

Spacecraft Dynamics and Control

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Lecture 15: Attitude Dynamics and Control

Attitude Dynamics

In this Lecture we will cover:

- Mission Requirements
- Forms of Attitude Control

The Problem of Attitude Stabilization

- Actuators

Newton's Laws

- $\sum \vec{M}_i = \frac{d}{dt} \vec{H}$
- $\sum \vec{F}_i = m \frac{d}{dt} \vec{v}$

Rotating Frames of Reference

- Equations of Motion in Body-Fixed Frame
- Often Confusing

Orientation of a spacecraft

Let's begin with some examples

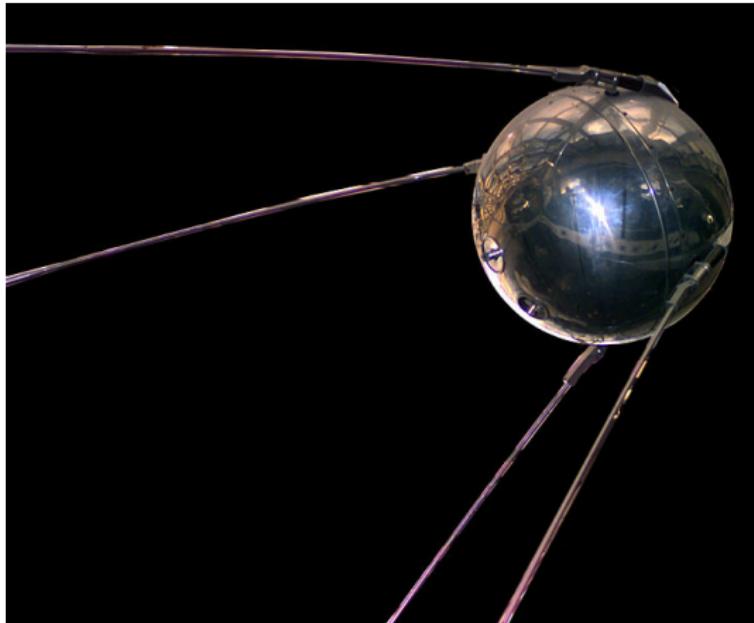


Figure: Sputnik I Satellite

Orbit: 947 x 228, 65° inclination. Spin Stabilized. Two planes of symmetry.

NASA Tracking and Data Relay Satellite (TDRS)



There have been 13 TDRS missions.

- Enable continuous real-time communications between space and ground.
- GEO, TDRS-K is currently at $\Omega = 150^\circ$ (Final $\Omega = 171^\circ$).

└ NASA Tracking and Data Relay Satellite (TDRS)

NASA Tracking and Data Relay Satellite (TDRS)



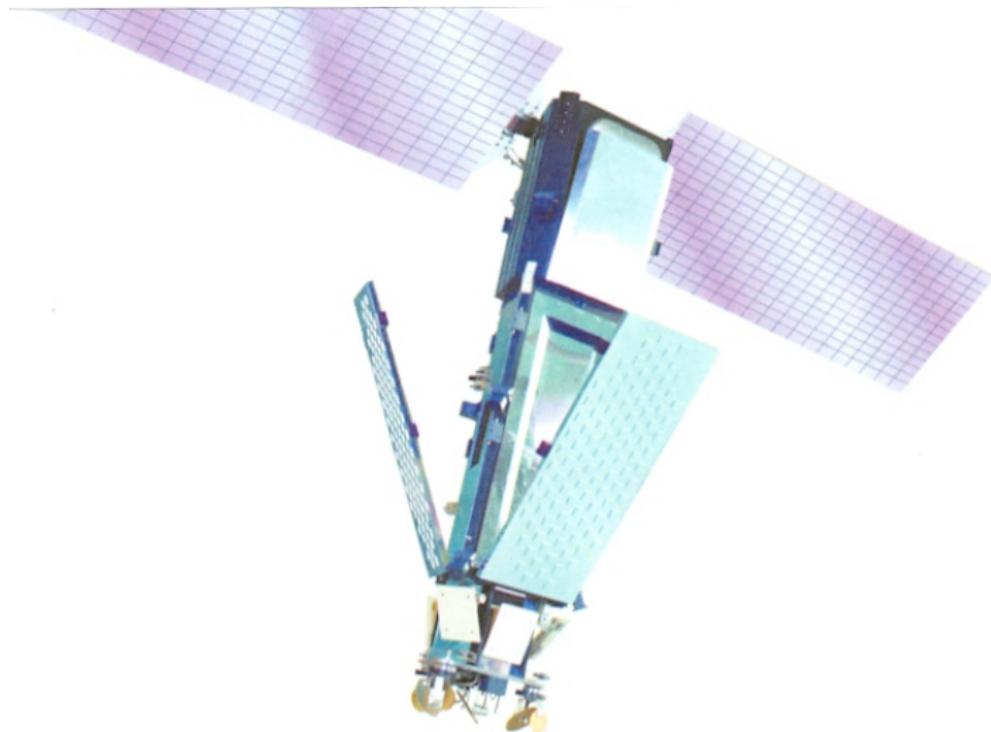
There have been 13 TDRS missions.

