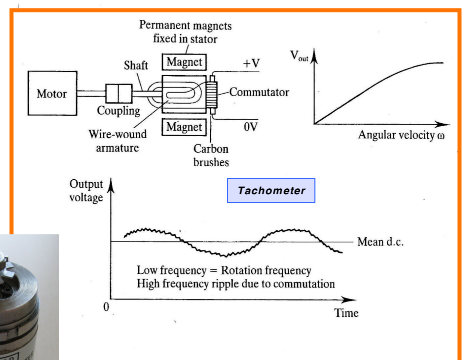
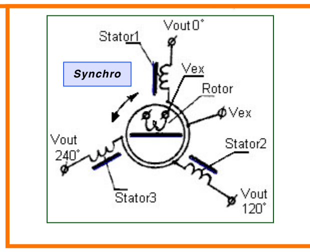
Potentiometer, Synchro, and Tachometer







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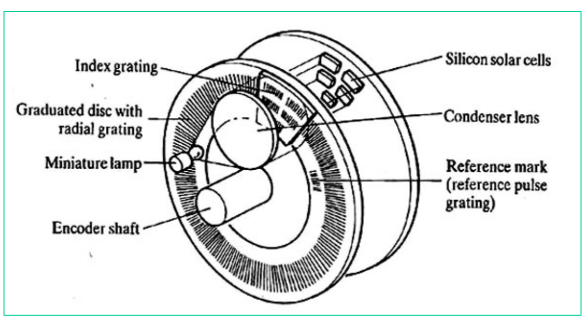
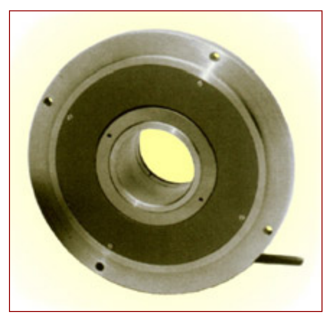
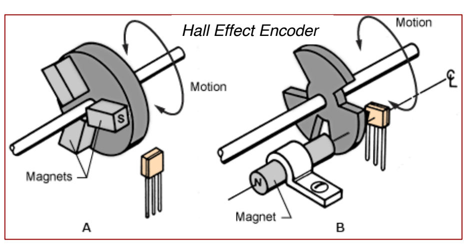
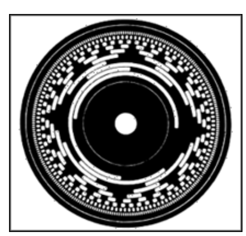
Angular Encoder









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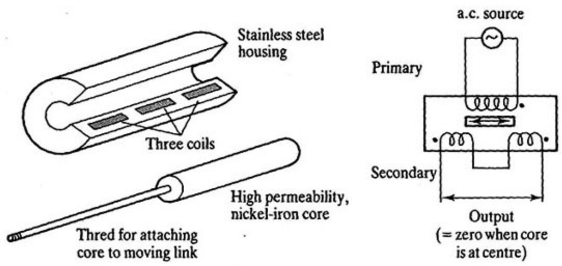
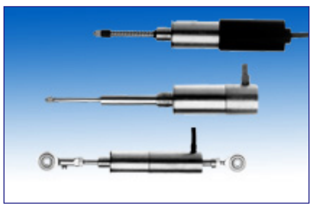
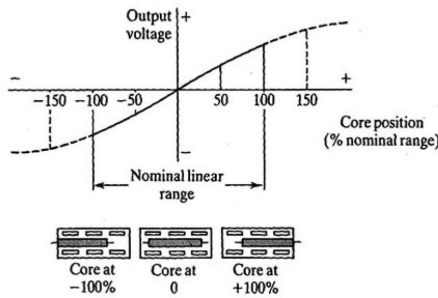
Linear Variable Differential Transformer







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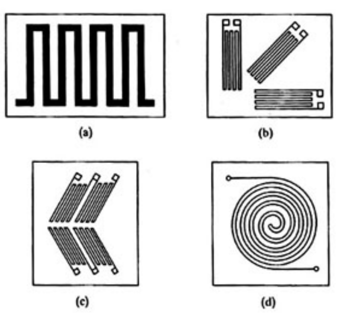
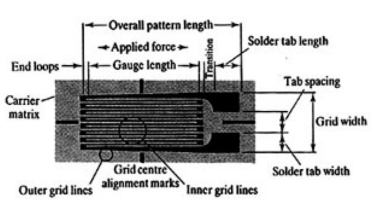
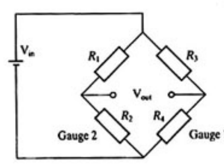
Strain Gage





