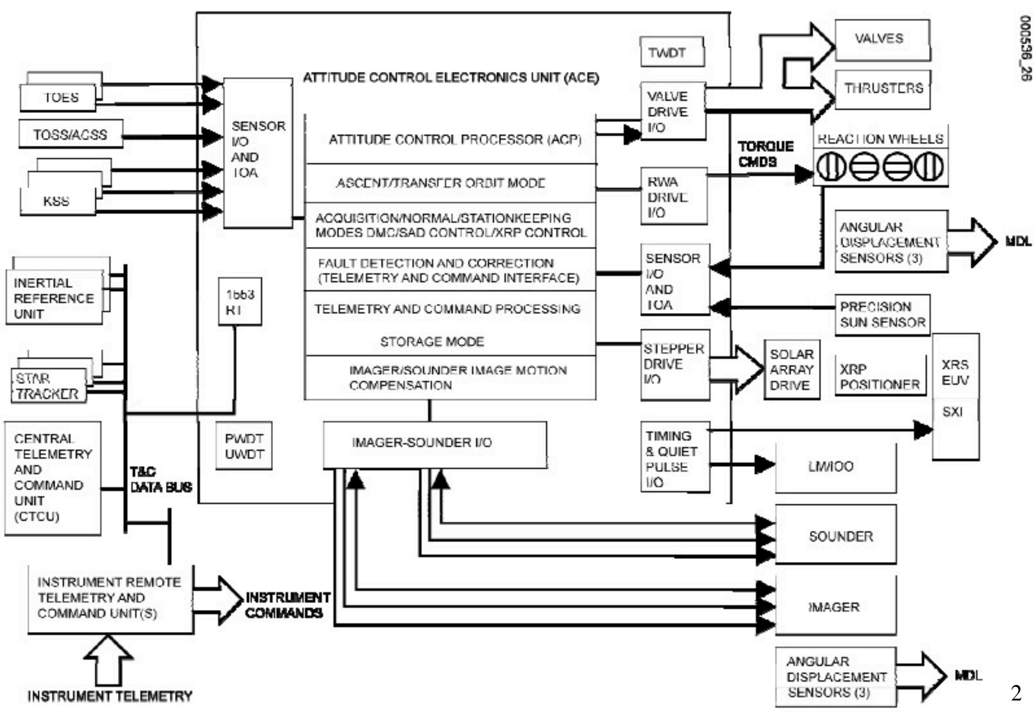
Spacecraft Sensors and Actuators

Space System Design, MAE 342, Princeton University
Robert Stengel

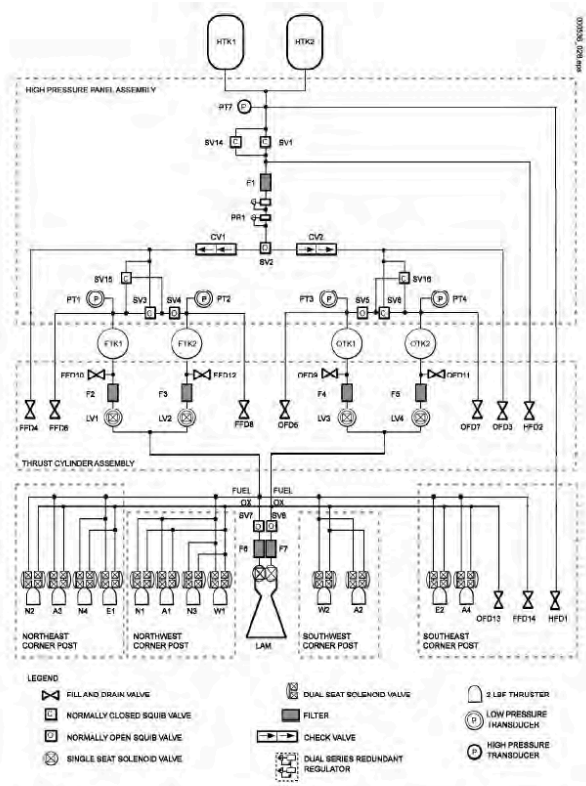
- Attitude Measurements
- Attitude Actuators
- Translational Measurements
- Mechanical Devices

GOES Attitude Control Sub-System

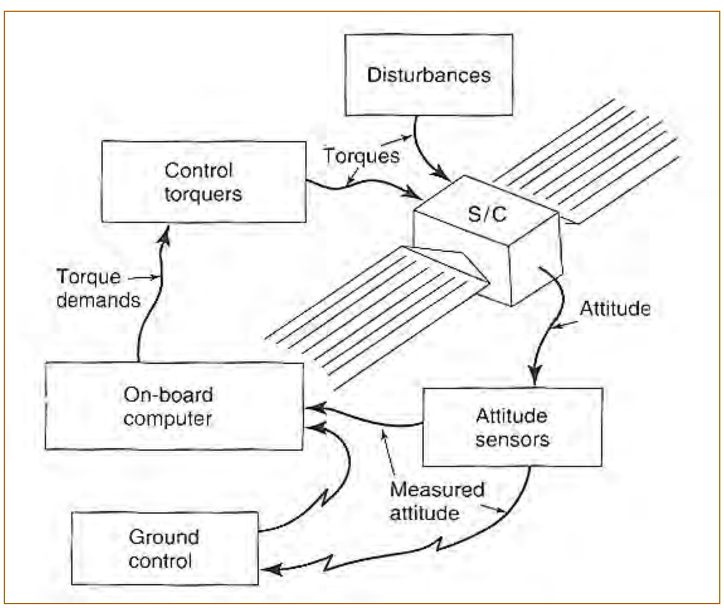


GOES Propulsion Sub-System

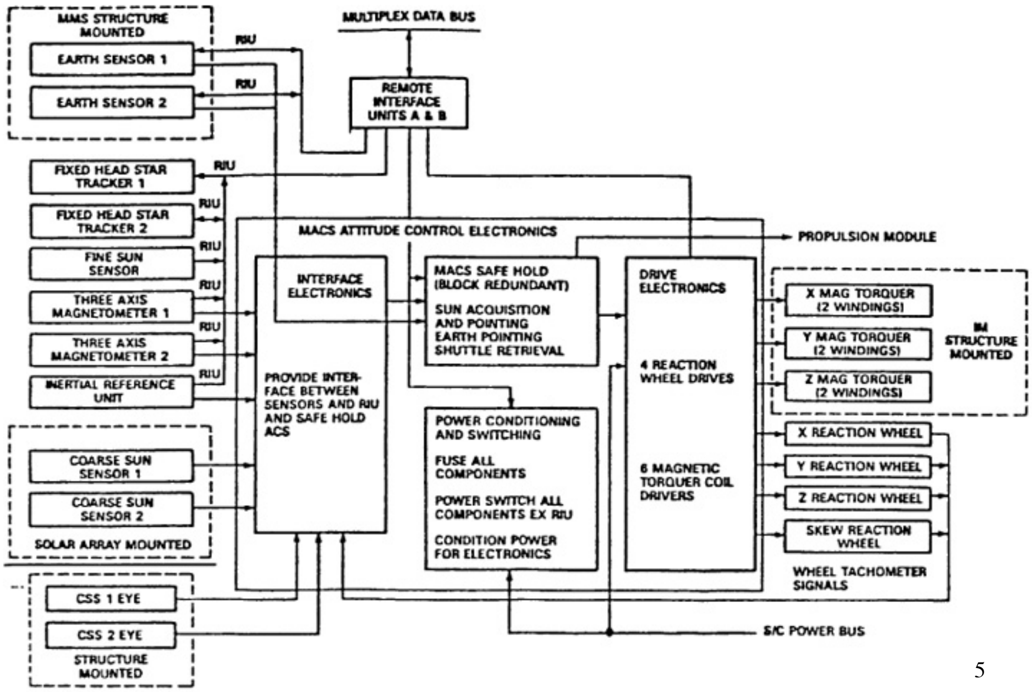
- Propellant tanks
- High-pressure control
- Valves
- Reaction control thrusters
- Main engine