- Enable continuous real-time communications between space and ground.
- GEO, TDRS-K is currently at $\Omega = 150^\circ$ [Final $\Omega = 171^\circ$].

- Approximately 1 plane of symmetry
- TDRS-A was launched in 1983 (currently in graveyard orbit)
- TDRS-B was aboard the Challenger.
- Image is 3rd gen. TDRS (2011+)



Iridium Satellite Constellation. Launched 1992-1999



Telephone. Originally commercial, now pseudo-military. 66 active satellites.
Orbit: 780km, 75° inclination, 6 orbital planes.

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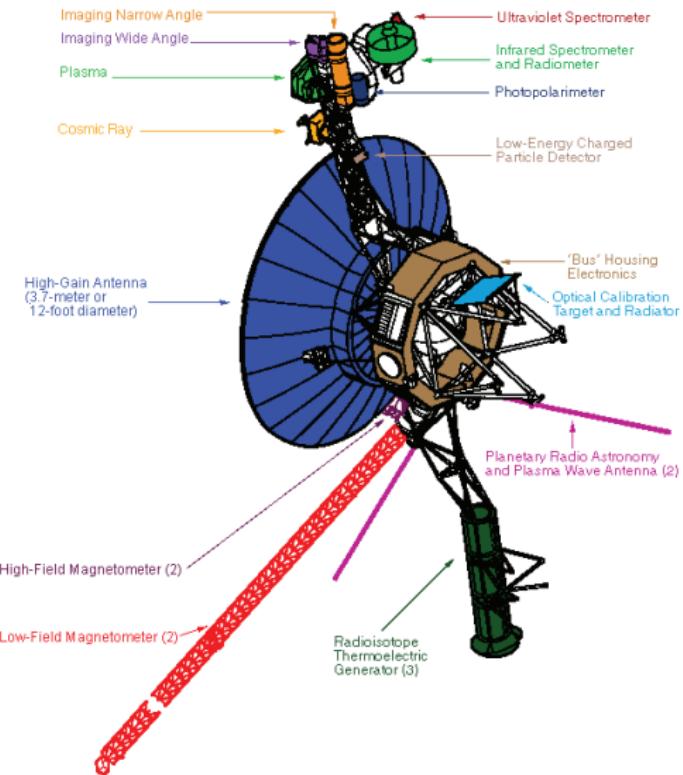
└ Iridium Satellite Constellation. Launched 1992-1999



- Approximately 1 plane of symmetry
- Operational in 1998
- Largest US bankruptcy in 1999 (originally to be de-orbited!)
- First Next-gen Iridium satellite launched in 2017.

