Attitude Determination and Con
(ADCS)

16.684 Space Systems Product Developmen
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ADCS Motivation

- Motivation
  - In order to point and slew optical systems, spacecraft attitude control provides coarse pointing while optics control provides fine pointing
- Spacecraft Control
  - Spacecraft Stabilization
    - Spin Stabilization
    - Gravity Gradient
    - Three-Axis Control
    - Formation Flight
  - Actuators
    - Reaction Wheel Assemblies (RWAs)
    - Control Moment Gyros (CMGs)
    - Magnetic Torque Rods
    - Thrusters
  - Sensors: GPS, sta sensors, rate gyro measurement unit
  - Control Laws
- Spacecraft Slew Ma
  - Euler Angles
  - Quaternions

Key Questio
What are the poi
requirements for sa

NEED expendable pr

- **On-board fuel often det**
- **Failing gyros are critica**

Outline

- Definitions and Terminology
- Coordinate Systems and Mathematical Attitude Repres
- Rigid Body Dynamics
- Disturbance Torques in Space
- Passive Attitude Control Schemes
- Actuators
- Sensors
- Active Attitude Control Concepts
- ADCS Performance and Stability Measures
- Estimation and Filtering in Attitude Determination
- Maneuvers
- Other System Consideration, Control/Structure interact
- Technological Trends and Advanced Concepts

Opening Remarks

- Nearly all ADCS Design and Performance can be vie
terms of RIGID BODY dynamics
- Typically a Major spacecraft system
- For large, light-weight structures with low fundament
frequencies the flexibility needs to be taken into acco
- ADCS requirements often drive overall S/C design
- Components are cumbersome, massive and power-co
- Field-of-View requirements and specific orientation a
- Design, analysis and testing are typically the most
challenging of all subsystems with the exception of p
design
- Need a true "systems orientation" to be successful at
designing and implementing an ADCS

Terminology

ATTITUDE : Orientation of a defined spacecraft body coor
system with respect to a defined external frame (GCI,H

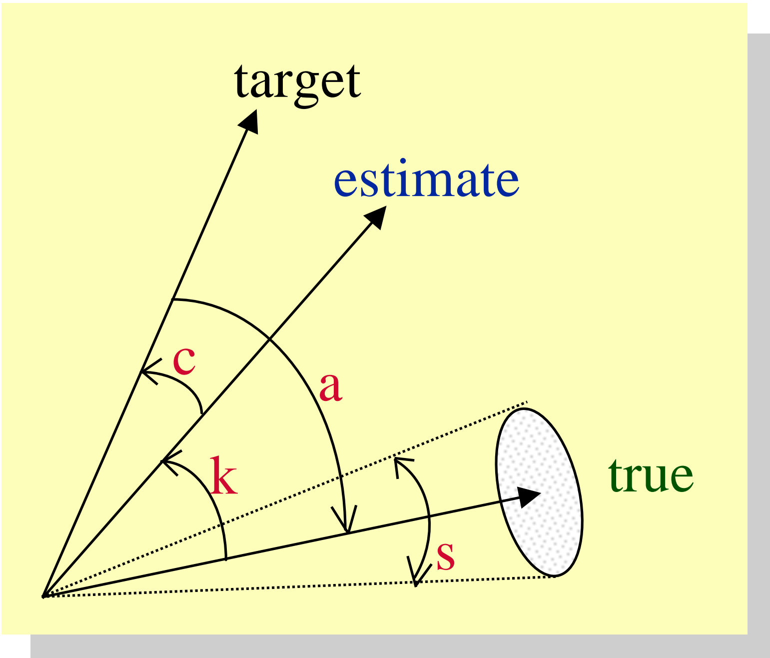
ATTITUDE DETERMINATION: Real-Time or Post-Facto kno
within a given tolerance, of the spacecraft attitude

ATTITUDE CONTROL: Maintenance of a desired, specified
within a given tolerance

ATTITUDE ERROR: "Low Frequency" spacecraft misalign
usually the intended topic of attitude control

ATTITUDE JITTER: "High Frequency" spacecraft misalign
usually ignored by ADCS; reduced by good design or
pointing/optical control.

Pointing Control Definitions



target	desired pointing d
true	actual pointing di
estimate	estimate of true (
a	pointing accuracy
s	stability (peak-pe
k	knowledge error
c	control error

a = pointing accuracy = attitude error

s = stability = attitude jitter

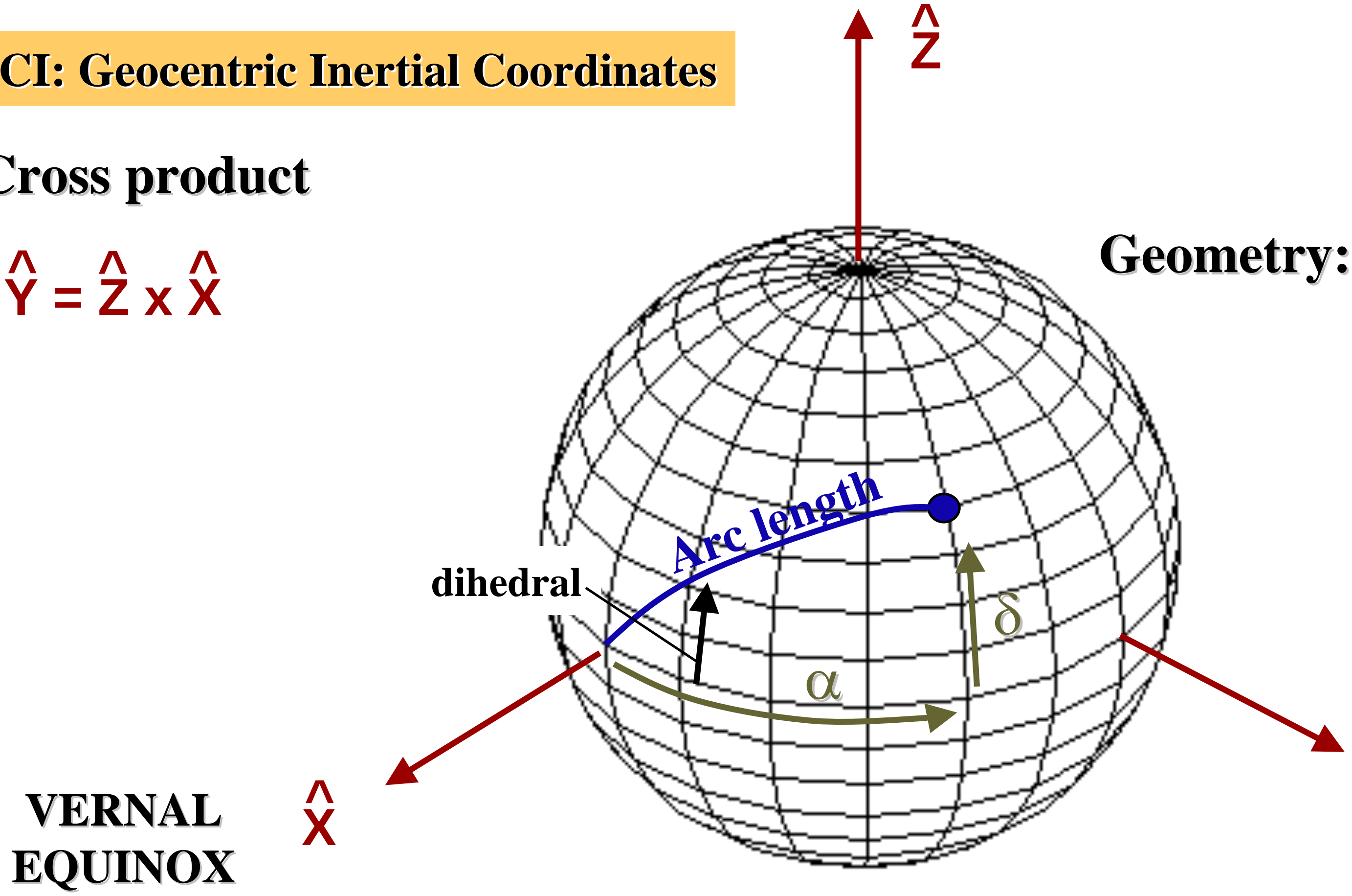
(North Celestial Pole)

GCI: Geocentric Inertial Coordinates

Cross product

$\hat{Y} = \hat{Z} \times \hat{X}$

Geometry: C



α : **Right Ascension**

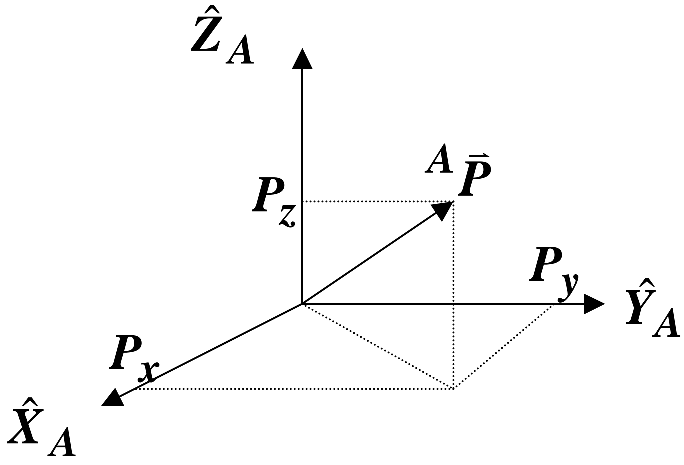
δ : **Declination**

Inertial Coordinate System

X

in the pla

Attitude Description Notations



$\{\cdot\}$ = **Coordinate syst**

$\vec{P}$ = **Vector**

$^A\vec{P}$ = **Position vecto**

$$^A\vec{P} = \begin{bmatrix} P_x \\ P_y \\ P_z \end{bmatrix}$$

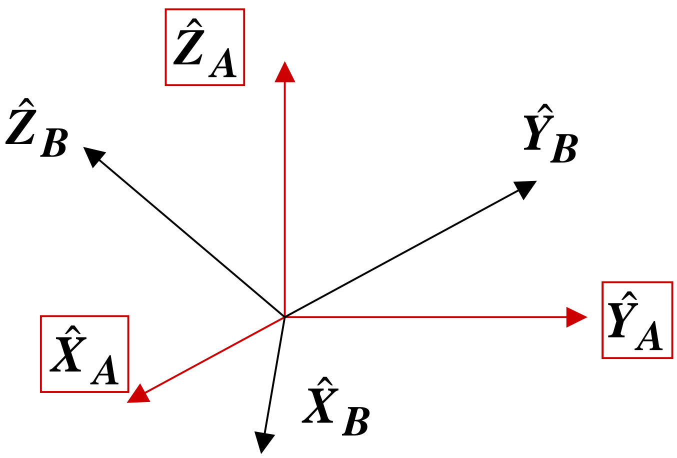
$$\textbf{Unit vectors of } \{A\} = \left[\hat{X}_A \;\; \hat{Y}_A \;\; \hat{Z}_A\right] = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Describe the orientation of a body:

(1) Attach a coordinate system to the body

(2) Describe a coordinate system relative to an inertial reference frame

Rotation Matrix

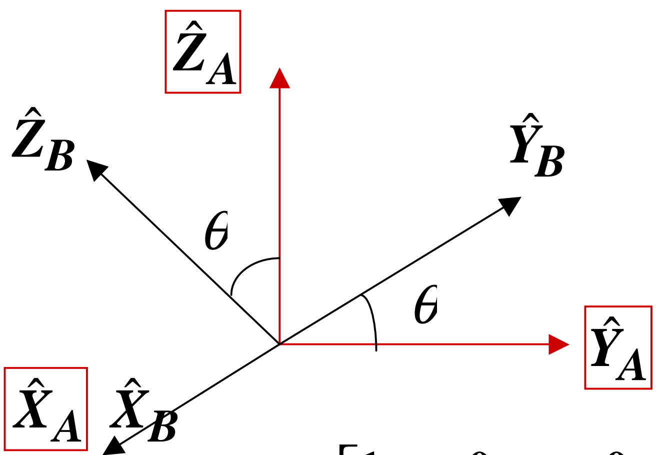


$\{A\} =$ **Reference coordinat**

$\{B\} =$ **Body coordinate sys**

Rotation matrix from

$${}^{A}_{B}R = \left\lfloor {}^{A}\hat{X}_B \quad {}^{A}\hat{Y}_B \quad {}^{A}\right.$$



$${}^{A}_{B}R = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & -\sin\theta \\ 0 & \sin\theta & \cos\theta \end{bmatrix}$$

Special properties of rota

(1) Orthogona

$$R^T R = I, \quad R^T =$$

(2) Orthonorm

$$\|R\| = 1$$

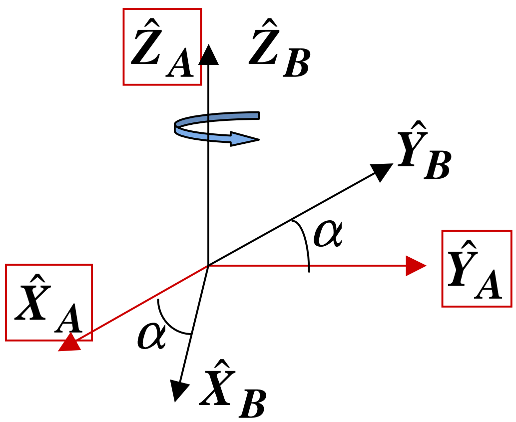
(3) Not commu

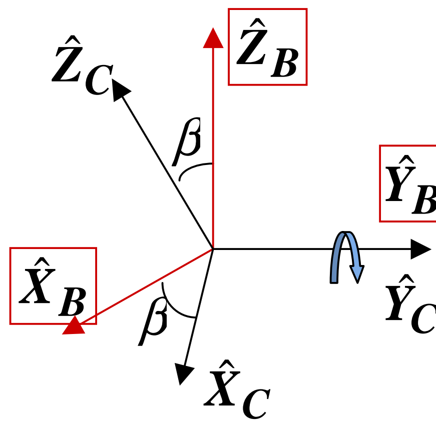
$${}^{A}_{B}R \; {}^{B}_{C}R \neq {}^{B}_{C}R$$