Attitude Control System



UARS Attitude Control System



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

Potential Accuracies of Attitude Measurements

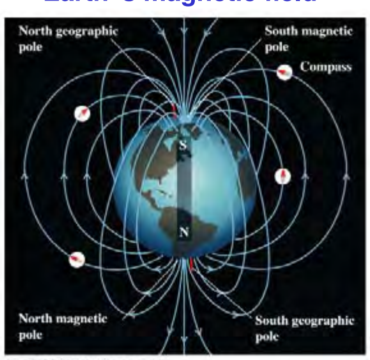
Reference object	Potential accuracy
Stars	1 arc second
Sun	1 arc minute
Earth (horizon)	6 arc minutes
RF beacon	1 arc minute
Magnetometer	30 arc minutes
Narstar Global Positioning System (GPS)	6 arc minutes

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

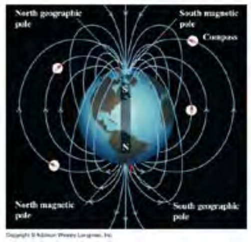
Fortescue

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**



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



Body Orientation from Magnetometer

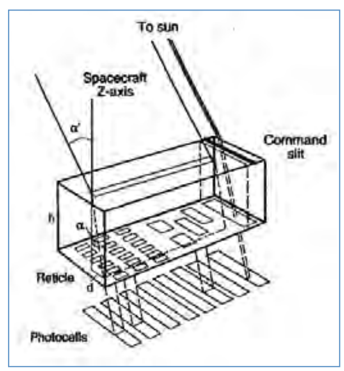
- **Earth's magnetic field vector, $\mathbf{b}_I$, function of spacecraft position, (x, y, z)**
- **Body orientation vector, $\mathbf{b}_B$, related to $\mathbf{b}_I$ by**
  - **rotation matrix, $\mathbf{H}_B^I$, from inertial to body frame and**
  - **calibration rotation matrix, S**

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

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

Single-Axis Sun Sensor

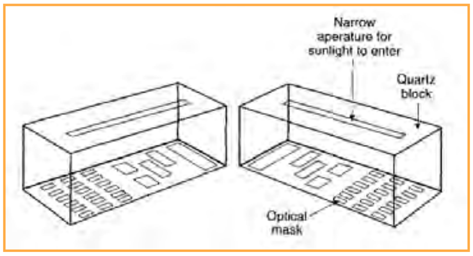
$$\tan\alpha = d/h$$
$$\sin\alpha' = n\sin\alpha \quad \text{(Snell's law)}$$
$$n = \text{index of refraction}$$

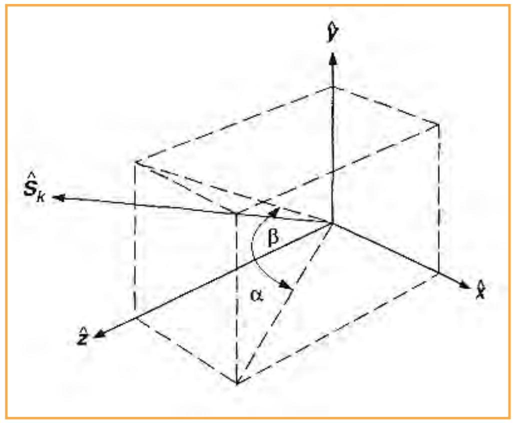


- **Transparent block of material, known refractive index, n, coated with opaque material**
- **Slit etched in top, receptive areas on bottom**
- **Sun light passing through slit forms a line over photodetectors**
- **Distance from centerline determines angle, α**
- **With index of refraction, n, angle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

Dual-Axis Sun Sensors

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





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

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

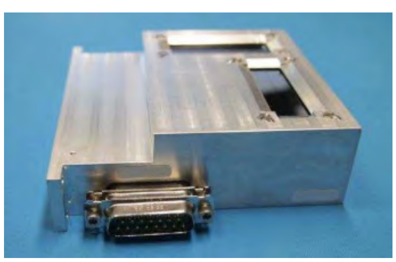
$$\mathbf{s}_I = \mathbf{H}_B^I\left(\mathbf{s}_B + \text{error}\right)$$

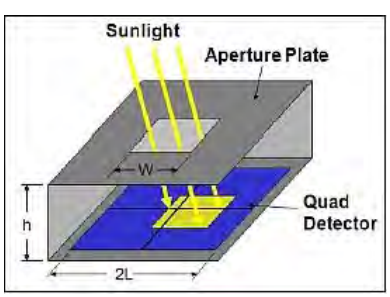
Two measurements, three unknowns

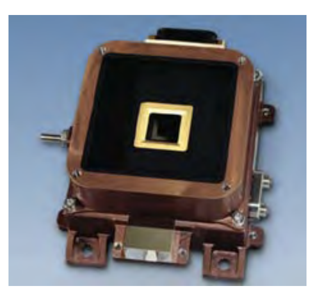
Three-axis attitude determination requires additional information

Dual-Axis Sun Sensors

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

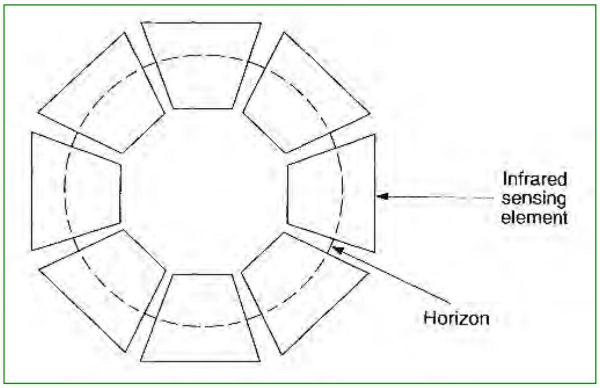


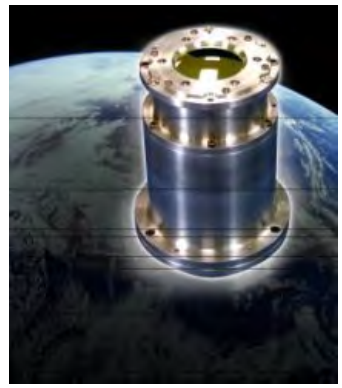




Static Earth Horizon Sensor

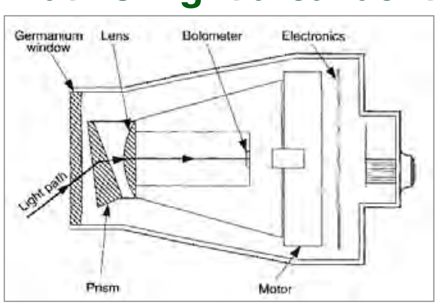
- Infrared sensing
- Field of view larger than the entire earth's edge (limb)
- Determines local vertical: provides orientation with respect to the nadir