Wheatstone Bridge



$$V_{out} = \left(\frac{R_2}{R_1 + R_2} - \frac{R_4}{R_3 + R_4}\right) V_{in}$$

$$\varepsilon = \left(\frac{\Delta R}{R_o}\right) \Big/ Gage\ Factor$$

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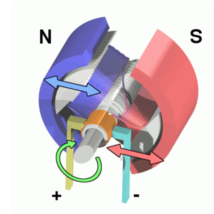
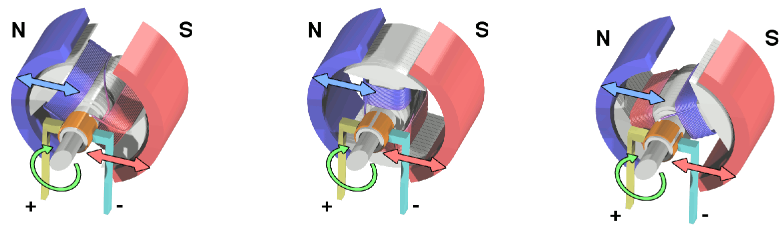
Electric Actuator
Brushed DC Motor



Two-pole DC Motor



- **Current flowing through armature generates a magnetic field**
- **Permanent magnets torque the armature**
- **When armature is aligned with magnets, commutator reverses current and magnetic field**
- **Multiple poles added to allow motor to smooth output torque and to start from any position**

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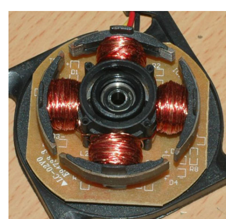
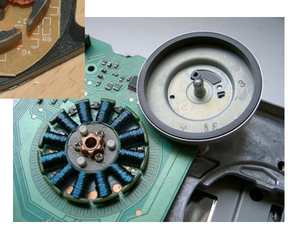
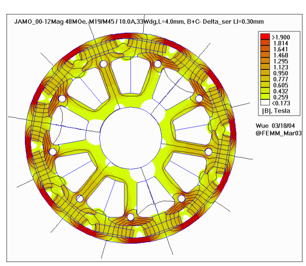
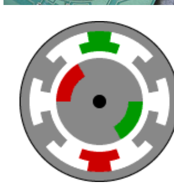
Electric Actuator
Brushless DC Motor

- **Armature is fixed, and permanent magnets rotate**
- **Electronic controller commutates the electromagnetic force, providing a rotating field**
- **Advantages**
  - **Efficiency**
  - **Noise**
  - **Lifetime**
  - **Reduced EMI**
  - **Cooling**
  - **Water-resistant**









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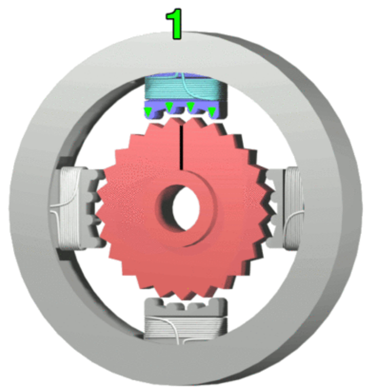
Electric Actuator
Stepper Motor

- Brushless, synchronous motor that moves in discrete steps
- Precise, quantized control without feedback
- Armature teeth offset to induce rotary motion



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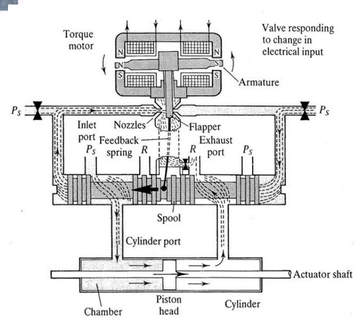
Hydraulic Actuator



Used principally for launch vehicle thrust vector and propellant control

Not widely used on spacecraft

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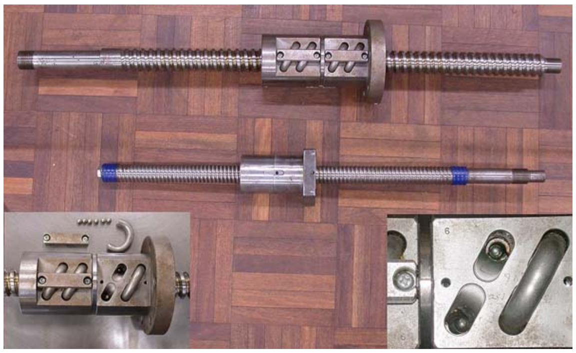
Ball/Roller Screw Linear Actuator

Transforms rotary to linear motion



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Next Time:
Electrical Power Systems

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Supplemental Material

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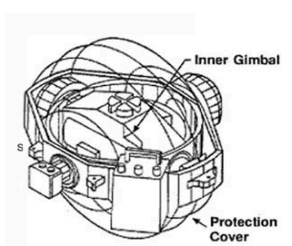
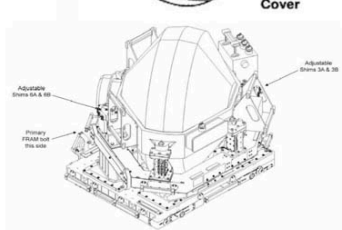
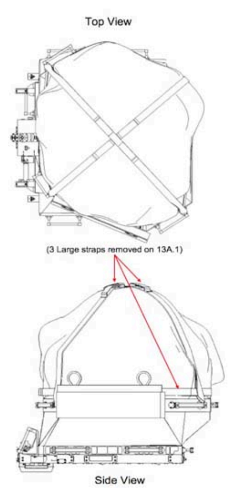
Control-Moment Gyro

Flywheel on a motor shaft

RPM is fixed, axis is rotated to impart torque







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