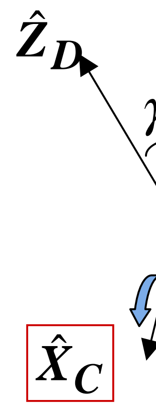
Euler Angles (1)

Euler angles describe a sequence of three rotations abo
axes in order to align one coord. system with a second

Rotate about $\hat{Z}_A$ by α **Rotate about $\hat{Y}_B$ by β** **Rotate a**







$$ {}^A_B R = \begin{bmatrix} \cos\alpha & -\sin\alpha & 0 \\ \sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 1 \end{bmatrix} $$

$$ {}^B_C R = \begin{bmatrix} \cos\beta & 0 & \sin\beta \\ 0 & 1 & 0 \\ -\sin\beta & 0 & \cos\beta \end{bmatrix} $$

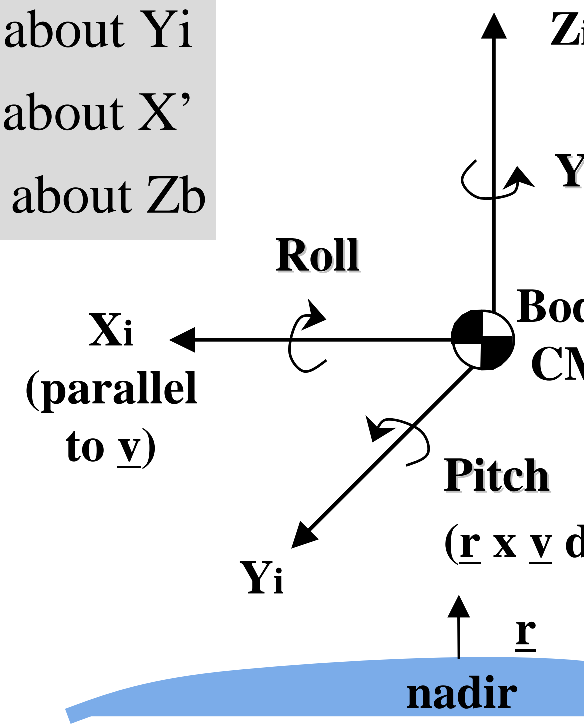
$$ {}^C_D R = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} $$

$$ {}^A_D R = {}^A_B R \; {}^B_C R \; {}^C_D R $$

Euler Angles (2)

- Concept used in rotational kinematics to describe body orientation w.r.t. inertial frame
- Sequence of three angles and prescription for rotating one reference frame into another
- Can be defined as a transformation matrix body/inertial as shown: $T_{B/I}$
- Euler angles are non-unique and exact <u>sequence</u> is critical

θ about Yi
ϕ about X'
ψ about Zb



<u>Goal:</u> Describe kinematics o frame with respect to rotating

(Pitch, Roll, Yaw) = (θ,φ,ψ) ⟶

Note: $T_{B/I}^{-1} = T_{I/B} = T_{B/I}^{T}$

Transformation from Body to "Inertial" frame:

$$T_{B/I} = \underbrace{\begin{bmatrix} \cos\psi & \sin\psi & 0 \\ -\sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix}}_{\text{YAW}} \cdot \underbrace{\begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\phi & \sin\phi \\ 0 & -\sin\phi & \cos\phi \end{bmatrix}}_{\text{ROLL}} \cdot \begin{bmatrix} \text{co} \\ 0 \\ \text{si} \end{bmatrix}$$

Quaternions

- Main problem computationally is the existence of a <u>singularity</u>
- Problem can be avoided by an application of Euler's theorem:

$$Q = \begin{bmatrix} q_1 \\ q_2 \\ q_3 \\ q_4 \end{bmatrix} = \begin{bmatrix} \vec{q} \\ q_4 \end{bmatrix}$$

$\vec{q}$ = A vecto

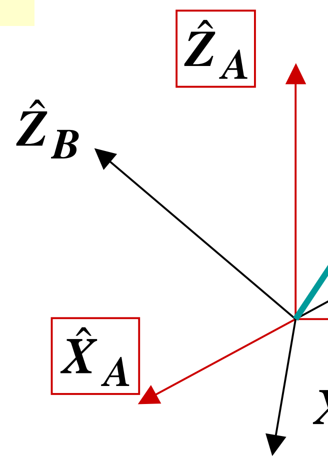
axis of rotat

q_4 = A scala

amount of r

EULER'S THEOREM

The Orientation of a body is uniquely specified by a vector giving the direction of a body axis and a scalar specifying a rotation angle about the axis.

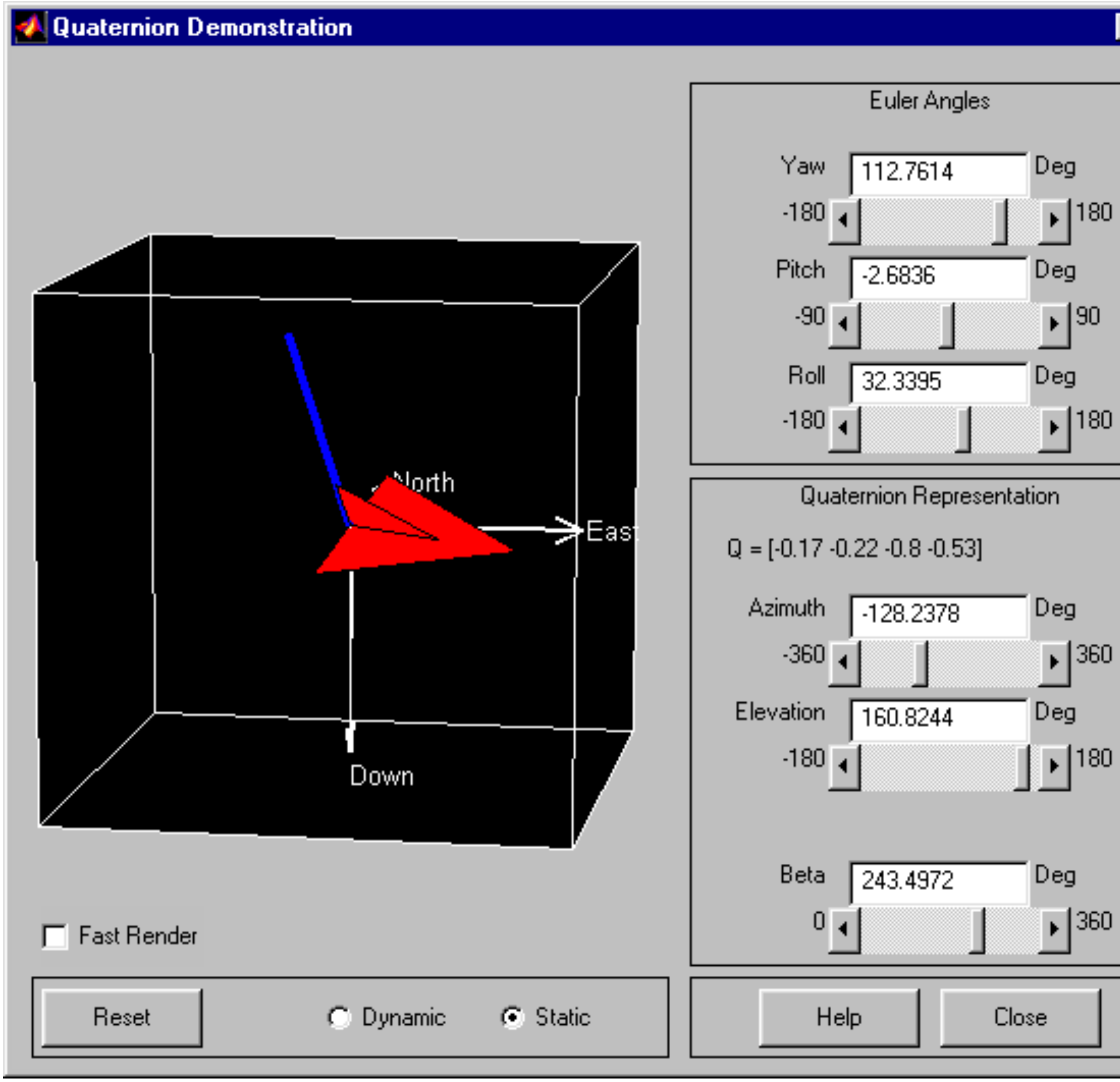


A: Inertial
B: Body

- Definition introduces a <u>redundant fourth element</u>, which eliminates the singularity.
- This is the **<u>"quaternion"</u>** concept
- Quaternions have no intuitively interpretable meaning to the human mind, but are computationally convenient

$${}^{A}\hat{K} = \begin{bmatrix} k_x \\ k_y \\ k_z \end{bmatrix}$$

Quaternion Demo (MATLAB)



Comparison of Attitude Descriptions

Method	**Euler Angles**	**Direction Cosines**	**Angular Velocity $\underline{\omega}$**	**Q**
Pluses	If given ϕ,ψ,θ then a unique orientation is defined	Orientation defines a unique dir-cos matrix **R**	Vector properties, commutes w.r.t addition	Con robu Idea cont
Minuses	Given orient then Euler non-unique Singularity	6 constraints must be met, non-intuitive	Integration w.r.t time does not give orientation Needs transform	Not Nee

Best for analytical and ACS design work

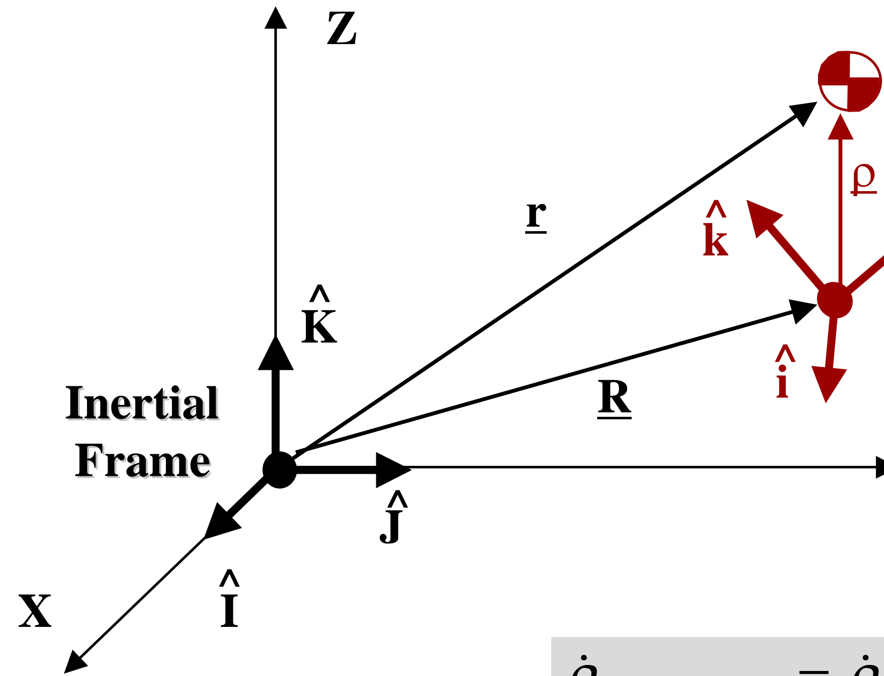
Must store initial condition

B digit impl

Rigid Body Kinematics

Time Derivatives:
(non-inertial)

$\underline{\omega}$ = Angular velocity of Body Frame



BASIC RULE: $\dot{\underline{\rho}}_{\text{INERTIAL}} = \dot{\underline{\rho}}$

Applied to position vector r:

$$\underline{r} = \underline{R} + \underline{\rho}$$

Position

Expressed in the Inertial Fran

$$\dot{\underline{r}} = \dot{\underline{R}} + \dot{\underline{\rho}}_{\text{BODY}} + \underline{\omega} \quad \underline{\rho}$$

Rate

$$\ddot{\underline{r}} = \ddot{\underline{R}} + \ddot{\underline{\rho}}_{\text{BODY}} + 2\underline{\omega} \quad \dot{\underline{\rho}}_{\text{BODY}} + \dot{\underline{\omega}} \quad \underline{\rho} + \underline{\omega} \quad (\underline{\omega} \quad \underline{\rho}$$

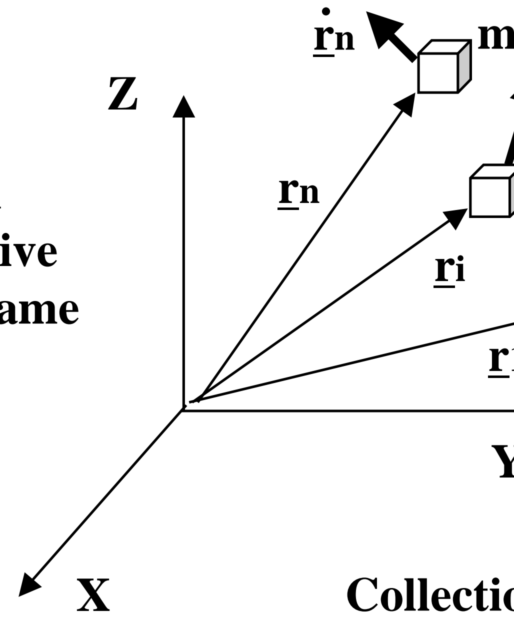
Inertial accel of CM — **relative accel w.r.t. CM** — **coriolis** — **angular accel** — **centripeta**

Angular Momentum (I)

Angular Momentum

$$\underline{H}_{\text{total}} = \sum_{i=1}^{n} \underline{r}_i \quad m_i \underline{\dot{r}}_i$$

System in motion relative to Inertial Frame



Collectio masses

If we assume that

(a) **Origin of Rotating Frame in Body CM**
(b) **Fixed Position Vectors ri in Body Frame (Rigid Body)**