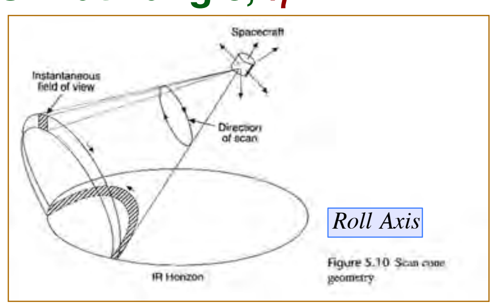




Scanning Earth Horizon Sensor

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





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

$t_{LOS/AOS}$: 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

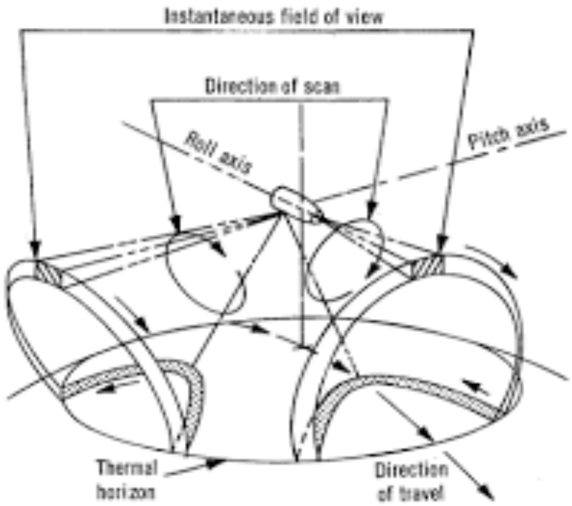
γ : Half-cone angle

η: Scanner nadir angle

Fortesque

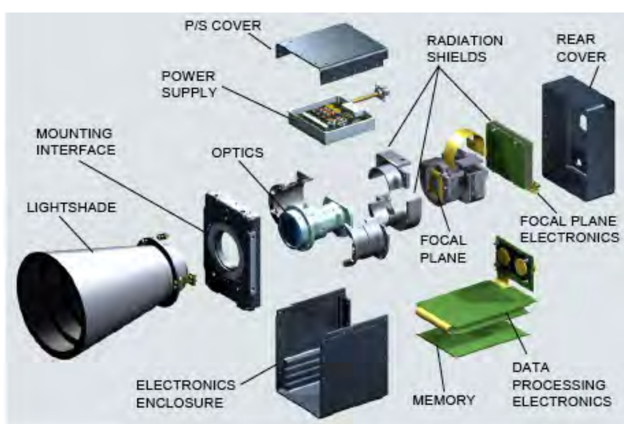
Dual Earth Horizon Sensor

Measures roll and pitch angles, more precise nadir angle



Star Tracker/Telescope

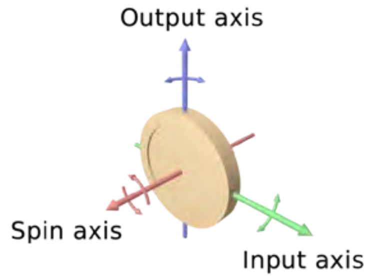
- **Coarse and fine fields field of view**
- **Star location catalog helps identify target**
- **Instrument base must have low angular velocity**
- ***(x, y)* location of star on focal plane determines angles to the star**



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

Mechanical Gyroscopes



- Body-axis moment equation

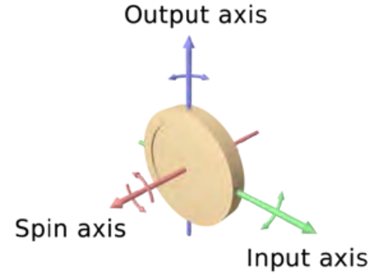
$$\boxed{\mathbf{M}_B = \dot{\mathbf{h}}_B + \tilde{\boldsymbol{\omega}}_B \mathbf{h}_B}$$

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

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

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

Gyroscope Equations of Motion



Linearized equations of angular rate change

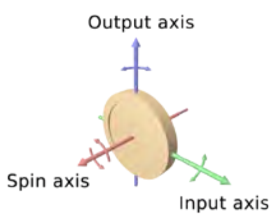
$$\begin{bmatrix} \Delta\dot{\omega}_x \\ \Delta\dot{\omega}_y \\ 0 \end{bmatrix} = \begin{bmatrix} I_{xx} & 0 & 0 \\ 0 & I_{yy} & 0 \\ 0 & 0 & I_{zz} \end{bmatrix}^{-1} \left[\begin{bmatrix} M_x \\ M_y \\ 0 \end{bmatrix} - \begin{pmatrix} 0 & -\omega_{z_o} & \Delta\omega_y \\ \omega_{z_o} & 0 & -\Delta\omega_x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

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

or

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

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

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

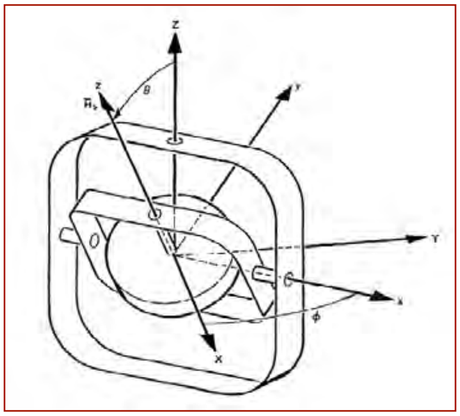
Example

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

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

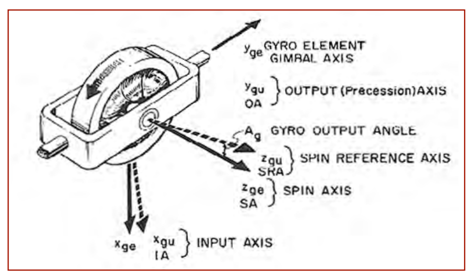
$$\omega_n = 3{,}770 \text{ rad/sec} = 600 \text{ Hz}$$

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

Single-Degree of Freedom Gyroscope



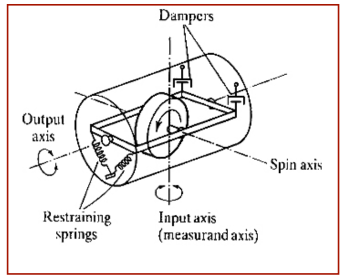
- Gyro axis, *z*, constrained to rotate with respect to the output axis, *y*, only

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

- “Synchro” measures axis rotation, and “torquer” keeps *Δy* small
- Torque applied is a measure of the input about the *x* axis

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

Rate and Integrating Gyroscopes



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

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

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

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

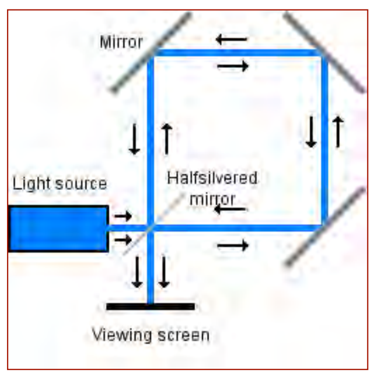
$$\Delta\dot{\omega}_{y_{SS}} = 0 = \left(h_{rotor}\Delta\omega_{x_{SS}} + k_\omega \Delta\omega_{y_{SS}}\right)\Big/ I_{yy}$$

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

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

Optical Gyroscopes

- **Sagnac interferometer measures rotational rate, Ω**
  - $\Omega = 0$, 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:**



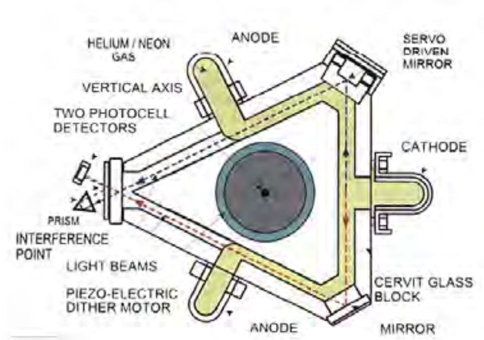
$$t_{CCW} = \frac{2\pi R}{c}\left(1 - \frac{R\Omega}{c}\right); \quad t_{CW} = \frac{2\pi R}{c}\left(1 + \frac{R\Omega}{c}\right)$$