Voyager I and II (1977)

Voyagers 1 & 2



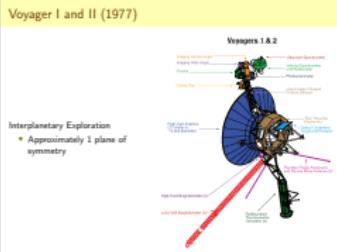
Interplanetary Exploration

- Approximately 1 plane of symmetry

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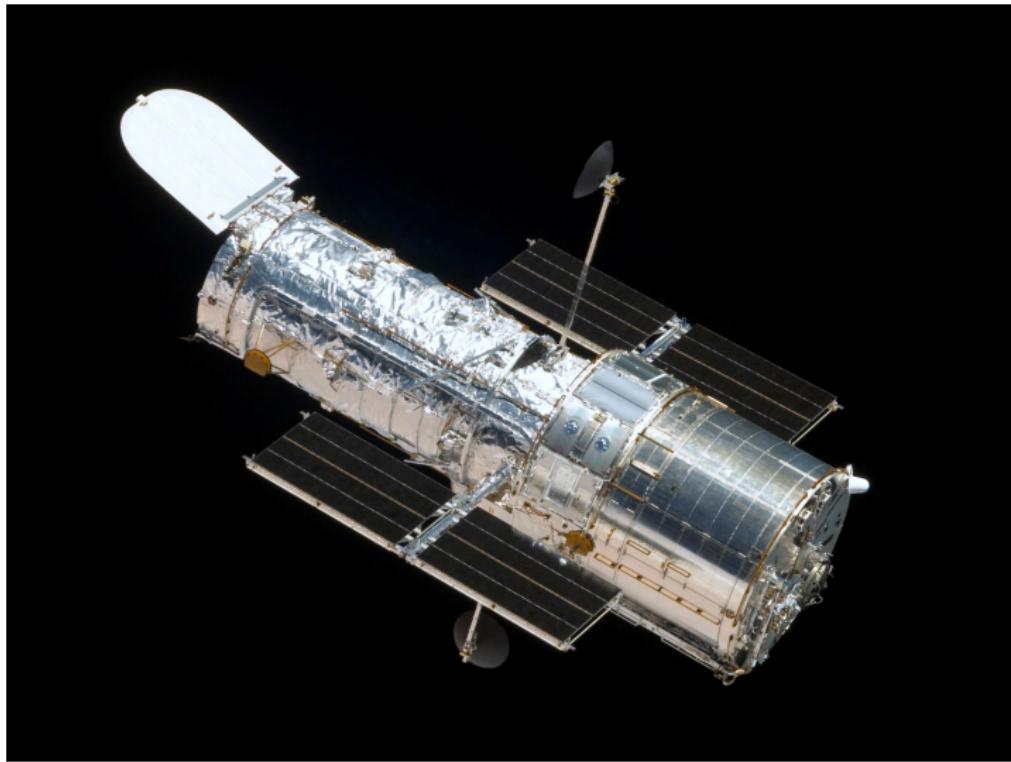
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└ Voyager I and II (1977)



- Requires constant communication link with earth.
- 3-axis stabilized

Hubble Space Telescope (HST) - 1990



Orbit: 613×620 , 28.5° inclination



Orbit: 613 x 620, 28.5° inclination

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└ Hubble Space Telescope (HST) - 1990

- approximate radial symmetry
- 3-axis stabilized

NRO Reconnaissance Satellite

Advanced Orion/MENTOR

- Signals Intelligence
- Duration 1994-???
- L-32 is the largest satellite ever launched with a dish size of $\cong 100\text{m}$



Figure: Orion/RIO (The Intercept, 2009)