Angular Momentum Decomposition

Then :

$$\underline{H}_{\text{total}} = \underbrace{\left(\sum_{i=1}^{n} m_i\right) \underline{R} \quad \underline{\dot{R}}}_{\text{ANGULAR MOMENTUM OF TOTAL MASS W.R.T INERTIAL ORIGIN}} + \underbrace{\sum_{i=1}^{n} m_i \underline{\rho}_i \quad \underline{\dot{\rho}}_i}_{\underline{H}_{BODY}}$$

ANGULAR MOMENTUM OF TOTAL MASS W.R.T INERTIAL ORIGIN

$\underline{H}_{BODY}$ BODY ANGULAR MOMENTUM ABOUT CENTER OFMASS

Not meas iner

Angular Momentum (II)

For a RIGID BODY we can write:

$$\dot{\underline{\rho}}_i = \underbrace{\dot{\underline{\rho}}_{i,\mathrm{BODY}}}_{\text{RELATIVE MOTION IN BODY}} + \underline{\omega} \quad \underline{\rho}_i =$$

And we are able to write:

$$\underline{H} = I\underline{\omega}$$

RIIGID BODY, CM CO
$\underline{H}$ and $\underline{\omega}$ are resolved in

"The vector of angular momentum in the body frame is the pro of the 3x3 Inertia matrix and the 3x1 vector of angular velociti

Inertia Matrix Properties:

Real Symmetric ; 3x3 Tensor ; coordinate depend

$$I = \begin{bmatrix} I_{11} & I_{12} & I_{13} \\ I_{21} & I_{22} & I_{23} \\ I_{31} & I_{32} & I_{33} \end{bmatrix}$$

$$I_{11} = \sum_{i=1}^{n} m_i \left(\rho_{i2}^2 + \rho_{i3}^2\right) \qquad I_{12} = I_{21} =$$

$$I_{22} = \sum_{i=1}^{n} m_i \left(\rho_{i1}^2 + \rho_{i3}^2\right) \qquad I_{13} = I_{31} =$$

$$I_{33} = \sum_{i=1}^{n} m_i \left(\rho_{i1}^2 + \rho_{i2}^2\right) \qquad I_{23} = I_{32} =$$

Kinetic Energy and Euler Equations

Kinetic Energy

$$E_{\text{total}} = \underbrace{\frac{1}{2}\left(\sum_{i=1}^{n} m_i\right)\dot{R}^2}_{\text{E-TRANS}} + \underbrace{\frac{1}{2}\sum_{i=1}^{n} m_i \dot{\rho}_i^2}_{\text{E-ROT}}$$

For a RIGID BODY, CM Coordinates with $\underline{\omega}$ resolved in body axis frame

$$E_{\text{ROT}} = \frac{1}{2}\underline{\omega} \cdot \underline{H} = \frac{1}{2}$$

$$\underline{\dot{H}} = \underline{T} - \underline{\omega} \; \left[\underline{\underline{I}}\,\underline{\omega}\right]$$

Sum of external and interna

In a BODY-FIXED, PRINCIPAL AXES CM FRAME: **Euler E**

$$\dot{H}_1 = I_1\dot{\omega}_1 = T_1 + (I_{22} - I_{33})\omega_2\omega_3$$

$$\dot{H}_2 = I_2\dot{\omega}_2 = T_2 + (I_{33} - I_{11})\omega_3\omega_1$$

$$\dot{H}_3 = I_3\dot{\omega}_3 = T_3 + (I_{11} - I_{22})\omega_1\omega_2$$

No general so
Particular solut
simple torque
simulation usu

Torque Free Solutions of Euler's Eq.

TORQUE-FREE CASE:

An important special case is the torque-free motio symmetric body spinning primarily about its sy

By these assumptions: $\omega_x, \omega_y << \omega_z = \Omega$ $\quad I_{xx}$

The components of angular velocity then become:

$$\omega_x(t) = \omega_{xo} \cos \omega_n t$$

$$\omega_y(t) = \omega_{yo} \cos \omega_n t$$

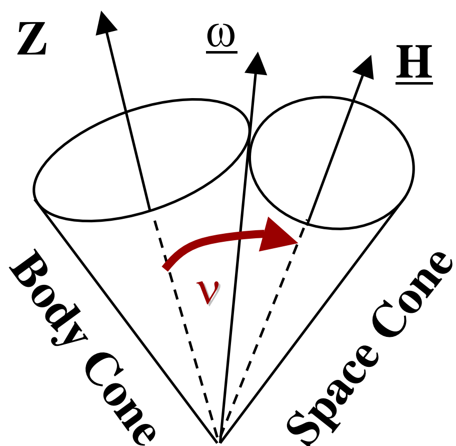
The ω_n is defined as the "natural" or "nutation" frequency of the body: $\omega_n^2 = K_x K_y \Omega^2$

And the Euler equ

$\dot{\omega}_x = -$

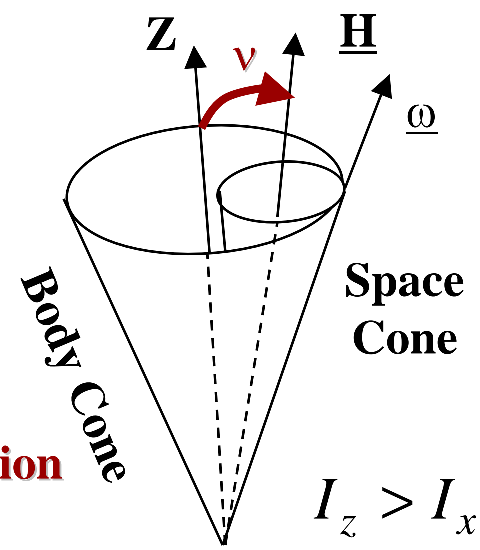
$\dot{\omega}_y = \frac{I_{zz}}{}$

$\dot{\omega}_z = 0$



$I_z < I_x = I_y$

ν : nutation angle



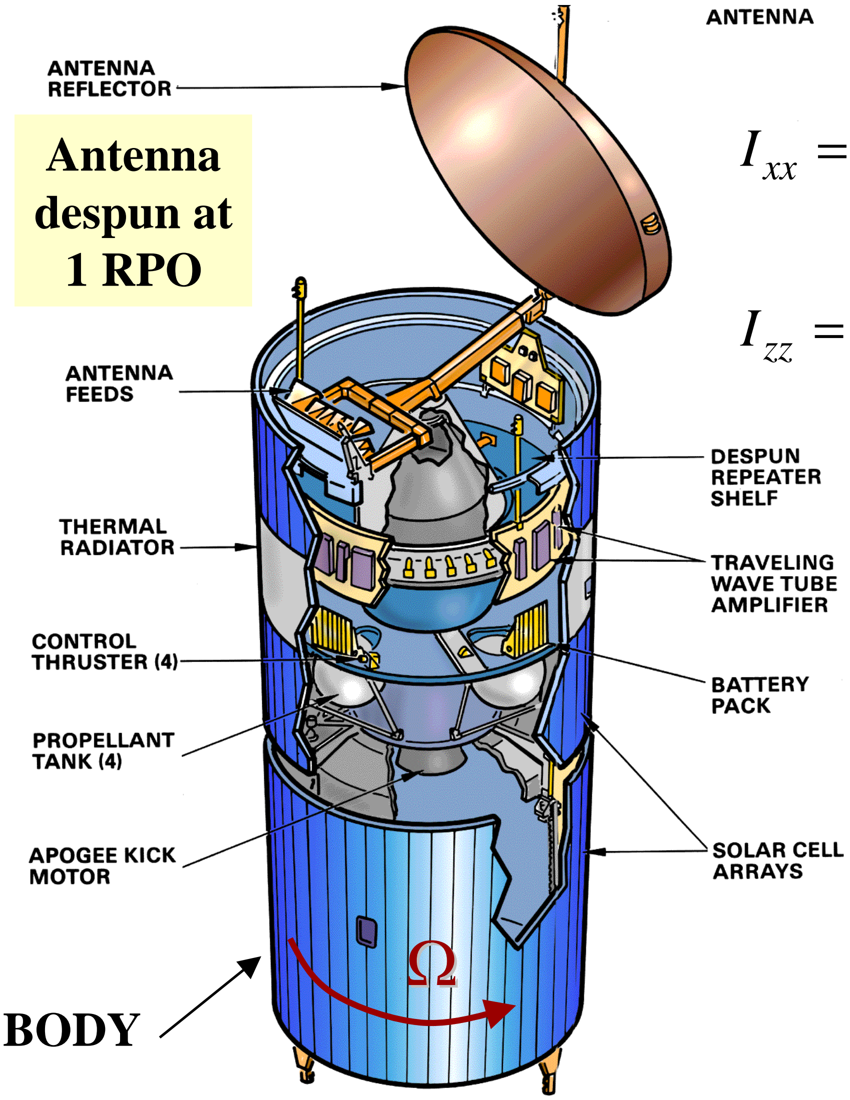
$I_z > I_x = I_y$

H and unless a pri

Spin Stabilized Spacecraft

UTILIZED TO STABILIZE SPINNERS

Antenna despun at 1 RPO

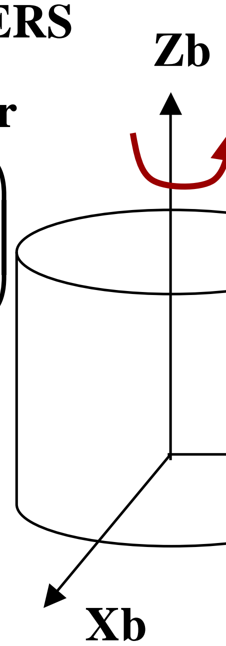


HS 376
SPACECRAFT CONFIGURATION

Perfect Cylinder

$$I_{xx} = I_{yy} = \frac{m}{4}\left(\frac{L^2}{3} + R^2\right)$$

$$I_{zz} = \frac{mR^2}{2}$$



DUAL SPIN

- Two bodies rotating a
about a common axis
- Behaves like simple s
is despun (antennas, s
- requires torquers (jets
momentum control an
dampers for stability
- allows relaxation of m

Disturbance Torques

**Assessment of expected disturbance torques is an esse
of rigorous spacecraft attitude control desig**

Typical Disturbances

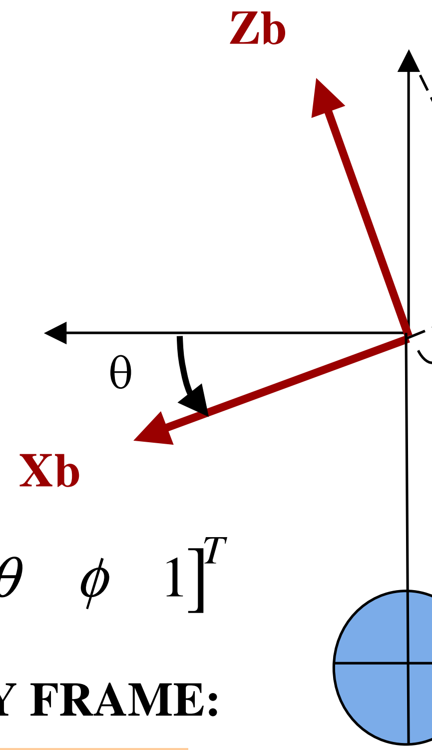
- Gravity Gradient: "Tidal" Force due to 1/r2 gravitational f
for long, extended bodies (e.g. Space Shuttle, Tethered ve
- Aerodynamic Drag: "Weathervane" Effect due to an offse
CM and the drag center of Pressure (CP). Only a factor in
- Magnetic Torques: Induced by residual magnetic moment
spacecraft as a magnetic dipole. Only within magnetosphe
- Solar Radiation: Torques induced by CM and solar CP of
compensate with differential reflectivity or reaction whee
- Mass Expulsion: Torques induced by leaks or jettisoned o
- Internal: On-board Equipment (machinery, wheels, cryoc
etc…). No net effect, but internal momentum exchange af

Gravity Gradient

$$n = \sqrt{\;\;/ a^3} = \text{ORB}$$

Gravity Gradient:

1) ⊥ Local vertical
2) 0 for symmetric spacecraft
3) proportional to ∝ $1/r^3$



Gravity Gradient Torques

$$\underline{T} = 3n^2 \cdot \hat{r} \;\; \left[\underline{\underline{I}} \, \hat{r} \right]$$

In Body Frame

Small angle approximation

$$\hat{r} = \left[-\sin\theta \quad \sin\phi \quad 1 - \sin^2\theta - \sin^2\phi \right]^T \cong \left[-\theta \quad \phi \quad 1 \right]^T$$

Resulting torque in BODY FRAME:

Typical Values:
I=1000 kgm^2
n=0.001 s^{-1}
T= 6.7 x 10^{-5} Nm/deg

$$\therefore T \cong 3n^2 \begin{bmatrix} (I_{zz} - I_{yy})\phi \\ (I_{zz} - I_{xx})\theta \\ 0 \end{bmatrix}$$

Pitc

$$\omega_{lib} = r$$

Aerodynamic Torque

$$\underline{T} = \underline{r} \quad \underline{F}_a$$

$\underline{r}$ = Vector from body CM to Aerodynamic CP

$\underline{F}_a$ = Aerodynamic Drag Vector in Body coordinates

$$F_a = \frac{1}{2}\rho V^2 S C_D$$

Aerodynamic Drag Coefficient $$1 \le C_D \le 2$$ **Typically in this Ran Free Molecular Fl**

S = Frontal projected Area

V = Orbital Velocity

ρ = Atmosp

Typical Values:
C_d = 2.0
S = 5 m^2
r = 0.1 m
r = 4 x 10^{-12} kg/m^3
T = 1.2 x 10^{-4} Nm

Notes

(1) $\underline{r}$ varies with Attitude
(2) ρ varies by factor of 5-10 at a given altitude
(3) C_D is uncertain by 50 %

2 x 10^{-9} kg/
3 x 10^{-10} kg/
7 x 10^{-11} kg/
4 x 10^{-12} kg/

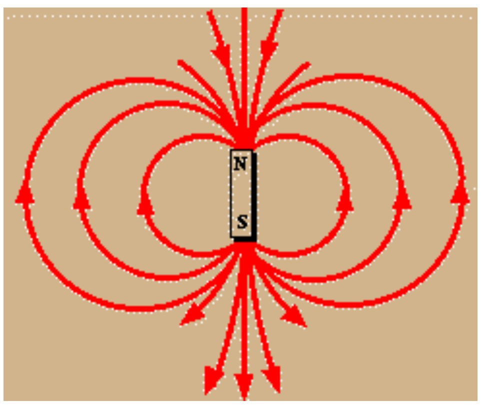
Exponential I

Magnetic Torque

$$\underline{T} = \underline{M} \quad \underline{B}$$

<u>M</u> = Spacecraft residual dipole in AMPERE-TURN-m2 (SI) or POLE-CM (CGS)

<u>M</u> = is due to current loops and residual magnetization, and will be on the order of 100 POLE-CM or more for small spacecraft.