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

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

Ring Laser Gyro

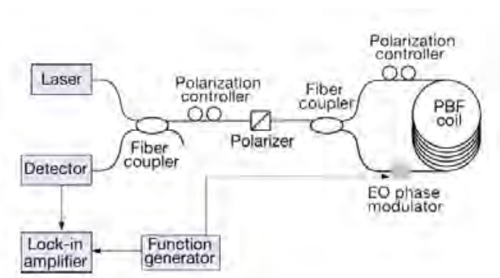
- Laser in optical path creates photon resonance at wavelength, λ
- Frequency change in cavity is proportional to angular rate
- Three RLGs needed to measure three angular rates



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

P : perimeter length

Fiber Optic Gyro



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

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

A : included area

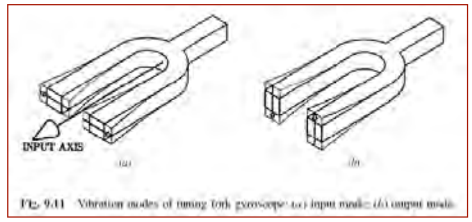
N : number of turns

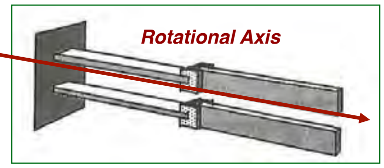
$$\Delta\varphi = \frac{8\pi AN}{\lambda c}\Omega$$

- Phase difference proportional to angular rate

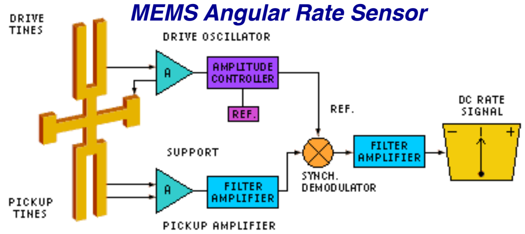
Vibrating Piezoelectric Crystal Angular Rate Sensor

- “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

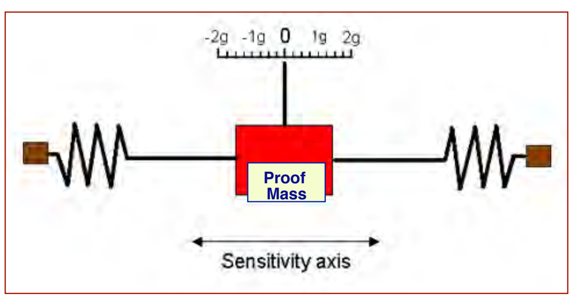




MEMS Angular Rate Sensor



Spring Deflection Accelerometer



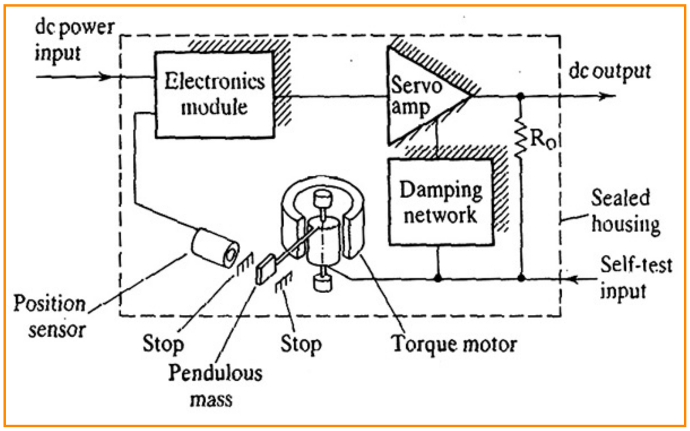
$$\Delta\ddot{x} = -k_s \Delta x / m$$

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

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

Force Rebalance Accelerometer

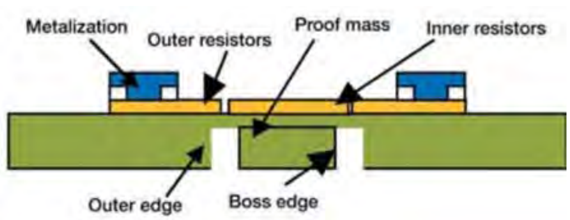
$$\boxed{f = ma}$$

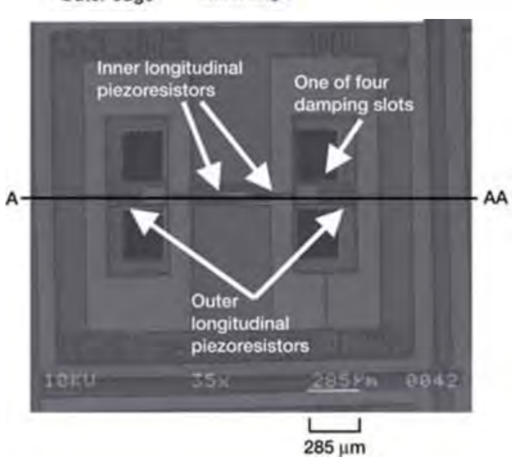


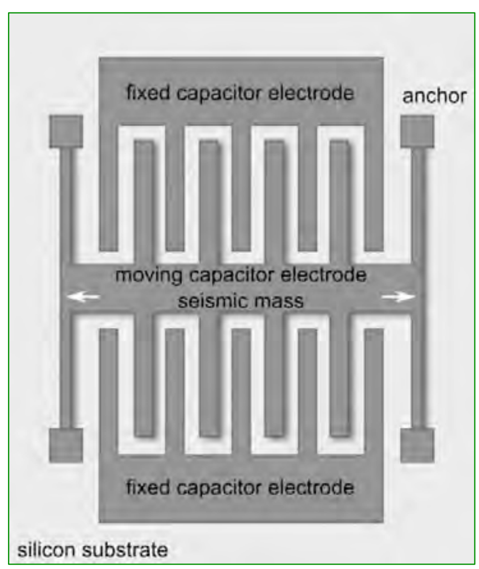
$$\boxed{\Delta\ddot{x} = f_x/m = \left(-k_d\Delta\dot{x} - k_s\Delta x\right)/m}$$

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

MicroElectroMechanical System (MEMS) Accelerometer







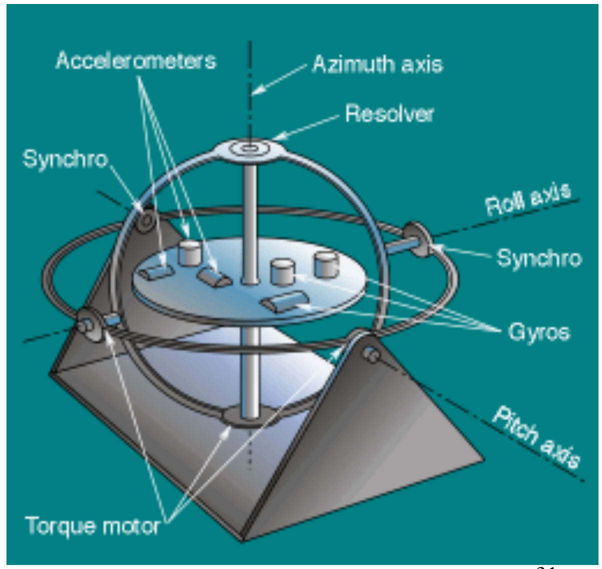
$$\begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix} \Rightarrow \begin{bmatrix} v_x \\ v_y \\ v_z \end{bmatrix} \Rightarrow \begin{bmatrix} x \\ y \\ z \end{bmatrix}$$

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

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)