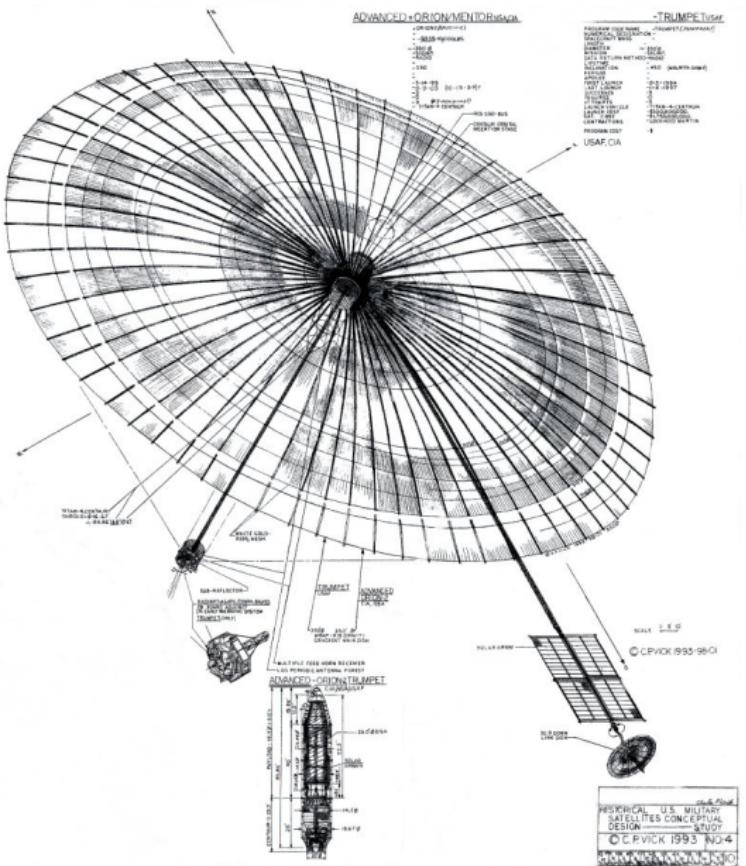
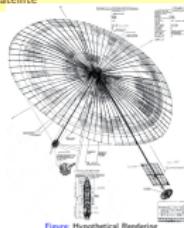


Figure: Hypothetical Rendering

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└ NRO Reconnaissance Satellite

NRO Reconnaissance Satellite



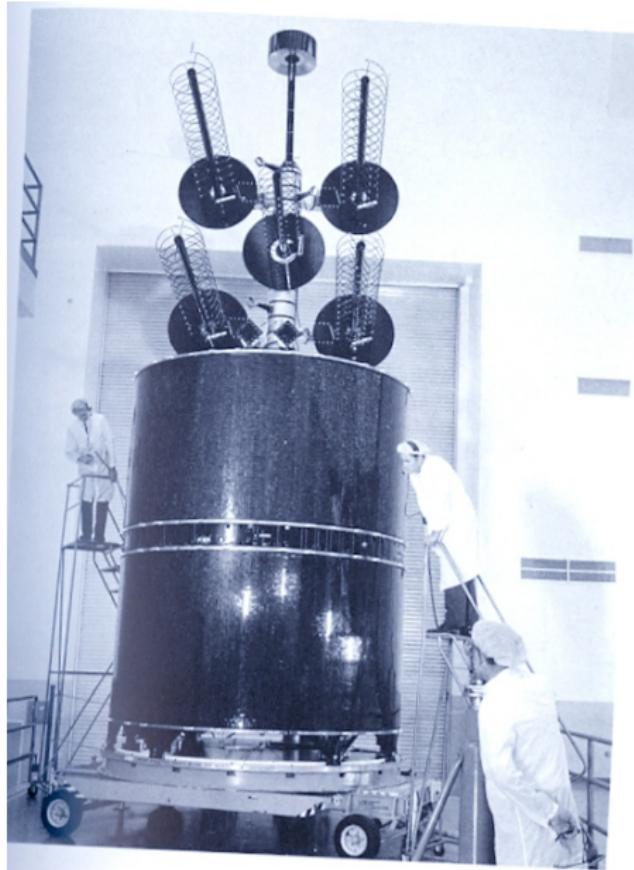
- Classified Top Secret
- Largest in the world quote is from Ben Carlson, NRO director
- Trumpet is in Molniya orbit 39000×1300 , $i = 64^\circ$
- Advanced ORION is in GEO (so is PAN - whatever that does)
- Replaces Magnum Series
- 3-axis stabilized
- Single plane of symmetry
- Description of Spy Satellites included in the Snowden Leak

TACSAT I (1969-1972)

Military Tactical Communications Satellite.