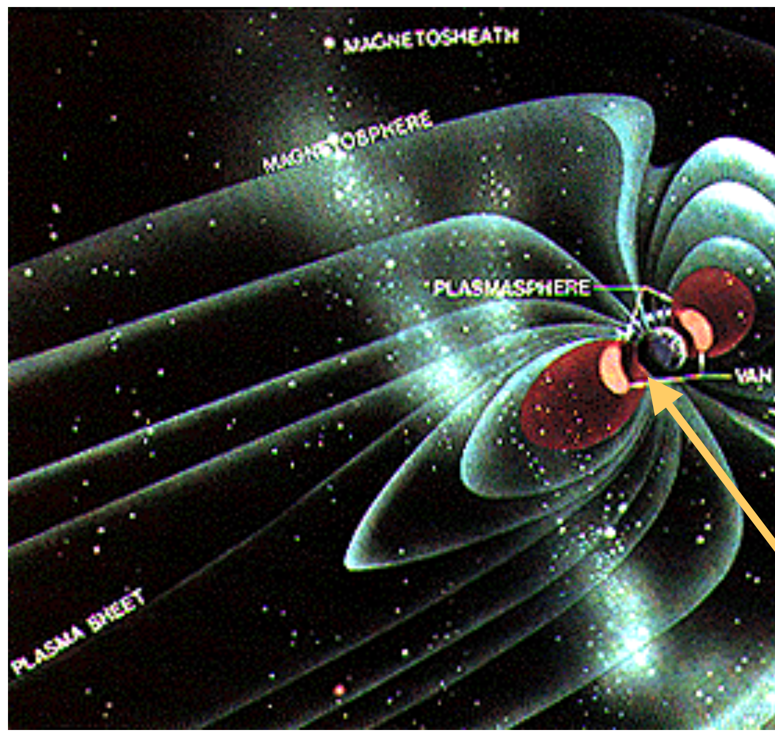


<u>Typical Values:</u>
B= 3 x 10^{-5} TESLA
M = 0.1 Atm^2
T = 3 x 10^{-6} Nm

<u>B</u> = Earth magnetic field vector spacecraft coordinates (BODY FR in TESLA (SI) or Gauss (CGS) u

<u>B</u> varies as 1/r3, with its dire along local magnetic field li

Conversions:
1 Atm2 = 1000 POLE-CM , 1 TESL



Solar Radiation Torque

$$\underline{T} = \underline{r} \quad \underline{F}_s$$

$$F_s = (1 + K) P_s S$$

$$P_s = I_s / c$$

$$I_s = 1400 \text{ W/m}^2 \quad @ \; 1 \; \text{A.U.}$$

Notes:

(a) Torque is always ⊥ to sun line
(b) Independent of position or velocity as long as in sunlight

Typical Values:
K = 0.5
S =5 m^2
r =0.1 m
T = 3.5 x 10^{-6} Nm

$\underline{r}$ = Vector from Body CM to optical Center-of-Pressure (C

$\underline{F}_s$ = Solar Radiation pressur BODY FRAME coordinat

K = Reflectivity , 0 < K

S = Frontal Area

I_s = Solar constant, deper heliocentric altitude

SUN

Significant for spacecraft with large frontal area (e.g. NGST)

Mass Expulsion and Internal Torques

Mass Expulsion Torque: $\underline{T} = \underline{r} \quad \underline{F}$

Notes:

(1) May be deliberate (Jets, Gas venting) or accidenta

(2) Wide Range of r, F possible; torques can dominat

(3) Also due to jettisoning of parts (covers, cannisters

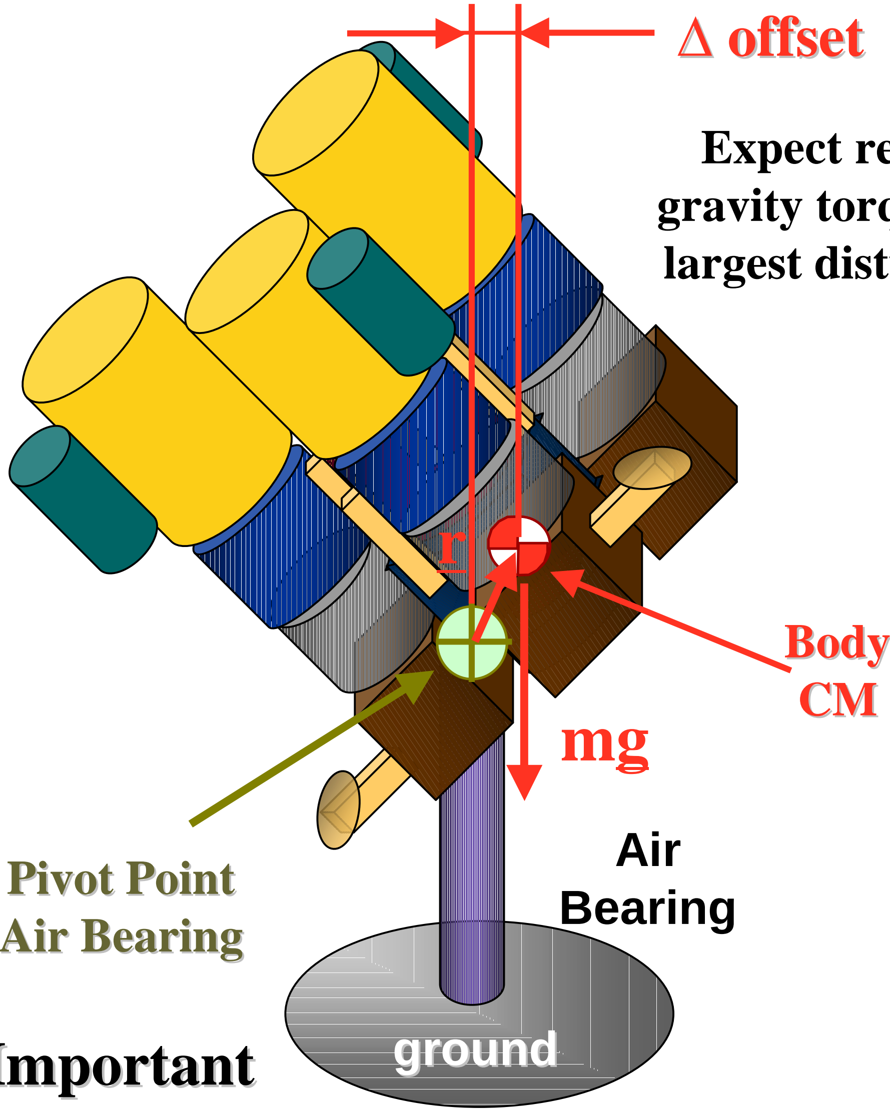
Internal Torque:

Notes:

(1) Momentum exchange between movi has no effect on System H, but will a attitude control loops

(2) Typically due to antenna, solar arra motion or to deployable booms and

Disturbance Torque for CDIO



Expect residual gravity torque to be largest disturbance

Important to balance precisely !

Initial Assumption: $|T| = |\underline{r} \quad m\underline{g}| \cong 0.001 \cdot 100 \cdot$

Passive Attitude Control (1)

Passive control techniques take advantage of basic phys
principles and/or naturally occurring forces by designi
the spacecraft so as to enhance the effect of one forc
while reducing the effect of others.

SPIN STABILIZED

$\dot{H} =$

- Requires Stable Inertia Ratio: Iz > Iy =Ix
- Requires Nutation damper: Eddy Current, Ball-in-Tube, Viscous Ring, Active Damping
- Requires Torquers to control precession (spin axis drift) magnetically or with jets
- Inertially oriented

$\dot{H} =$

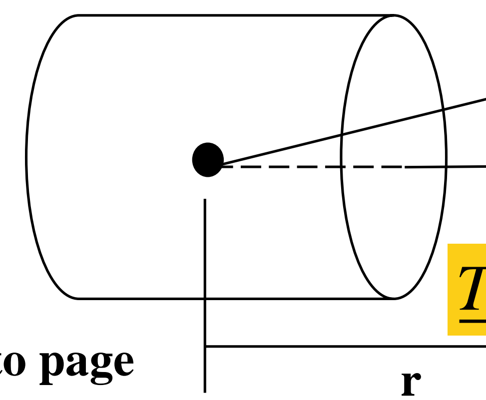
$\therefore \Delta$

Precession:

$$\Delta H = 2H \sin\frac{\Delta\theta}{2} \cong H\Delta\theta = I\omega \cdot \Delta\theta$$

Large ω = **gyroscopic stability**

$$\Delta\theta \cong \frac{rF\Delta t}{H} = \frac{rF}{I\omega}\Delta t$$

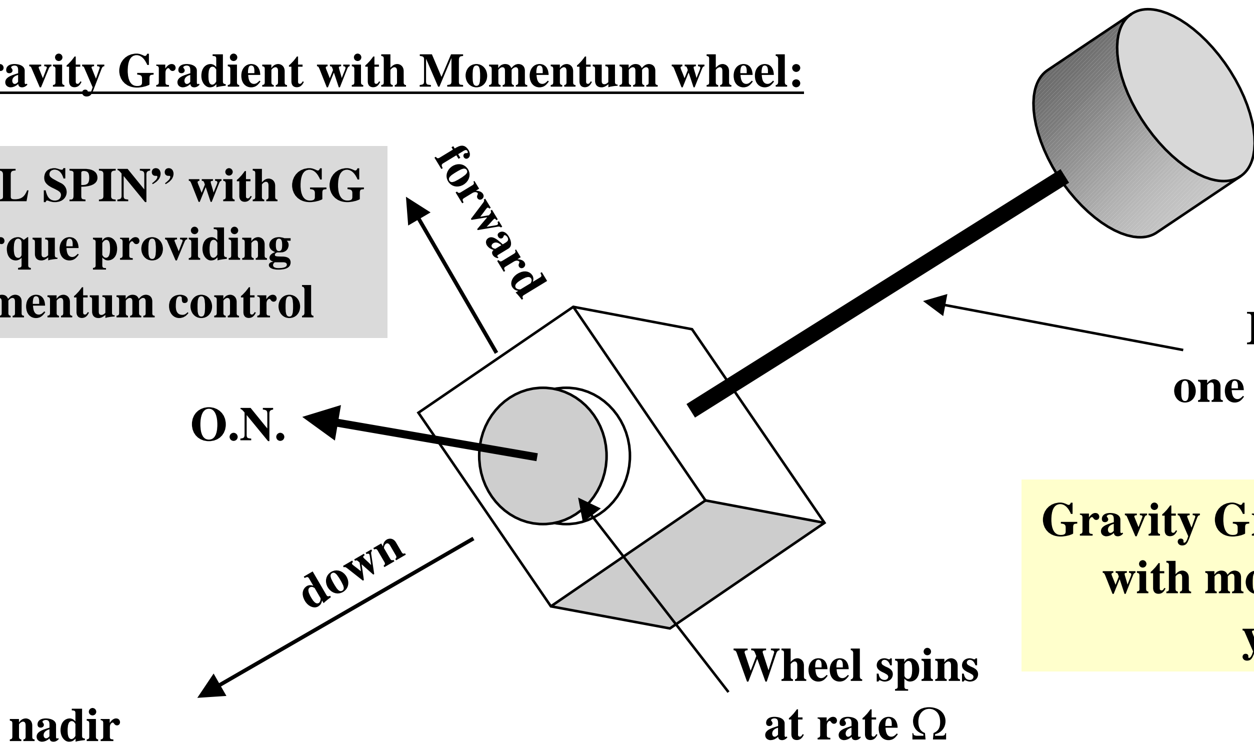


GRAVITY GRADIENT

- Requires stable Inertias: $I_z << I_x, I_y$
- Requires Libration Damper: Eddy C
  Hysteresis Rods
- Requires no Torquers
- Earth oriented
- No Yaw Stability (can add momentu

Gravity Gradient with Momentum wheel:

"DUAL SPIN" with GG torque providing momentum control



Gravity Gradien with momentu yaw sta

Active Attitude Control

Active Control Systems directly sense spacecraft att
and supply a torque command to alter it as required.
is the basic concept of feedback control.

- Reaction Wheels most common actuator
- Fast; continuous feedback control
- Moving Parts
- Internal Torque only; external still required for “momentum dumping”
- Relatively high power, weight, cost
- Control logic simple for independent axes (can get complicated with redundancy)

Typical Reaction (Momentum) Wheel Data:

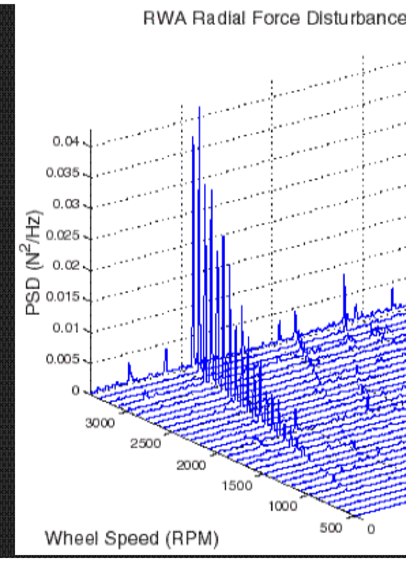
Operating Range
Angular Moment
1.3 N
Angular Moment
4.0 N
Reaction Torque

Actuators: Reaction Wheels

- One creates torques on a spacecraft by creating equal but
  torques on **Reaction Wheels** (flywheels on motors).
  - For three-axes of torque, three wheels are necessary. Usua
    wheels for redundancy (use wheel speed biasing equation)
  - If external torques exist, wheels will angularly accelerate t
    these torques. They will eventually reach an RPM limit (~
    RPM) at which time they must be desaturated.
  - Static & dynamic imbalances can induce vibrations (moun
  - Usually operate around some nominal spin rate to avoid sti

Ithaco RWA's (www.ithaco.com /products.html)

Waterfall plot:



Needs to be carefully balanced !