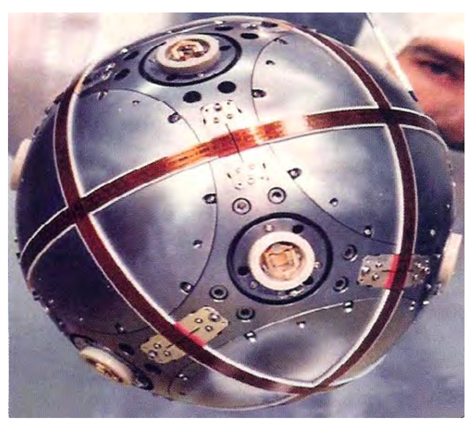
Gimbaled Physical Platform



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



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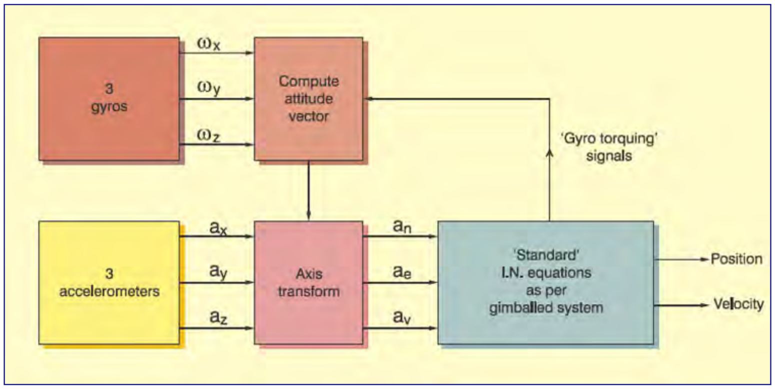
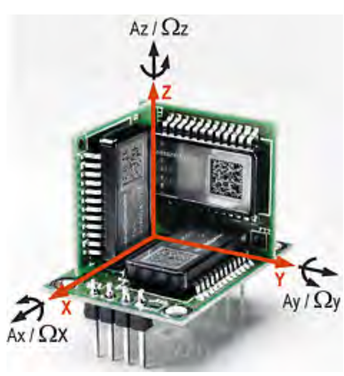
Strapdown Inertial Measurement Units

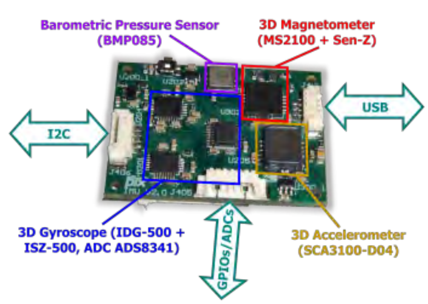


- Rate gyros and accelerometers rotate with vehicle
- High dynamic range of instruments is required
- Inertial reference frame is computed rather than physical
- Use of direction cosine matrix and quaternions for attitude reference

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

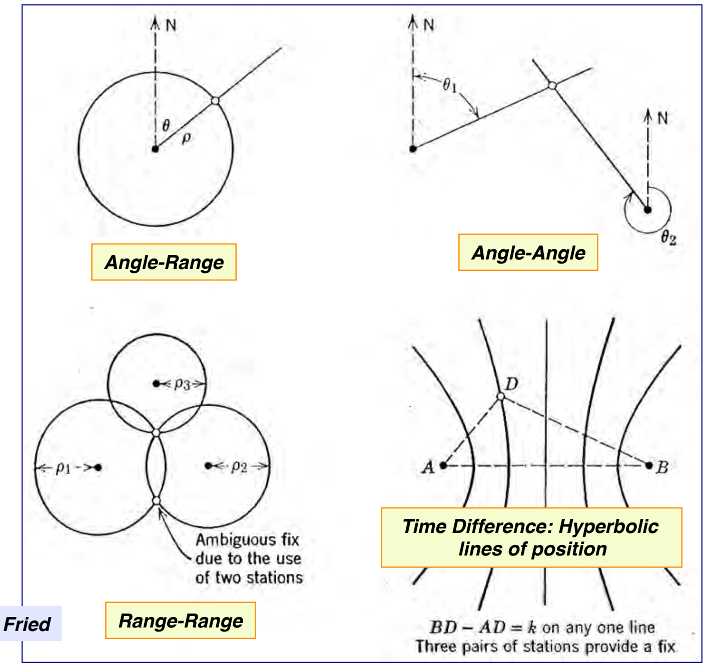




Position Fixing for Navigation

(2-D Examples)

Lines of Position: Lines, Circles, and Hyperbolae

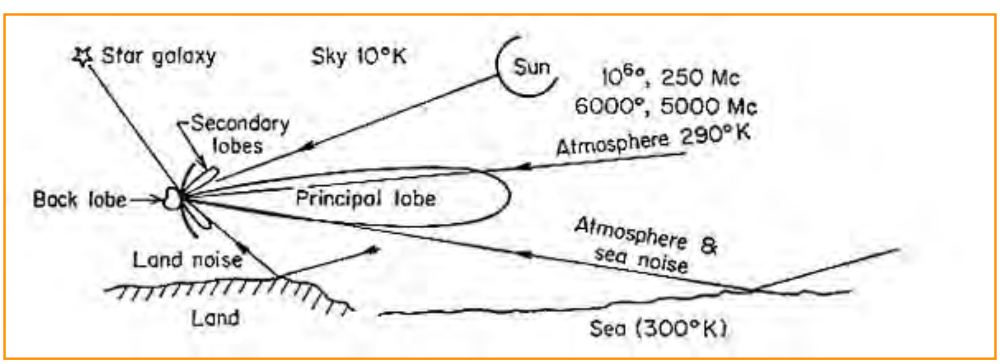


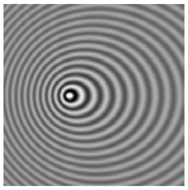
Kayton & Fried

• 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**

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

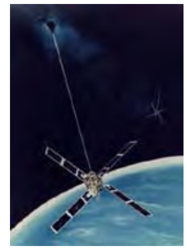




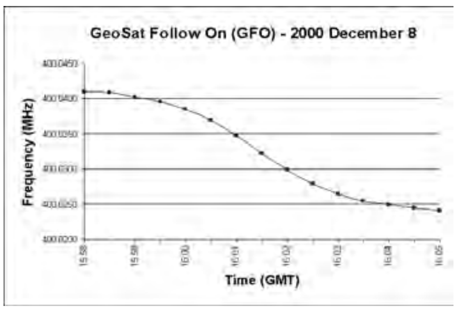
Doppler Effect (wave source moving to the left)

Doppler Radar

Doppler Effect Demo

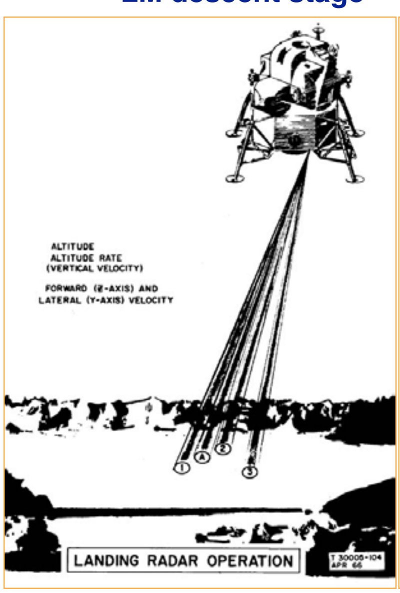


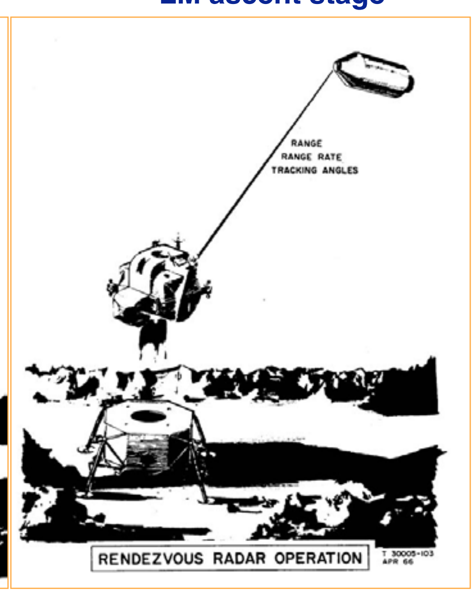
- Doppler radar measures velocity along line of sight
- *Transit* satellite constellation (5 satellites, minimum)
  - navigation signals to 200-m accuracy
  - point of closest approach determined by inflection in Doppler curve (received signal frequency vs. time)
  - http://en.wikipedia.org/wiki/Transit_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