- Approximate radial symmetry
- Dual Spinner

Orbit: GEO, $\Omega = 107^\circ$



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└ TACSAT I (1969-1972)

TACSAT I (1969-1972)

Military Tactical Communications Satellite.
▪ Approximate radial symmetry
▪ Dual Spinner
Orbit: GEO, $\Omega = 100^\circ$

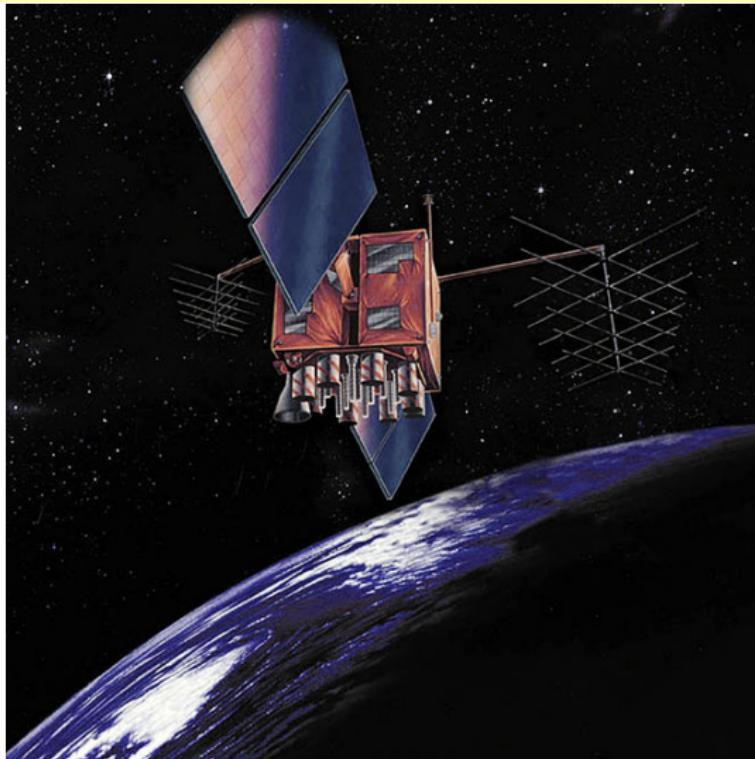


- Largest satellite at time of launch (25ft in length) - gunter's space page
- Used for direct communication with battlefield commanders.
- Not to be confused with TacSat

TacSat:

- TacSat is to obtain on-battlefield live imaging.
- TacSat 1 planned launch in January 2004.
- TacSat 1 launch was repeatedly delayed
- TacSat 2 launch in Dec. 2006
- TacSat 3 launch May, 2009, reentry April 2012
- Last scheduled TacSat 1 launch was 2009. Canceled for being obsolete.
- TacSat 4 launch Sept. 2011. 4 hr period, 7000 x 12,000 orbit. $\omega = 210$, $i = 63.4$

GPS Block IIR (2005-2009)



Orbit: 20,182km, 55° inclination. Single plane of symmetry
GPS constellation has 24 satellites in 6 planes.

GPS Constellation

Figure: GPS Constellation is designed to have at least 4 satellites visible at any given time anywhere in the world.

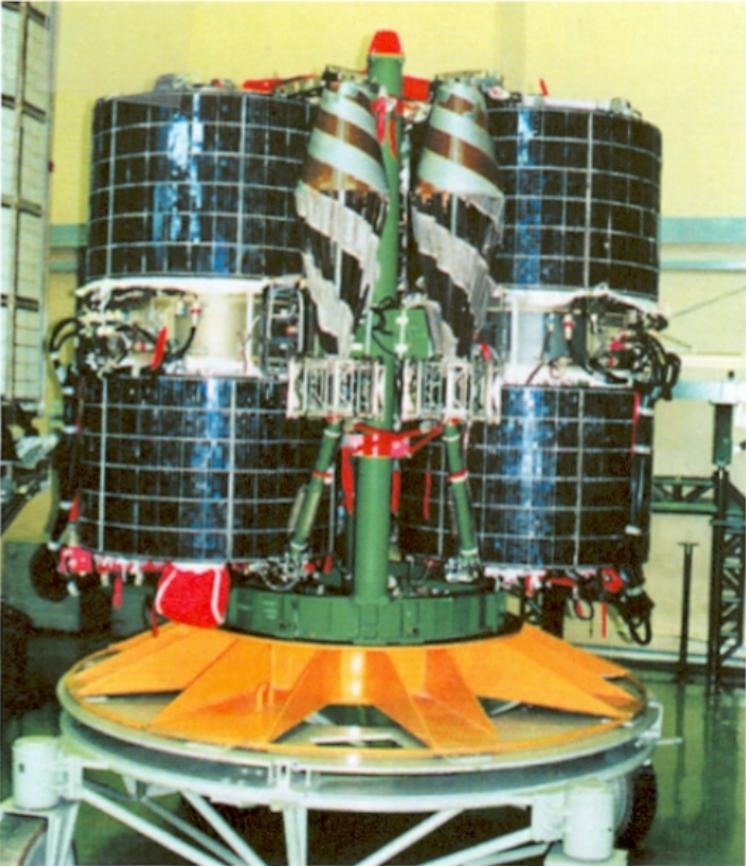
Strela-3 Satellite Constellation (1985)