Actuators: Magnetic Torquers

Magnetic Torquers

- Often used for Low Earth Orbit (LEO) satellites
- Useful for initial acquisition maneuvers
- Commonly use for momentum desaturation (“dumping”) in reaction wheel systems
- May cause harmful influence on star trackers

- Can be used
  - for attitude control
  - to de-saturate reactio
- Torque Rods and Coil
  - Torque rods are long
  - Use current to gener field
  - This field will try to Earth’s magnetic fie creating a torque on
  - Can also be used to as well as orbital loc

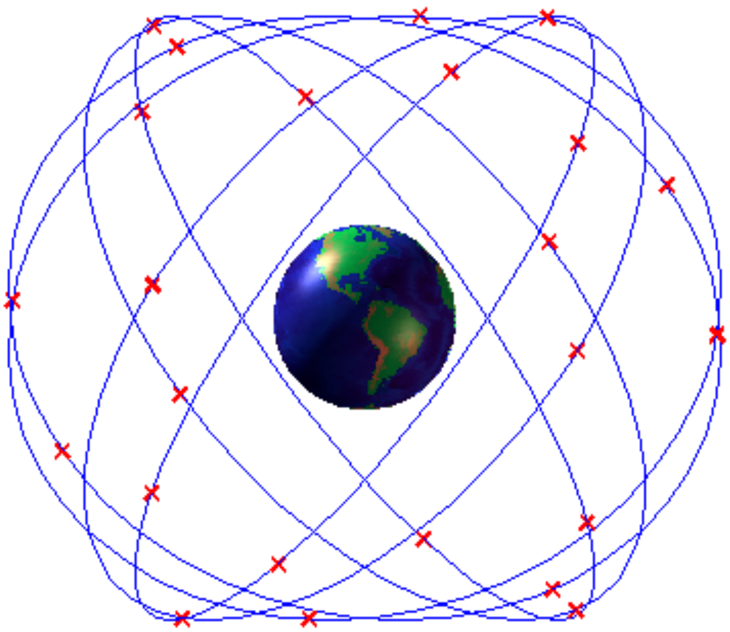
ACS Actuators: Jets / Thrusters

- Thrusters / Jets
  - Thrust can be used to control attitude but at the cost of consuming fuel
  - Calculate required fuel using "Rocket Equation"
  - Advances in micro-propulsion make this approach more feasible. Typically want I_{sp} > 1000 sec

- Use consumables such a
(Freon, N2) or Hydrazi
- Must be ON/OFF opera
proportional control usu
feasible: pulse width mo
(PWM)
- Redundancy usually req
the system more compl
expensive
- Fast, powerful
- Often introduces attitud
coupling
- Standard equipment on
spacecraft
- May be used to "unload
angular momentum on
controlled spacecraft.

ACS Sensors: GPS and Magnetometers

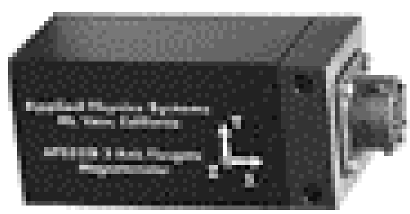
- Global Positioning System (GPS)
  - Currently 27 Satellites
  - 12hr Orbits
  - Accurate Ephemeris
  - Accurate Timing
    - Stand-Alone 100m
    - DGPS 5m
    - Carrier-smoothed DGPS 1-2m

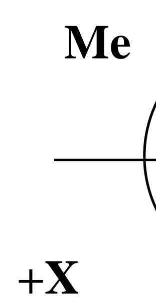


- Magnetometers
  - Measure componen
    ambient magnetic fi
  - Sensitive to field fr
    (electronics), mount
  - Get attitude informa
    comparing measure
  - Tilted dipole model

$$\begin{bmatrix} B_{north} \\ B_{east} \\ B_{down} \end{bmatrix} = \left(\frac{6378}{r_{km}}\right)^3 \begin{bmatrix} -C_\varphi & S_\varphi C_\lambda \\ 0 & S_\lambda \\ -2S_\varphi & -2C_\varphi C_\lambda \end{bmatrix}$$

Where: C=cos , S=sin, ϕ=latit
Units: nTesla





ACS Sensors: Rate Gyros and IMUs

- Rate Gyros (Gyroscopes)
  - Measure the angular rate of a spacecraft relative to inertial space
  - Need at least three. Usually use more for redundancy.
  - Can integrate to get angle. However,
    - DC bias errors in electronics will cause the output of the integrator to ramp and eventually saturate (drift)
    - Thus, need inertial update

Courtesy of Silicon Sensing Systems, Ltd. Used with permission.

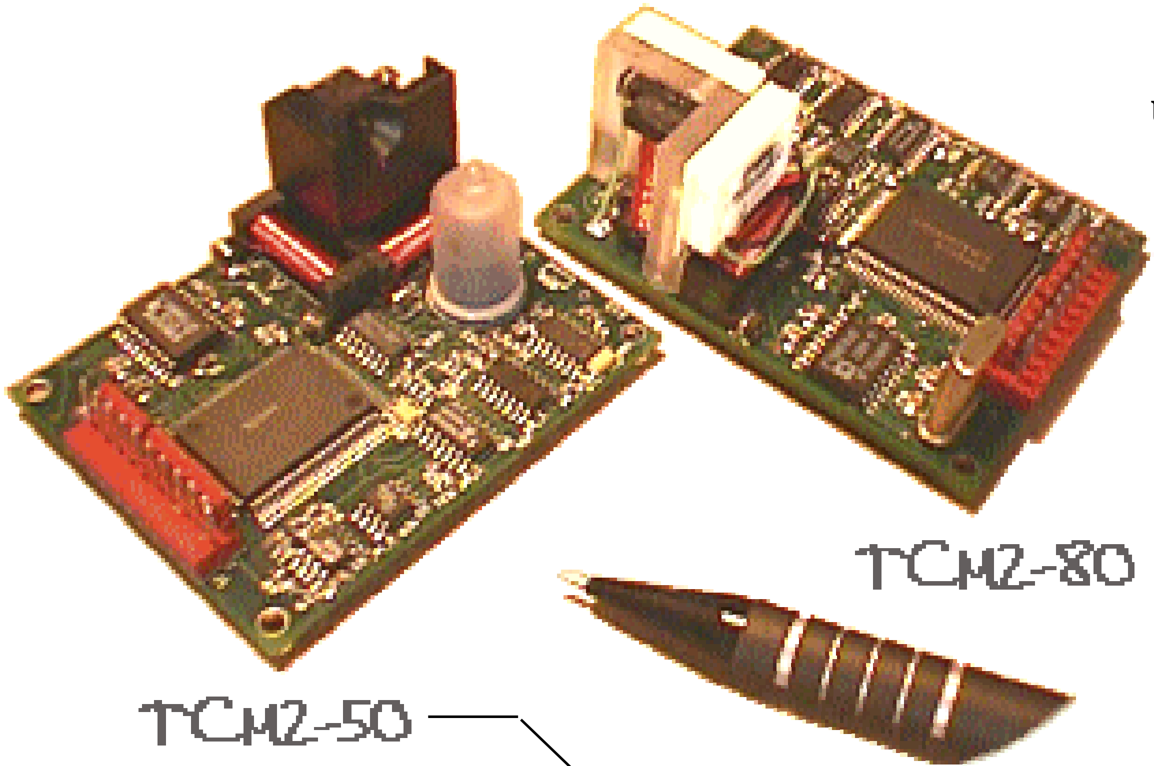
- Mechanical gyros (accurate, heavy)
- Ring Laser (RLG)
- MEMS-gyros

- Inertial Measuremen
  - Integrated unit wi mounting hardwar software
  - measure rotation o rate gyros
  - measure translatio with accelerometer
  - often mounted on platform (fixed in
  - Performance 1: gy (range: 0 .003 deg
  - Performance 2: lin to 5E-06 g/g^2 ov
  - Typically frequen external measuren Trackers, Sun sen Kalman Filter

ACS Sensor Performance Summary

Reference	Typical Accuracy	Remarks
Sun	1 min	Simple, reliable, low cost, not always visible
Earth	0.1 deg	Orbit dependent; usually requires scan; relatively expensive
Magnetic Field	1 deg	Economical; orbit dependent; low altitude only; low accuracy
Stars	0.001 deg	Heavy, complex, expensive, most accurate
Inertial Space	0.01 deg/hour	Rate only; good short term reference; can be heavy, power, cost

CDIO Attitude Sensing



Will not be
use/afford STAR

From whe
an attitu
for inerti

Potentia
Electroni
Magneto
Tilt Sens

Specifications:

Heading accuracy: +/- 1.0 deg RMS @ +/- 20 deg tilt
Resolution 0.1 deg, repeatability: +/- 0.3 deg
Tilt accuracy: +/- 0.4 deg, Resolution 0.3 deg
Sampling rate: 1-30 Hz

Problem: Accuracy insufficient to meet requirements a
will need FINE POINTING mode

Spacecraft Attitude Schemes

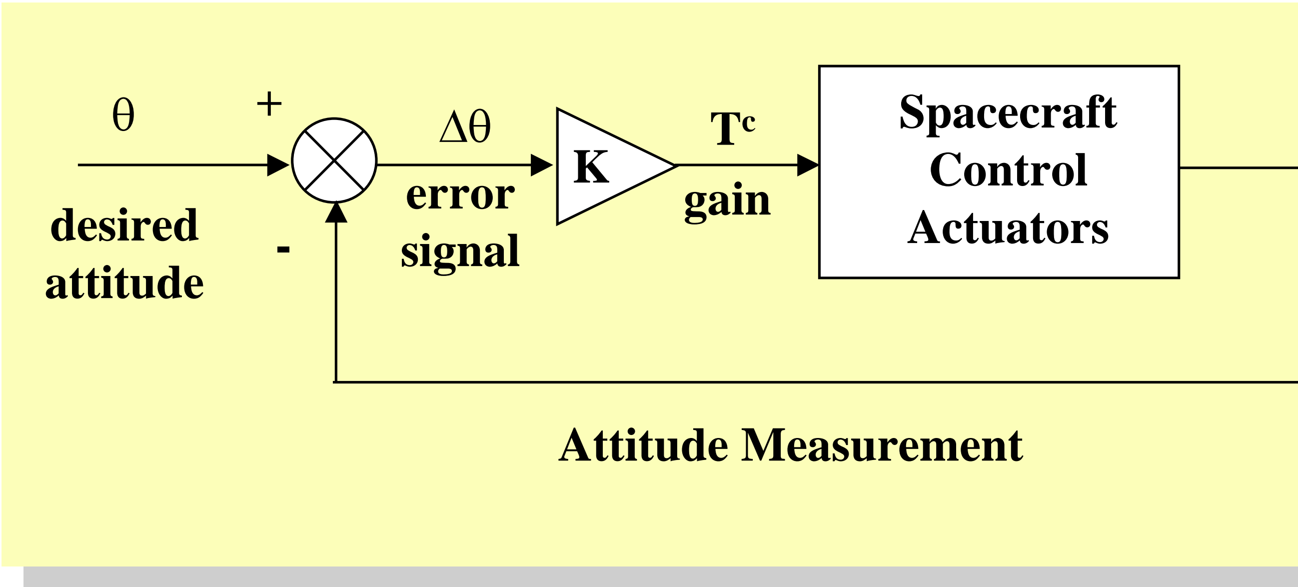
- Spin Stabilized Satellites
  - Spin the satellite to give it gyroscopic stability in inertial space
  - Body mount the solar arrays to guarantee partial illumination by sun at all times
  - EX: early communication satellites, stabilization for orbit changes
  - Torques are applied to precess the angular momentum vector
- De-Spun Stages
  - Some sensor and antenna systems require inertial or Earth referenced pointing
  - Place on de-spun stage
  - EX: Galileo instrument platform
- Gravity Gradient St
  - "Long" satellites
    towards Earth sin
    feels slightly mor
    force.
  - Good for Earth-re
  - EX: Shuttle grav
    minimizes ACS t
- Three-Axis Stabiliz
  - For inertial or Ea
    pointing
  - Requires active c
  - EX: Modern com
    satellites, Interna
    Station, MIR, Hu
    Telescope

ADCS Performance Comparison

Method	Typical Accuracy	Remarks
Spin Stabilized	0.1 deg	Passive, simple; s inertial, low cost, rings
Gravity Gradient	1-3 deg	Passive, simple; c body oriented; lov
Jets	0.1 deg	Consumables requ high cost
Magnetic	1 deg	Near Earth; slow weight, low cost
Reaction Wheels	0.01 deg	Internal torque; re other momentum high power, cost

3-axis stabilized, active control most common choice for precisi

ACS Block Diagram (1)



Feedback Control Concept: $T^c = K \cdot \Delta\theta$ Correc torqu

Force or torque is proportional to deflection. T is the equation, which governs a simple linea or rotational "spring" system. If the spacecra responds "quickly we can estimate the requir gain and system bandwidth.

Gain and Bandwidth

Assume control saturation half-width θ_{sat} at torque command T

$$K \cong \frac{T_{sat}}{\theta_{sat}} \quad \textbf{hence} \quad \ddot{\theta} + \left(\frac{K}{I}\right)\theta_{sat} \cong 0$$

Recall the oscillator frequency of a simple linear, torsional spring:

$$\omega = \sqrt{\frac{K}{I}} \quad \text{[rad/sec]}$$

I = moment of inertia

This natural frequency is approximately equal to the system bandwidth. Also,

$$f = \frac{\omega}{2\pi} \quad \text{[Hz]} \quad \Rightarrow \quad \tau = \frac{1}{\text{f}} = \frac{2\pi}{\omega}$$

Is approximately the system time constant τ.