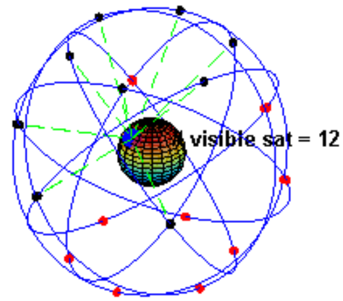
Apollo Lunar Module Radars

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





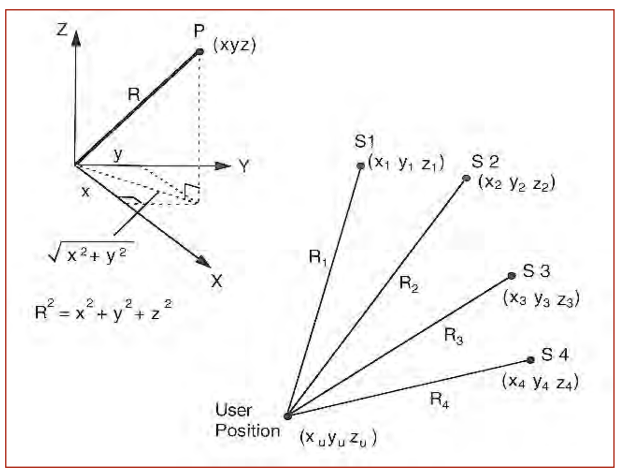
Global Positioning System



- 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

Position Fixing from 4 GPS Satellites

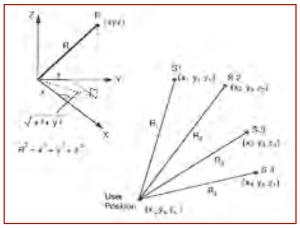
- **Pseudorange** estimated from speed of light and time required to receive signal



$$R_{1_p} = c\Delta t_1$$
$$R_{2_p} = c\Delta t_2$$

$$R_{3_p} = c\Delta t_3$$
$$R_{4_p} = c\Delta t_4$$

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

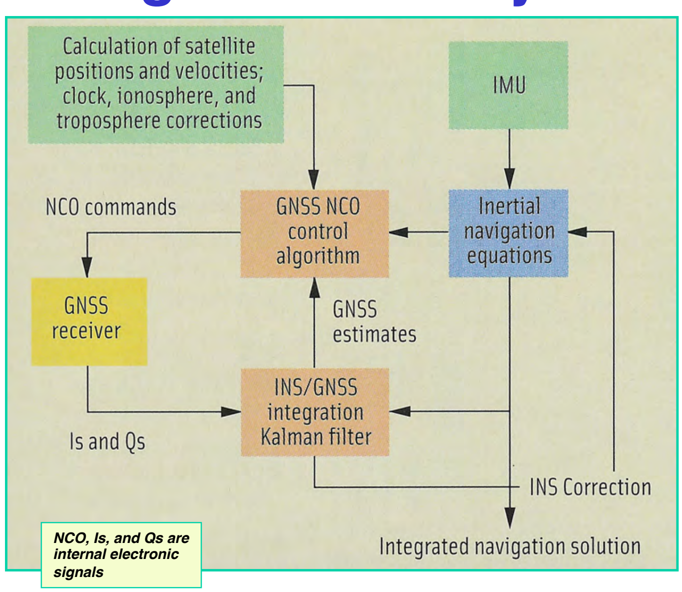


Position Fixing from Four GPS Satellites

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

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

Integrated Inertial Navigation/GPS System



Angular Attitude Actuators

Internal Devices

Momentum/reaction wheels
Control moment gyroscope
Nutation dampers

External Devices

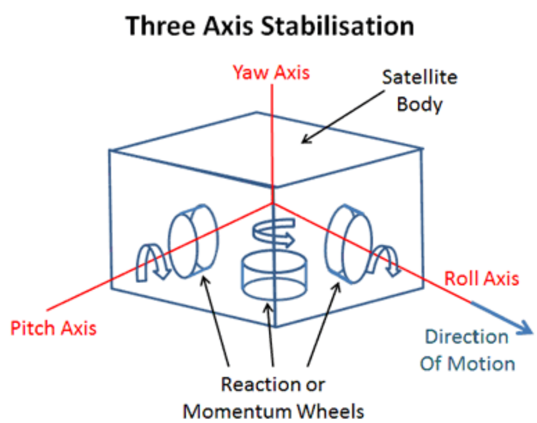
Magnetic coils
Thrusters
Solar radiation pressure

Momentum/Reaction Wheels

Flywheels on motor shafts

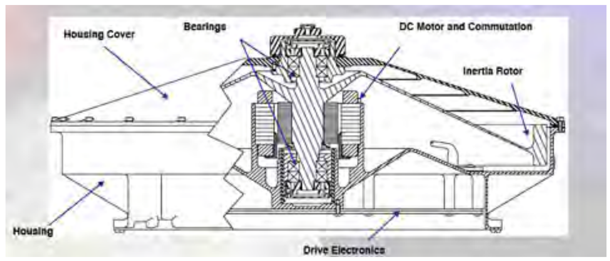
Reaction wheel *rpm* is varied to trade angular momentum with spacecraft for control

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



Momentum/ Reaction Wheels

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



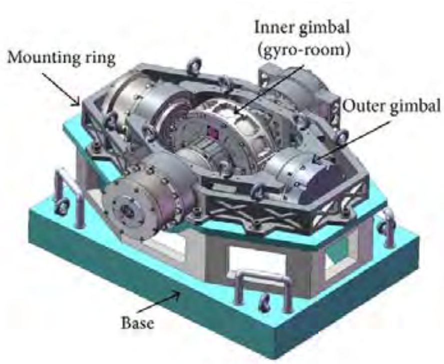
- **Reaction wheel** *rpm* is low, varied to trade angular momentum with the spacecraft for control
  - Three orthogonal wheels vary all components of angular momentum
  - Fourth wheel at oblique angle provides redundancy