Russian Military Communications

- 12 Satellites
- Gravity-Gradient Stabilization

Note: 2009 Satellite Collision between Strela 2M and Iridium 33

Orbit: 1440×1450 , 82.5° inclination.



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└ Strela-3 Satellite Constellation (1985)

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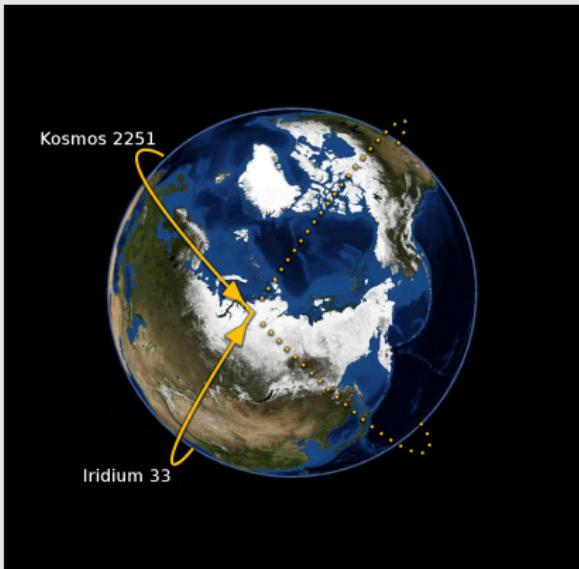


Russian Military Communications
▪ 12 Satellites
▪ Gravity-Gradient Stabilization

Note: 2009 Satellite Collision between Strela 2M and Iridium 33

Orbit: 1440 × 1450, 82.5° inclination.

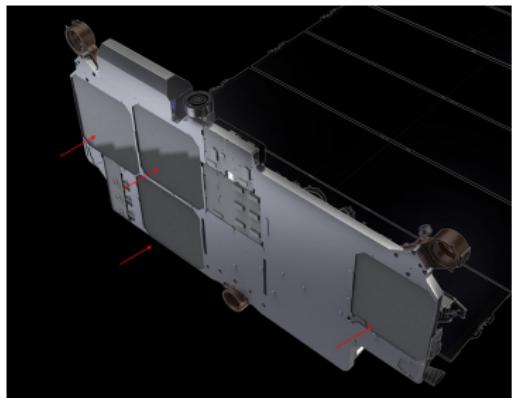
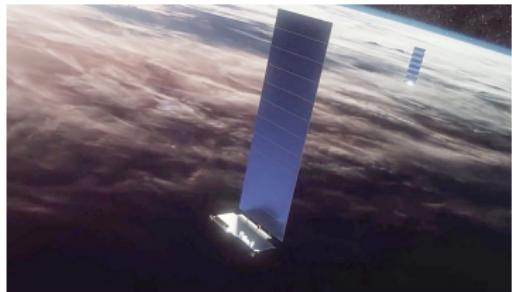
- Relative velocity at impact: 11.7 km/s
- Altitude at impact: 789 km
- Strela Satellite was dead as of 1995 and likely in a decaying orbit.