Note: we can choose any two of the set:

$$\ddot{\theta}, \theta_{sat}, \omega$$

EXAMI

$$\theta_{sat} = 10^{-2}$$

$$T_{sat} = 1($$

$$I = 1000$$

$$\therefore K = 1000$$

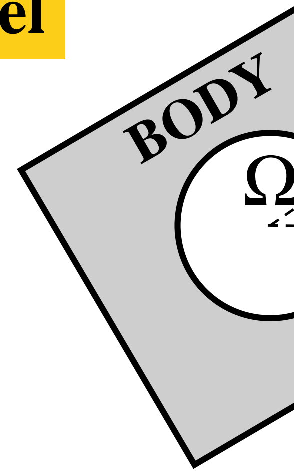
$$\omega = 1$$

$$f = 0.16$$

$$\tau = 6.3$$

Feedback Control Example

Pitch Control with a single reaction wheel



Rigid Body Dynamics

$$I\ddot{\theta} = T_w + T_{ext} = I\dot{\omega} = \dot{H}$$

Wheel Dynamics

$$J(\dot{\Omega} + \ddot{\theta}) = -T_w = \dot{h}$$

Feedback Law, Choose

$$T_w = \underbrace{-K_p\theta}_{\text{Position feedback}} - \underbrace{K_r\dot{\theta}}_{\text{Rate feedback}}$$

Position feedback **Rate feedback**

Stabilize RIGID BODY

Then:

$$\ddot{\theta} + (K_r / I)\dot{\theta} + (K_p / I) = 0 \quad \rightarrow Laplace\ Transfor$$

$$s^2 + (K_r / I)s + (K_p / I) = 0$$

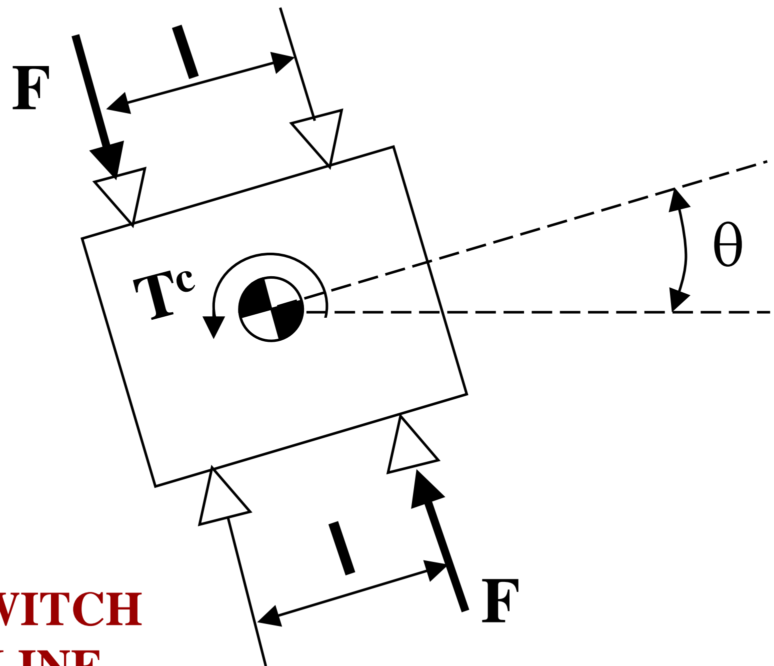
Characteristic E

$$s^2 + 2\zeta\omega s + \omega^2 = 0$$

Nat. frequency **d**

$$\omega = \sqrt{K_p / I} \qquad \zeta = \text{K}$$

Jet Control Example (1)



Introduce control torque
force couple from jet th

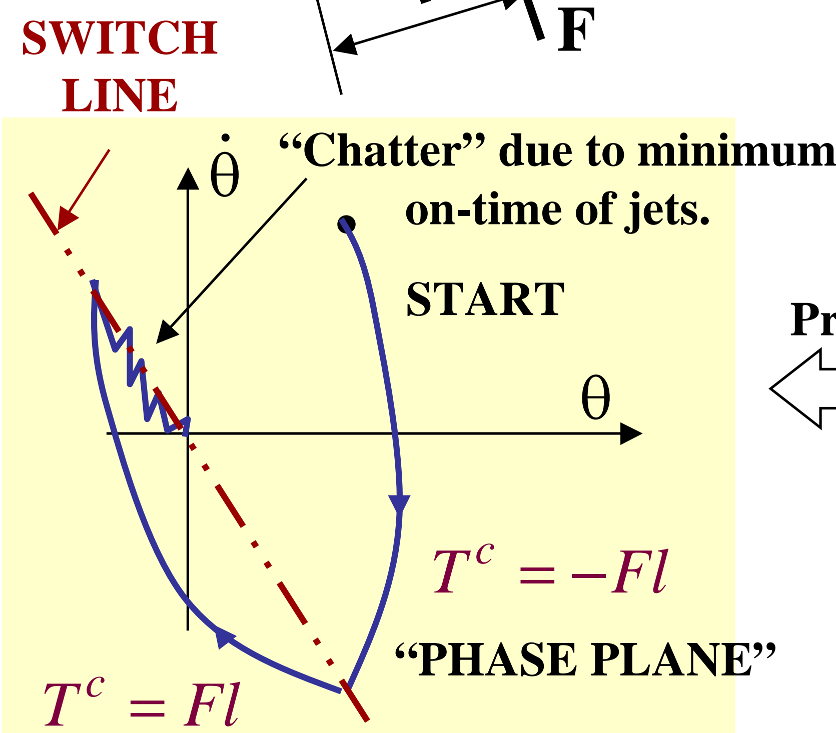
$$I\ddot{\theta} = T^c$$

Only three possible values fo

$$T^c = \begin{cases} Fl \\ 0 \\ -Fl \end{cases}$$

O
C

Can stabilize (drive θ to
by feedback law:



Problem

$$T^c = -Fl \cdot \operatorname{sgn}\left(\theta +\right.$$

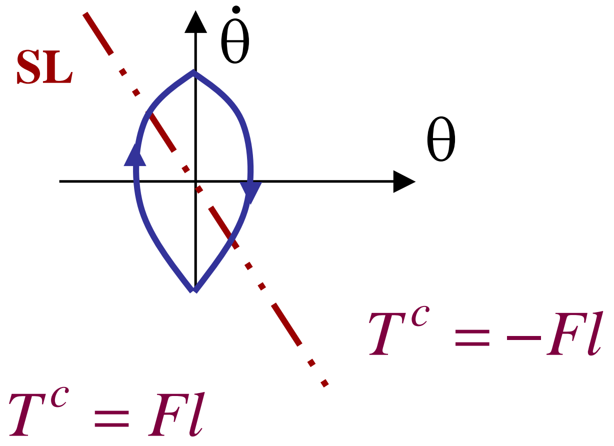
Where

$$\operatorname{sgn}(x) = \frac{x}{|x|}$$

τ =

Jet Control Example (2)

“Chatter” leads to a “limit cycle”, quickly wasting fuel



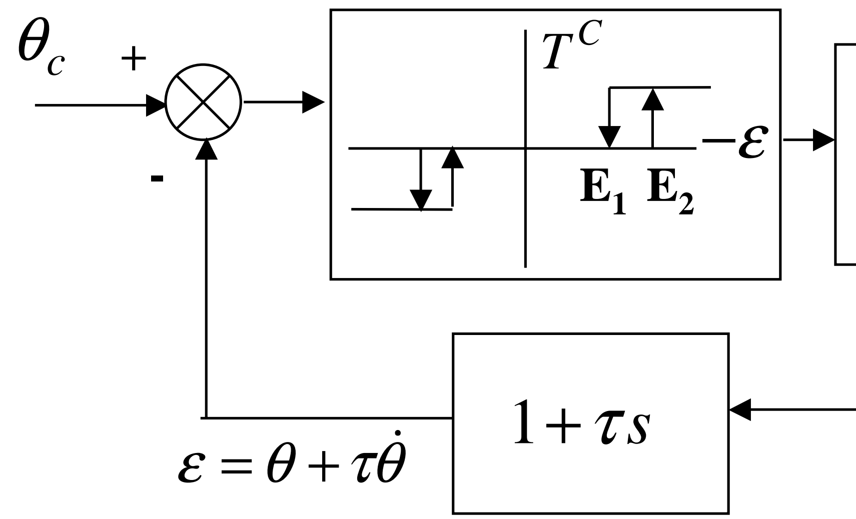
“PHASE PLANE”

At Switch Line: $\theta + \tau\dot{\theta} = 0$

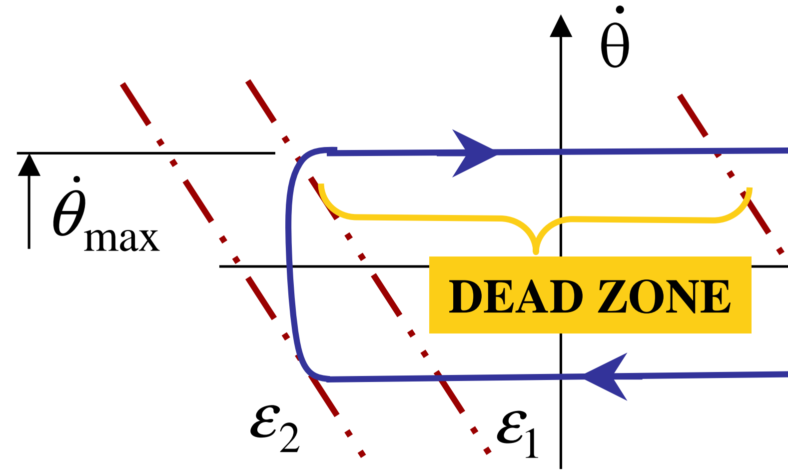
- **Low Frequency Limit Cycle**
- **Mostly Coasting**
- **Low Fuel Usage**
- θ **and** $\dot{\theta}$ **bounded**

Solution:

Eliminate “Chatter” by “Dead Zone” ; w

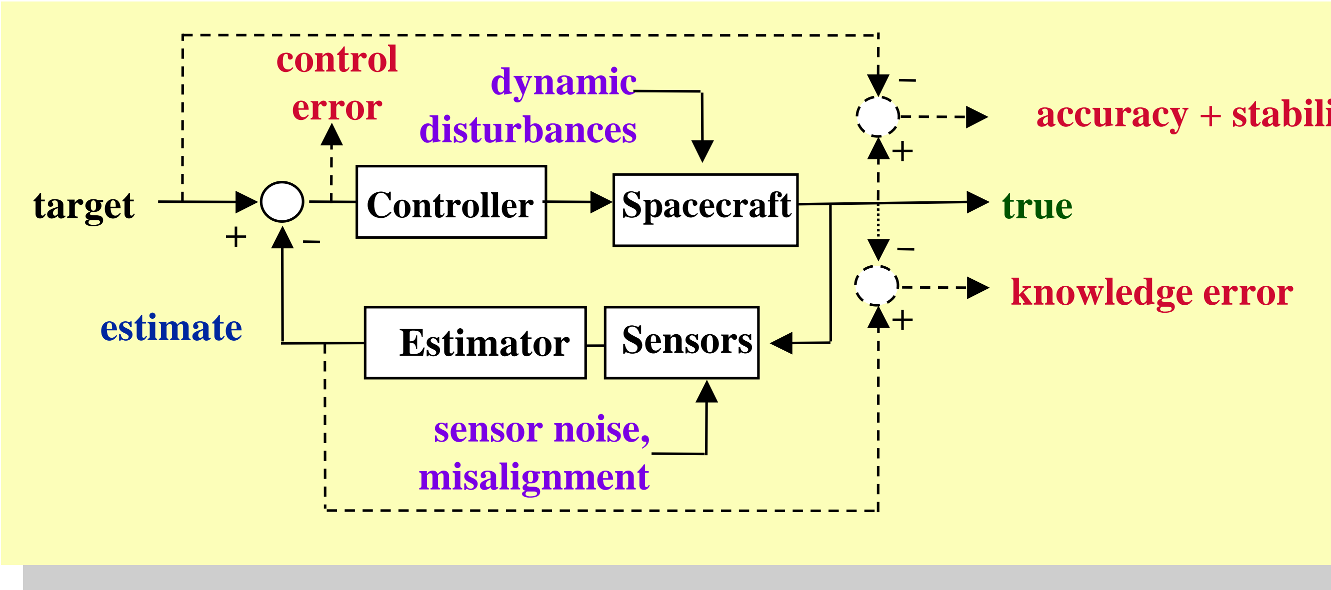


Results in the following motion



ACS Block Diagram (2)