Control Moment Gyroscope

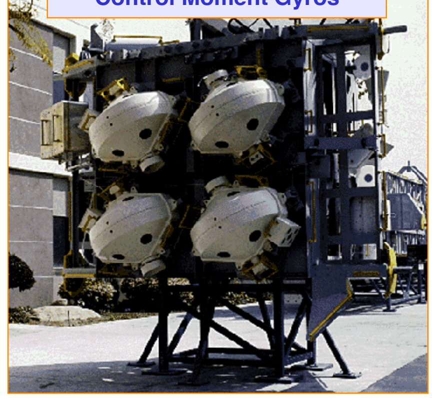
Gyros operate at *constant rpm*

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

One or two degrees of freedom

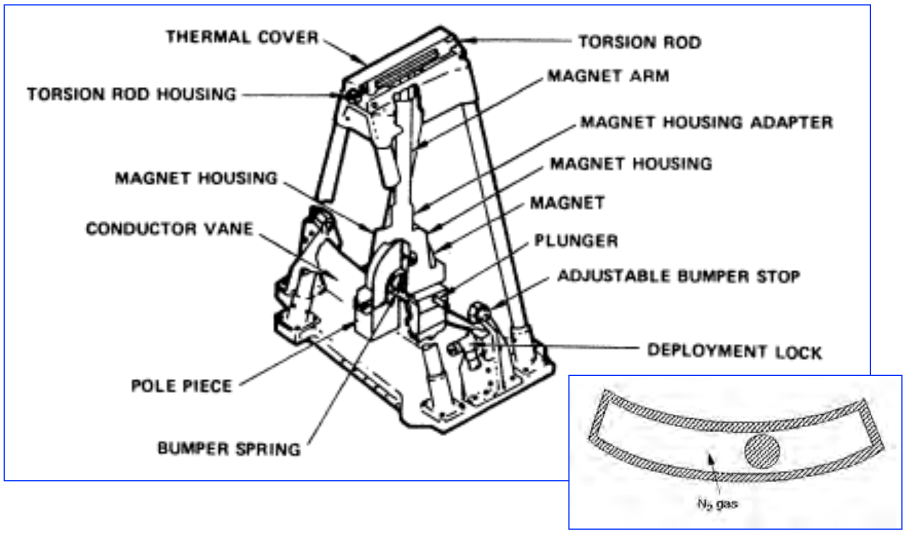


International Space Station Control Moment Gyros



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**

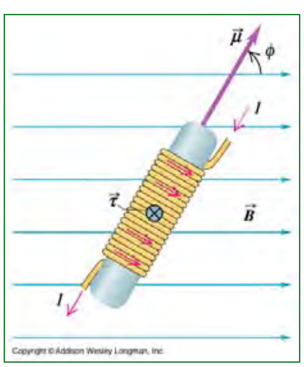


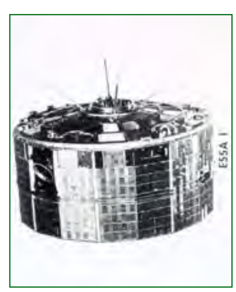
Magnetic Torquers

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

- **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*



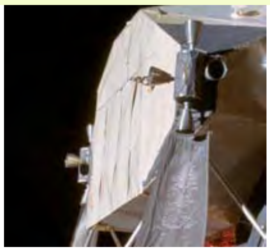


Reaction Control Thrusters

- 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

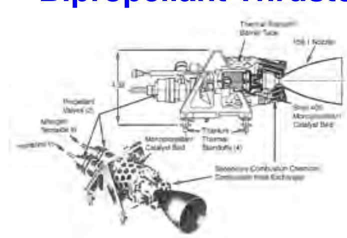
- Thrusters commanded in pairs for *pure couple*

Reaction Control Thrusters

Cold Gas Thruster
(used with inert gas)

Monopropellant Hydrazine Thruster

Hypergolic, Storable Bipropellant Thruster



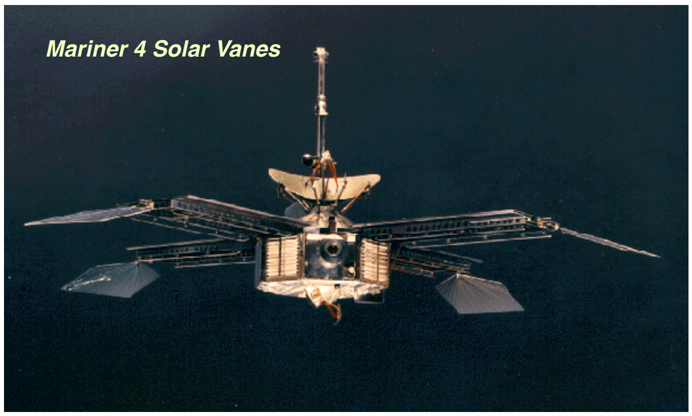
Solar Radiation Pressure Control Panels

Solar radiation pressure

Vanes deflected differentially

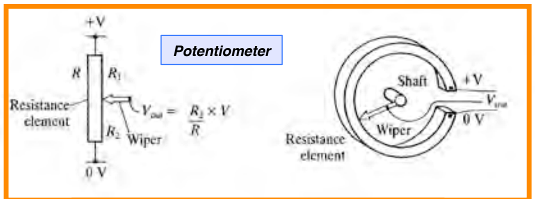
Analogous to aerodynamic control surfaces

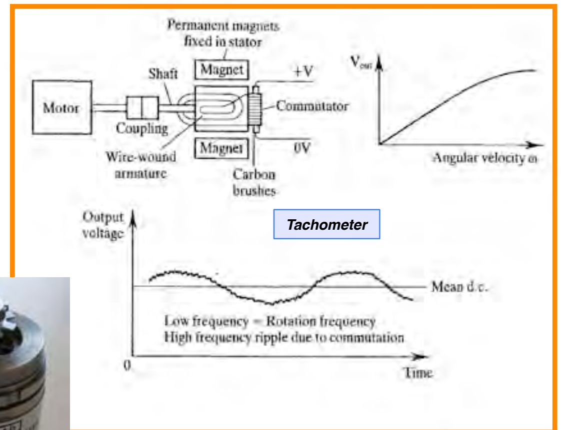
Long moment arm from center of mass

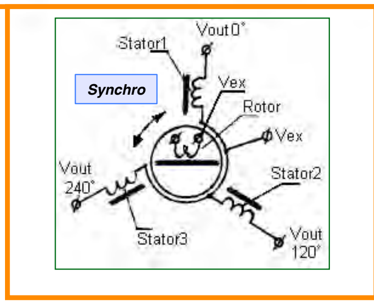


Sensors and Actuators for Spacecraft Mechanisms

Potentiometer, Synchro, and Tachometer







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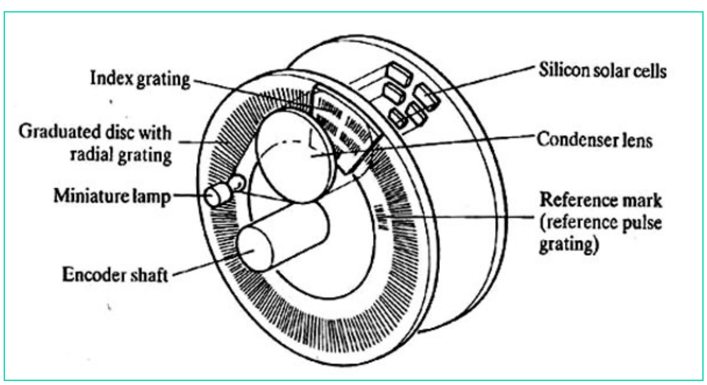
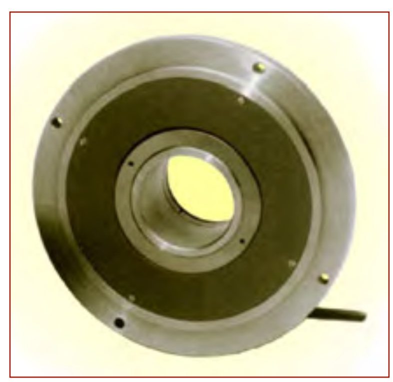
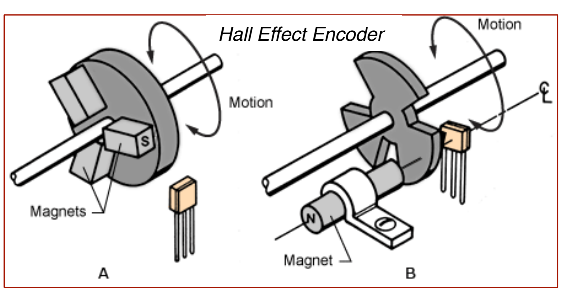
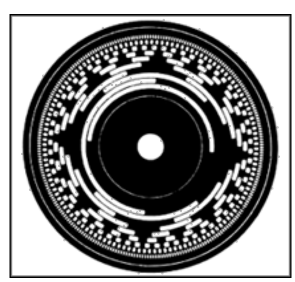
Angular Encoder