Starlink

Internet Communications

- 1584-12,000 Satellites
- Currently 350 in orbit (April, 2020) - all at 53° inclination
- Satellites weigh 500-600lb
- Currently, altitude is 550km (may increase)
- Use Hall-Effect Thrusters (HET-Kryptonon) for stationkeeping
- 3-axis stabilized (4 reaction wheels)
- star tracker for orientation



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└ Starlink

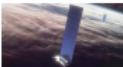
- First 1582 will be in 72 orbital planes of 22 satellites each
- Possible Explanation of the Starlink Operation and Orbit



Starlink

Internet Communications

- 1584-12,000 Satellites
- Currently 350 in orbit (April, 2020) - all at 55° inclination
- Satellites weigh 500-600lb
- Currently, altitude is 550km (may increase)
- Use Hall-Effect Thrusters (HET-Kryptonon) for stationkeeping
- 3-axis stabilized (4 reaction wheels)
- star tracker for orientation



Viking I



Interplanetary Mission to Mars. Two planes of symmetry.

Mars Orbit: $320 \times 56,000\text{km}$, 39.3° inclination. $e = .8822$.

└ Viking I

Viking I



Interplanetary Mission to Mars. Two planes of symmetry.
Mars Orbit: 320 x 56,000km, 39.3° inclination. $e = .8822$.

- Mars insertion on June 19, 1976.
- Operations terminated in 1980.
- Final Orbit designed to last until 2019
- Current Status: unknown
- Viking 2 orbiter developed ADCS propulsion leak and was shut down in 1978
- Second spacecraft to soft-land on Mars
- The first was the Soviet Mars 3, which lasted 20 seconds (due to a nasty dust storm)

Attitude Stability

What can go wrong?

Figure: Tumbling Satellites are sometimes visible in the Night Sky

Attitude Determination and Control System (ADCS)

Active attitude control is required for almost all satellite applications.

- Communication
- Reconnaissance
- Navigation
- Exception
 - ▶ LAGEOS
 - ▶ ECHO I, II

Even Sputnik was spin-stabilized

Problem: Unlike aircraft, spacecraft cannot rely on aerodynamic forces to provide stability.

- If a spacecraft is not attitude stabilized, small disturbances will cause it to tumble.

Question: How to stabilize a satellite

Attitude Determination and Control System (ADCS)

Mechanisms for Control

There are many varieties and methods for attitude control of spacecraft.

- 3-axis Stabilization
 - ▶ Thrusters (.1 – .5°)
 - ▶ Control-Moment Gyros (CMGs) (.001 – 1°)
 - ▶ Momentum wheels (Reaction wheels) (.001 – 1°)
- Spin Stabilization (.1 – 1°)
 - ▶ Also good for pre-insertion.
- Gravity-Gradient Stabilization (5°)
- Magnetic Torquers (5°)

Lets go through a few of these.

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└ Attitude Determination and Control System (ADCS)

Attitude Determination Sensors:

Rate Sensors:

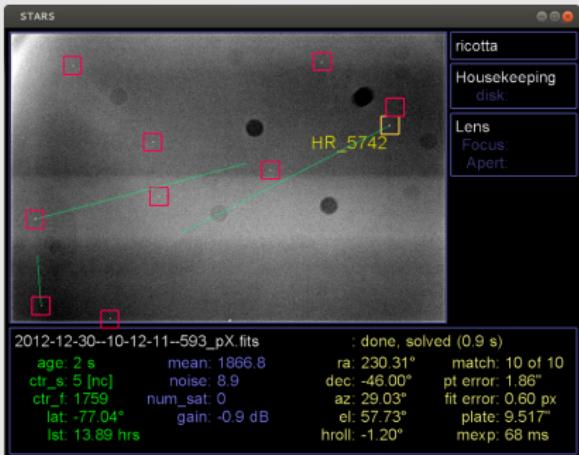
- Gyroscopes
- Inertial Mass Units (IMUs)
- Other Inertial Navigation Systems (INS)

Attitude Sensors:

- Horizon Sensor (IR earth horizon sensor)
- Gyrocompass
- Sun Sensor
- Earth Sensor
- Star Tracker
- Magnetometer (Compass)