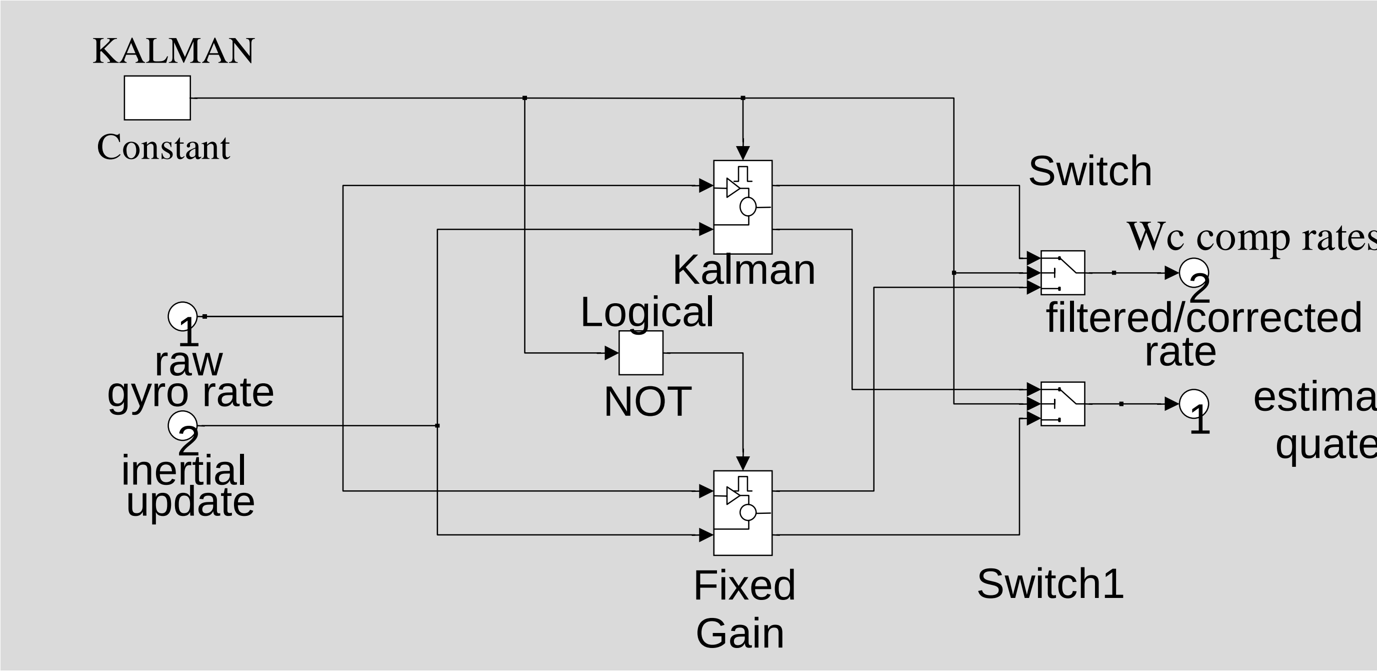
In the "REAL WORLD" things are somewhat more complicated



- Spacecraft <u>not</u> a RIGID body, sensor , actuator & avionic
- Digital implementation: work in the z-domain
- Time delay (lag) introduced by digital controller
- A/D and D/A conversions take time and introduce errors: 16-bit electronics, sensor noise present (e.g rate gyro @ D
- Filtering and estimation of attitude, never get <u>q</u> directly

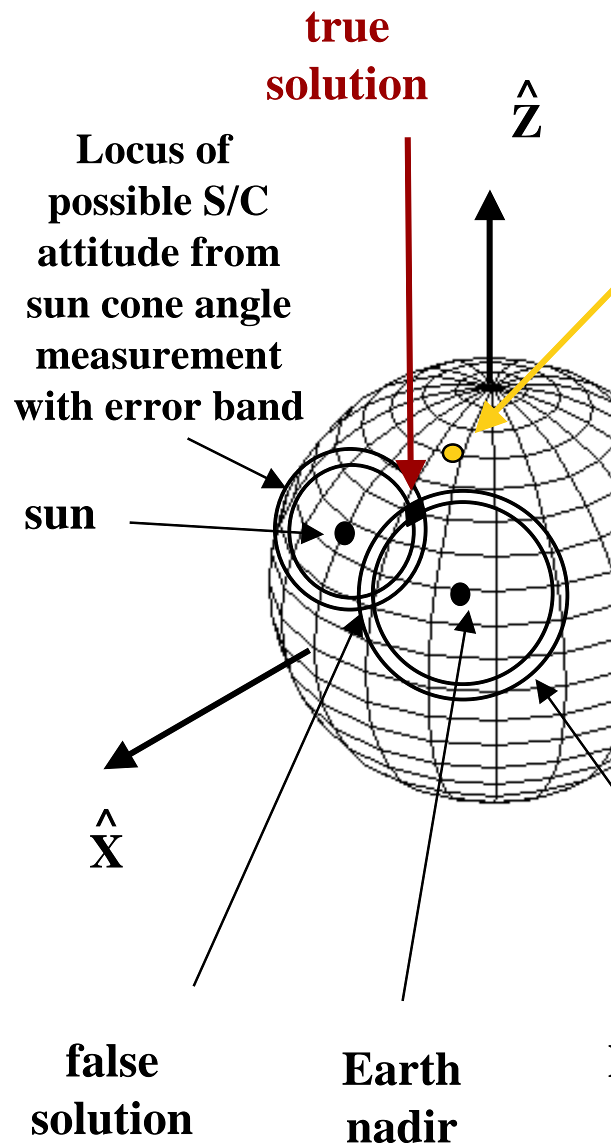
Attitude Determination

- Attitude Determination (AD) is the process of of deriving
of spacecraft attitude from (sensor) measurement data. Ex
determination is NOT POSSIBLE, always have some erro
- Single Axis AD: Determine orientation of a single spacec
in space (usually spin axis)
- Three Axis AD: Complete Orientation; single axis (Euler
when using Quaternions) plus rotation about that axis



Single-Axis Attitude Determination

- Utilizes sensors that yield an arc-length measurement between sensor boresight and known reference point (e.g. sun, nadir)
- Requires at least two independent measurements and a scheme to choose between the true and false solution
- Total lack of a priori estimate requires three measurements
- Cone angles only are measured, not full 3-component vectors. The reference (e.g. sun, earth) vectors are known in the reference frame, but only partially so in the body frame.



Three-Axis Attitude Determination

- Need two vectors (u,v) measured in the spacecraft frame and known in reference frame (e.g. star position on the celestial sphere)
- Generally there is redundant data available; can extend the calculations on this chart to include a least-squares estimate for the attitude
- Do generally not need to know absolute values

$$|u|, |v|$$

Define:

$$\hat{i} = u / |u|$$

$$j = (u \quad v) / |u$$

$$\hat{k} = \hat{i} \quad \hat{j}$$

Want Attitude Matrix

$$\underbrace{\begin{bmatrix} \hat{i}_B & \hat{j}_B & \hat{k}_B \end{bmatrix}}_{M} = T \cdot \begin{bmatrix} \hat{i}_R \end{bmatrix}$$

So: $T = MN^{-1}$

<u>Note:</u> N must be non-singular (= full rank)

Effects of Flexibility (Spinners)

The previous solutions for Euler's equations were only valid for a RIGID BODY. When flexibility exists, energy dissipation will occur.

$$\underline{H} = \underline{\underline{I}}\,\underline{\omega}$$ ⇒ **CONSTANT**

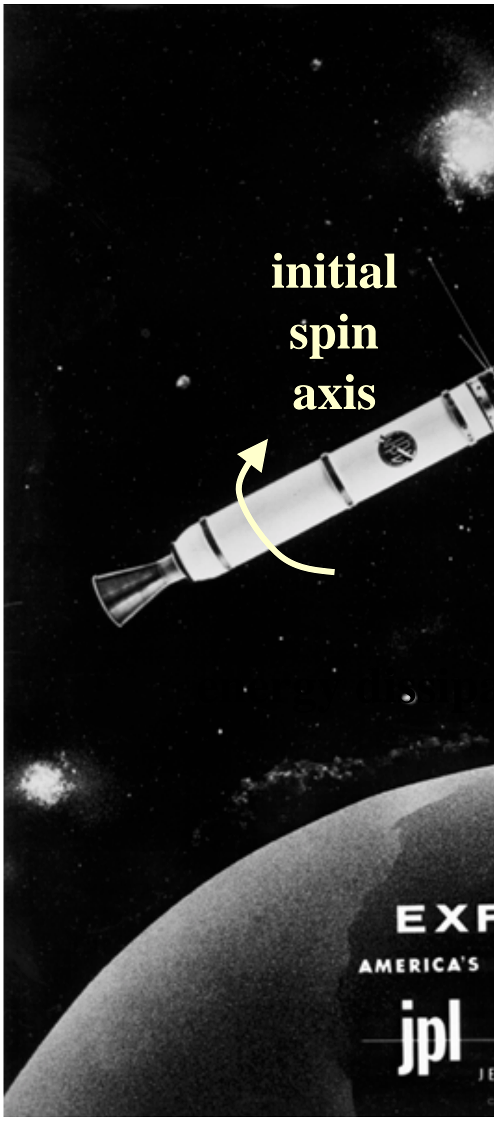
Conservation of Angular Momentum

$$E_{ROT} = \frac{1}{2}\underline{\omega}^T \underline{\underline{I}}\,\underline{\omega}$$ ⇒ **DECREASING**

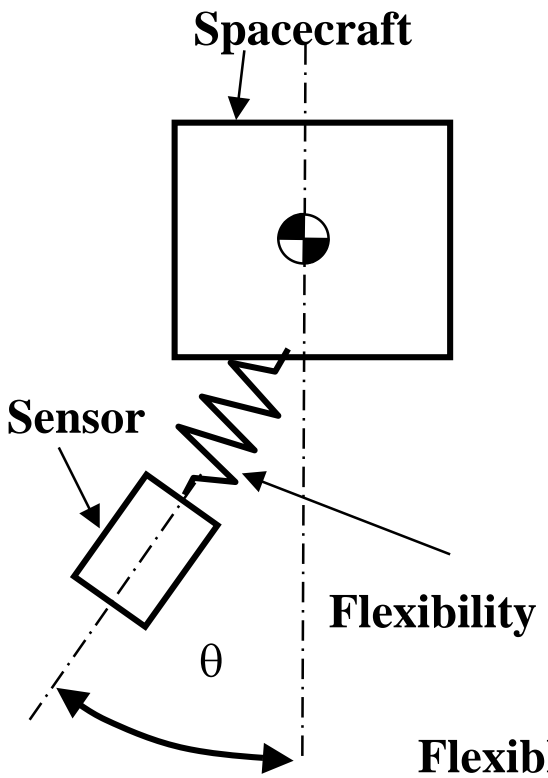
∴ **Spin goes to maximum I and minimum ω**

CONCLUSION: Stable Spin is only possible about the axis of maximum inertia.

Classical Example: EXPLORER 1

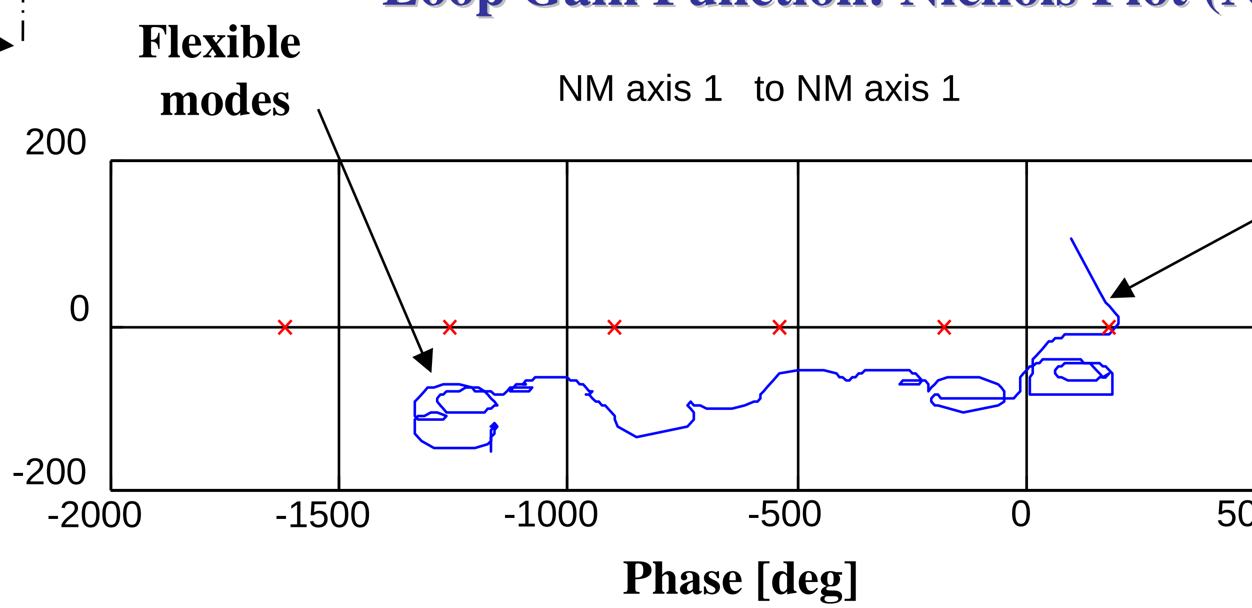


Controls/Structure Interaction



- Can’t always neglect flexible mode
arrays, sunshield)
- Sensor on flexible structure, modes
phase loss
- Feedback signal “corrupted” by fle
deflections; can become unstable
- Increasingly more important as spa
become larger and pointing goals b

Loop Gain Function: Nichols Plot (N

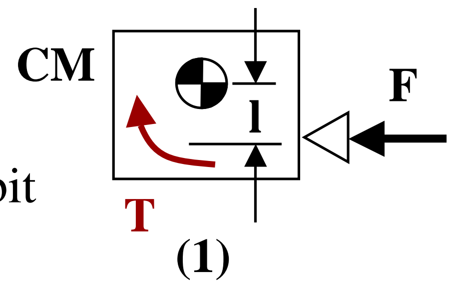


Other System Considerations (1)

- Need on-board COMPUTER
  - Increasing need for on-board performance and autonomy
  - Typical performance (somewhat outdated: early 1990's)
  - 35 pounds, 15 Watts, 200K words, 100 Kflops/sec, CMOS
  - Rapidly expanding technology in real-time space-based comput
  - Nowadays get smaller computers, rad-hard, more MIPS
  - Software development and testing, e.g. SIMULINK Real Time compilation from development environment MATLAB C, C++ processor is getting easier every year. Increased attention on so
- Ground Processing
  - Typical ground tasks: Data Formatting, control functions, data a
  - Don't neglect; can be a large program element (operations)
- Testing
  - Design must be such that it can be tested
  - Several levels of tests: (1) benchtop/component level, (2) enviro testing (vibration,thermal, vacuum), (3) ACS tests: air bearing, simulation with part hardware, part simulated

Other System Considerations (2)