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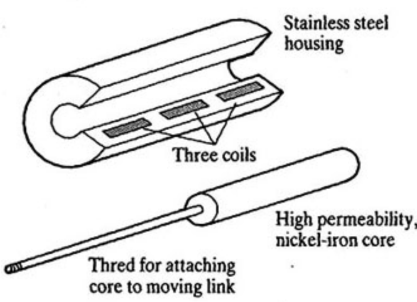
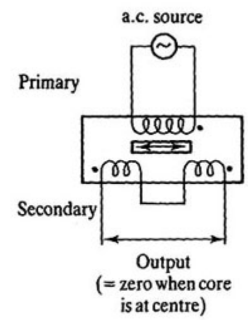
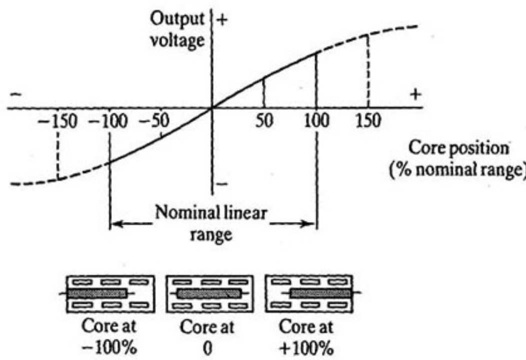
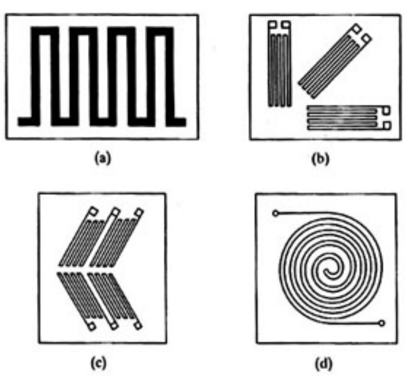
Linear Variable Differential Transformer

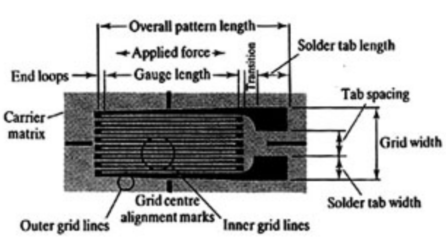




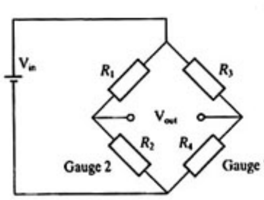


Strain Gage





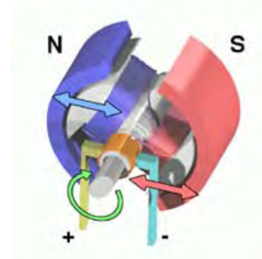
Wheatstone Bridge



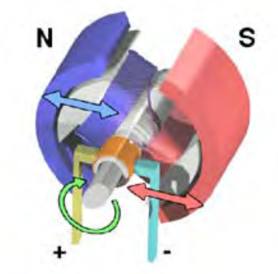
$$V_{out} = \left(\frac{R_2}{R_1 + R_2} - \frac{R_4}{R_3 + R_4}\right) V_{in}$$

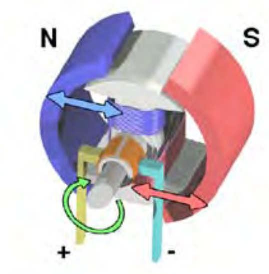
$$\varepsilon = \left(\frac{\Delta R}{R_o}\right) \Big/ Gage\ Factor$$

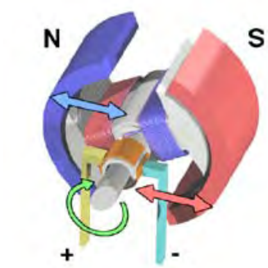
Electric Actuator
Brushed DC Motor



Two-pole DC Motor



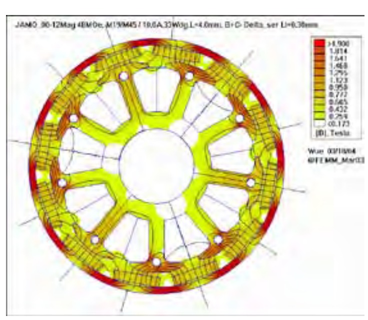


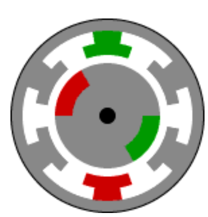


- **Current flowing through armature generates a magnetic field**
- **Permanent magnets torque the armature**
- **When armature is aligned with magnets, commutator reverses current and magnetic field**
- **Multiple poles added to allow motor to smooth output torque and to start from any position**

Electric Actuator
Brushless DC Motor

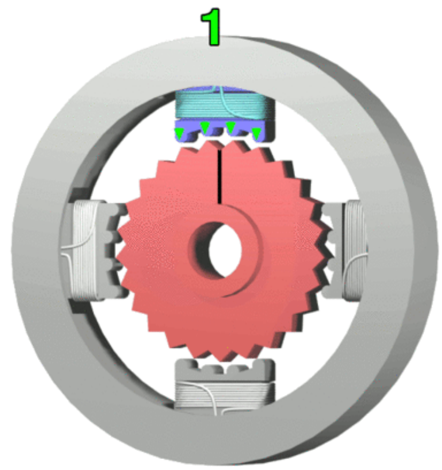
- **Armature is fixed, and permanent magnets rotate**
- **Electronic controller commutates the electromagnetic force, providing a rotating field**
- **Advantages**
  - **Efficiency**
  - **Noise**
  - **Lifetime**
  - **Reduced EMI**
  - **Cooling**
  - **Water-resistant**



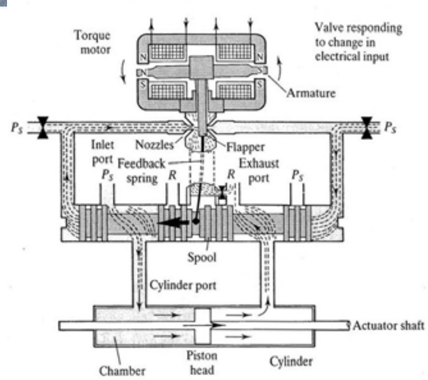


Electric Actuator
Stepper Motor

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



Hydraulic Actuator

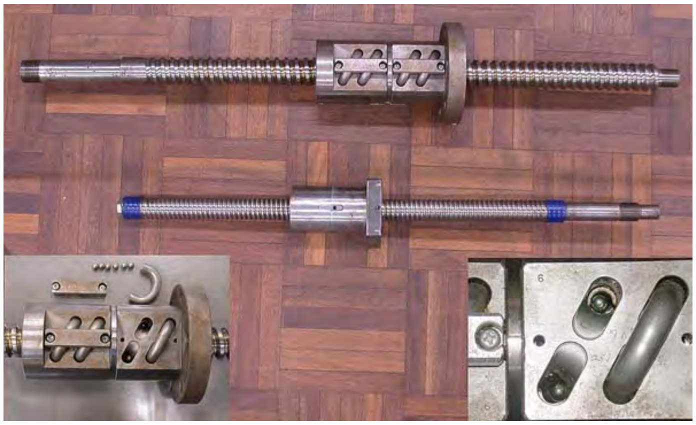


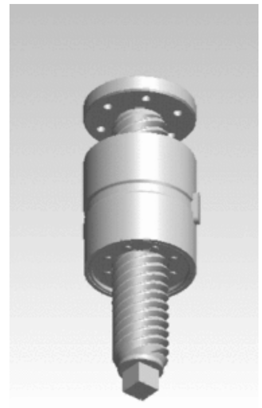
Used principally for launch vehicle thrust vector and propellant control

Not widely used on spacecraft

Ball/Roller Screw Linear Actuator

Transforms rotary to linear motion





Next Time:
Electrical Power Systems

Supplemental Material

Control-Moment Gyro

Flywheel on a motor shaft

RPM is fixed, axis is rotated to impart torque