- Maneuvers
  - Typically: Attitude and Position Hold,Tracking/Slewing, SAFE
  - Initial Acquisition maneuvers frequently required
  - Impacts control logic, operations, software
  - Sometimes constrains system design
  - Maneuver design must consider other systems, I.e.: solar arrays towards sun, radiators pointed toward space, antennas toward E
- Attitude/Translation Coupling
  - (1) **Δv** from thrusters can affect attitude
  - **(2)** Attitude thrusters can perturb the orbit



- Simulation
  - Numerical integration of dynamic equations of motion
  - Very useful for predicting and verifying attitude performance
  - Can also be used as “surrogate” data generator
  - “Hybrid” simulation: use some or all of actual hardware, digital the spacecraft dynamics (plant)
  - can be expensive, but save money later in the program

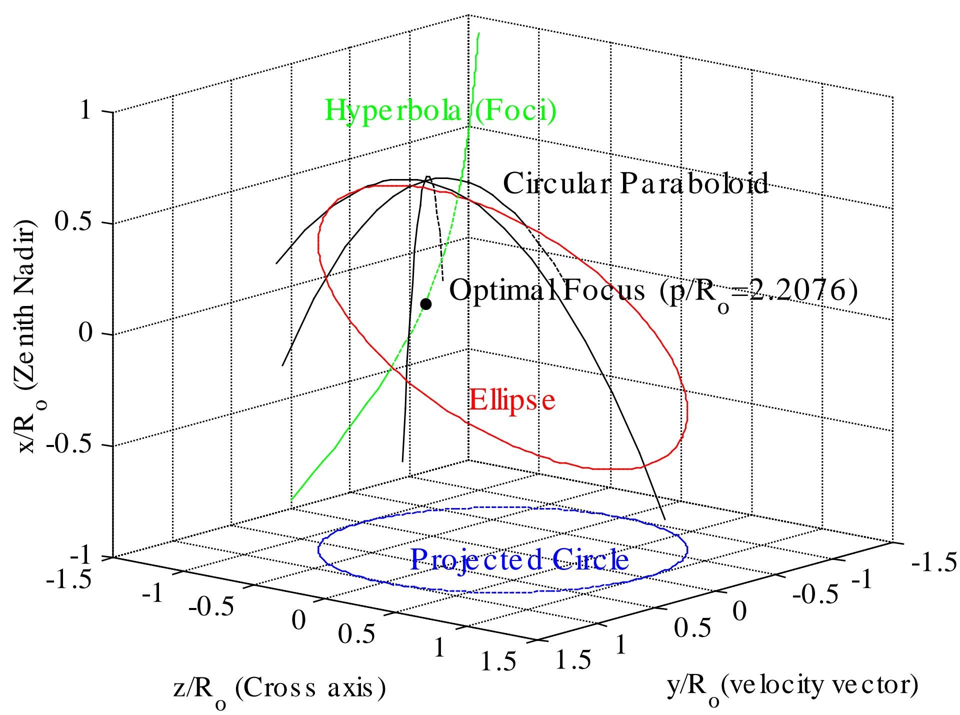
Future Trends in ACS Design

- Lower Cost
  - Standardized Spacecraft, Modularity
  - Smaller spacecraft, smaller Inertias
  - Technological progress: laser gyros, MEMS, magnetic wheel b
  - Greater on-board autonomy
  - Simpler spacecraft design
- Integration of GPS (LEO)
  - Allows spacecraft to perform on-board navigation; functions in from ground station control
  - Potential use for attitude sensing (large spacecraft only)
- Very large, evolving systems
  - Space station ACS requirements change with each added modu
  - Large spacecraft up to 1km under study (e.g. TPF Able "kilotru
  - Attitude control increasingly dominated by controls/structure in
  - Spacecraft shape sensing/distributed sensors and actuators

Advanced ACS concepts

Visible Earth Imager using a Distributed Satellite System

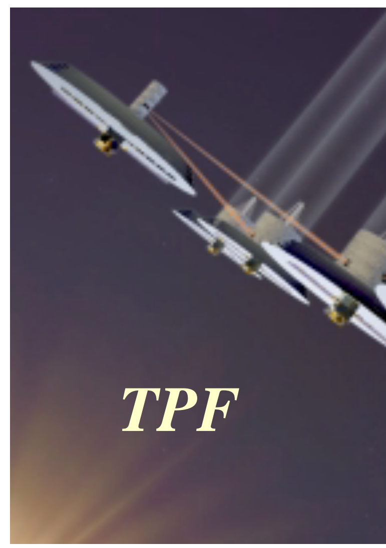
- No ΔV required for collector spacecraft
- Only need ΔV to hold combiner spacecraft at paraboloid's focus



Formation Flyi

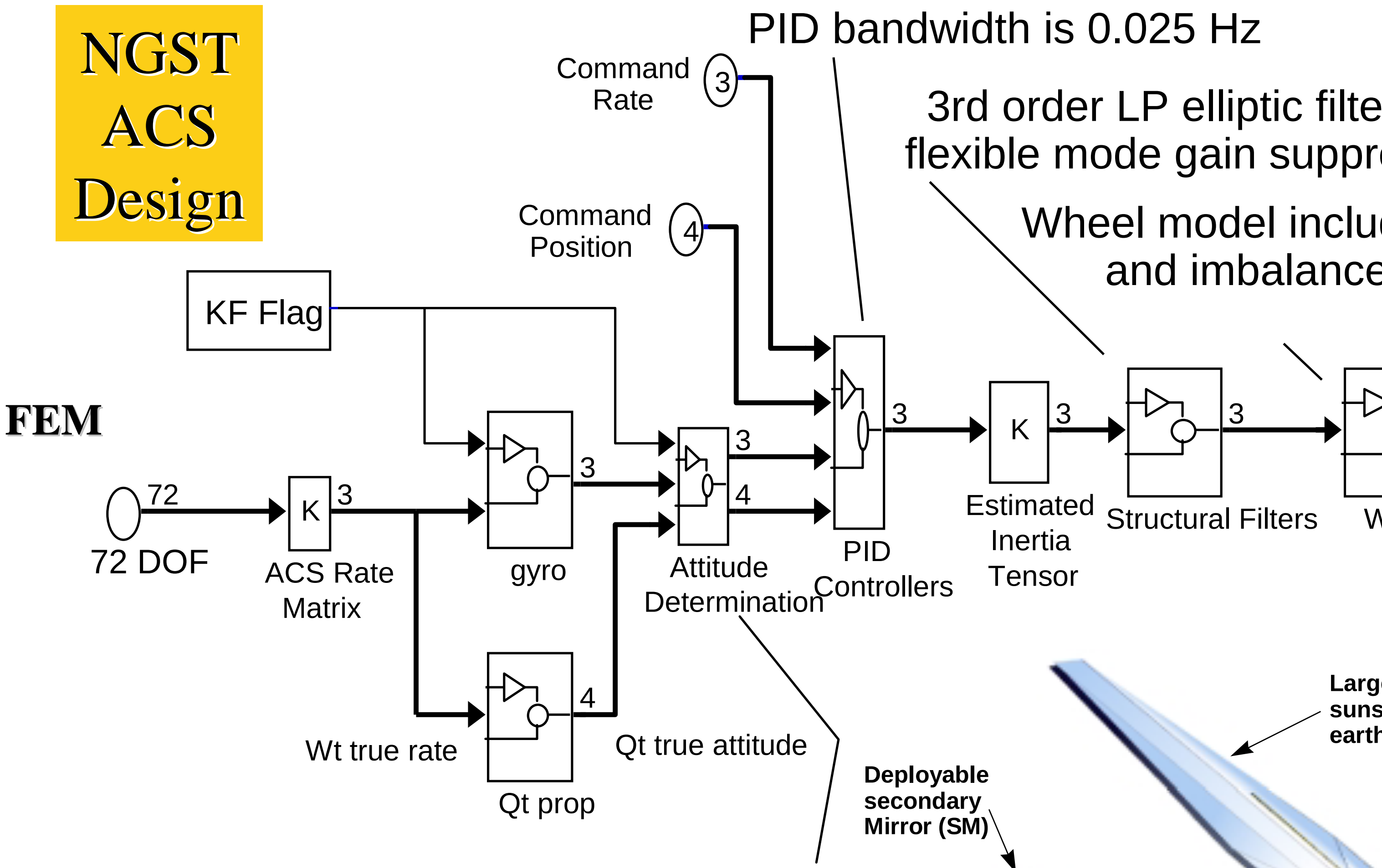
- Exploit natural orbi synthesize sparse a using formation fly
- Hill's equations exh orbit ellipse" soluti

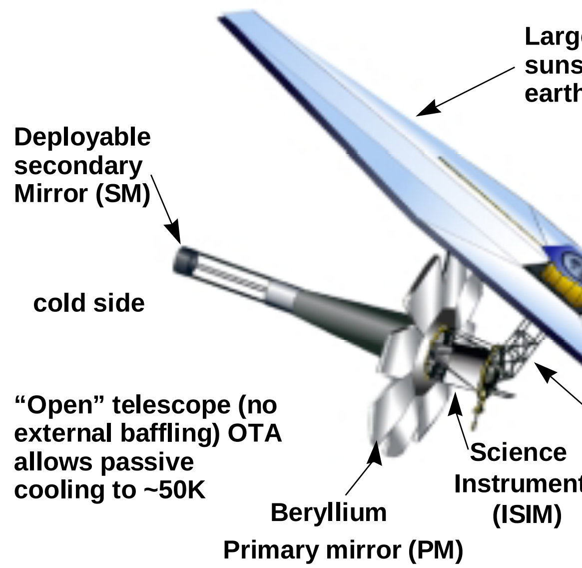
$$\ddot{x} \quad - \quad 2\dot{y}n \quad -$$
$$\ddot{y} \quad + \quad 2\dot{x}n$$
$$\ddot{z} \qquad\qquad +$$



ACS Model of NGST (large, flexible S/

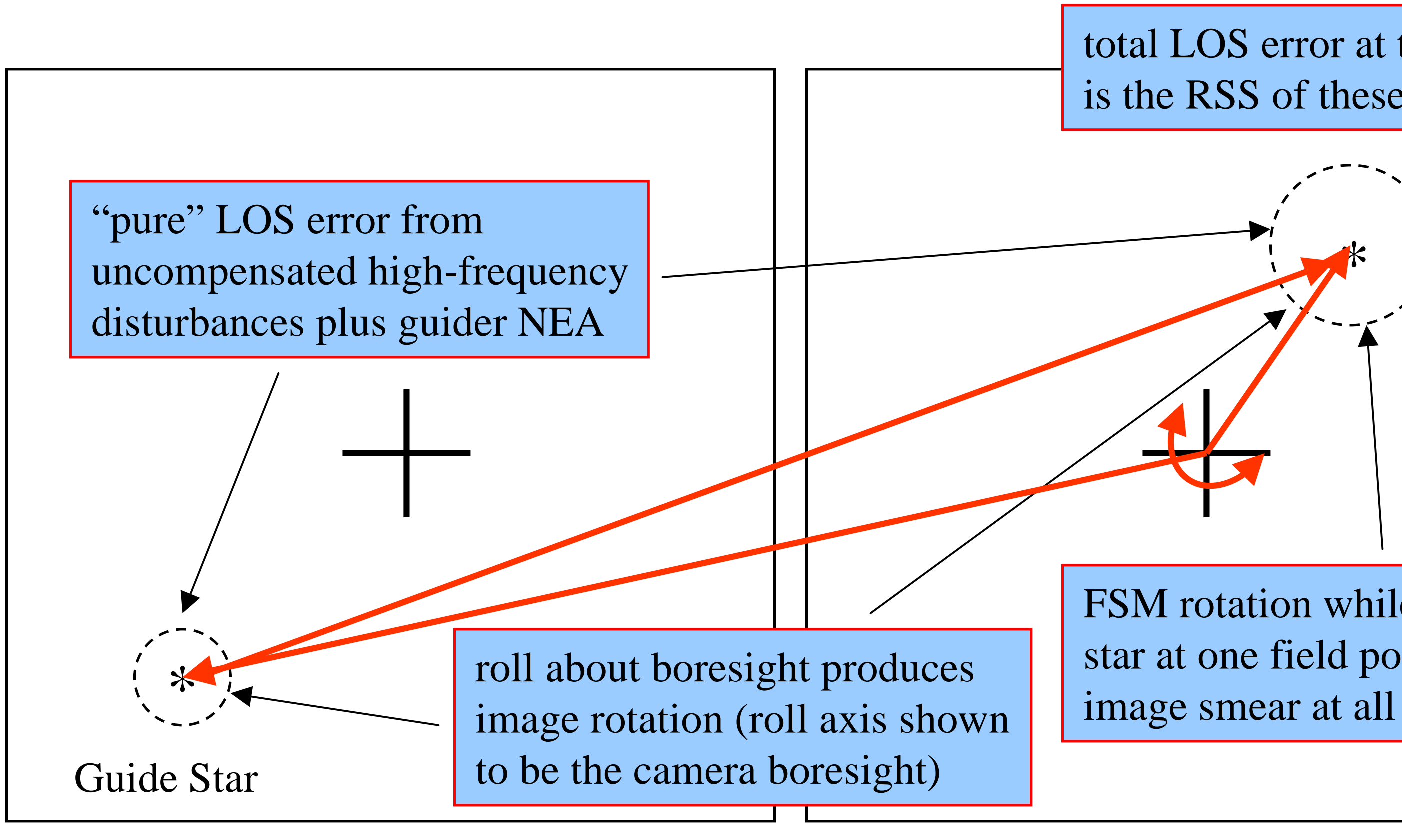
NGST ACS Design





Kalman Filter blends 10 Hz IRU and 2 Hz ST data to provide optimal attitude estimate; option exists to disable the KF and inject white noise, with amplitude given by steady-state KF covariance into the controller position channel

Attitude Jitter and Image Stability



Source: G. Mosier NASA GSFC

Guider

Camera

Important to assess impact of attitude jitter ("stability") on image quality. Can compensate with fine pointing system. Use a guider camera as sensor and a 2-axis FSM as actuator.

R
F
RMS

E.g. HST: RMS LOS =

References

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