- There are many varieties and methods for attitude control of spacecraft.
- 3-axis Stabilization
 - ▶ Thrusters ($1^\circ - 5^\circ$)
 - ▶ Control-Mass Gyroscopic (CMG) ($0.001^\circ - 1^\circ$)
 - ▶ Momentum wheels (Reaction wheels) ($0.001^\circ - 1^\circ$)
 - Spin Stabilization ($1^\circ - 1^\circ$)
 - ▶ Also good for pre-inversion.
 - Gravity-Gradient Stabilization (0°)
 - Magnetic Torquers (0°)

Let's go through a few of these.



<http://www.cubesatpointing.com/>
<https://www.cubesatshop.com/>
<https://www.clyde.space>

No Control (Lageos, ECHO)



Figure: LAGEOS Geodesy Satellite



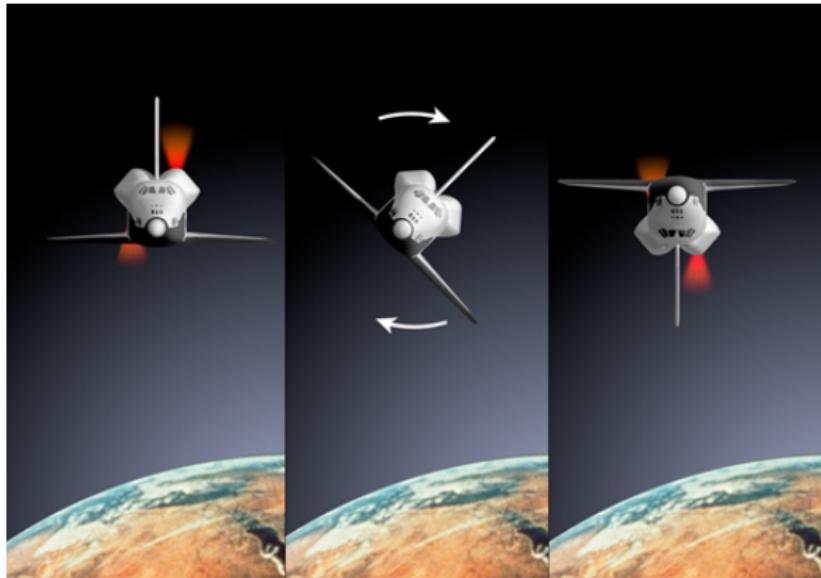
Figure: ECHO II communication satellite

Mechanisms for Attitude Control

Thrusters

Thrusters are grouped in pairs in order to provide pure moment

- no change in orbit.



- Thrusters are typically bang-bang
- Provide discrete units of angular momentum (spin up).

$$\Delta h = F \Delta x \Delta t$$

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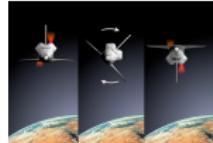
└ Mechanisms for Attitude Control

Mechanisms for Attitude Control

Thrusters

Thrusters are grouped in pairs in order to provide pure moment

- * no change in orbit.



- Thrusters are typically bang-bang

- Provide discrete units of angular momentum (spin up).

$$\Delta\dot{\theta} = F\Delta r \Delta t$$

- Space Shuttle used 6 paired Vernier thrusters.

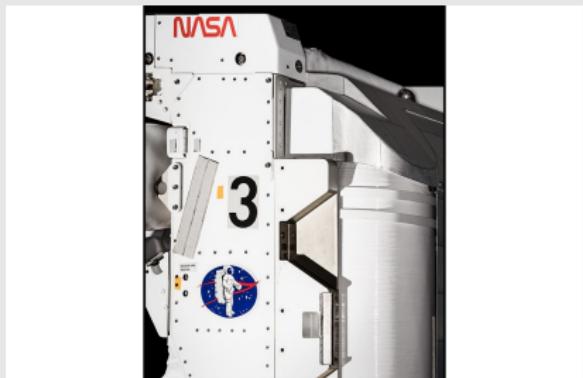


Figure: Thrusters on MMU



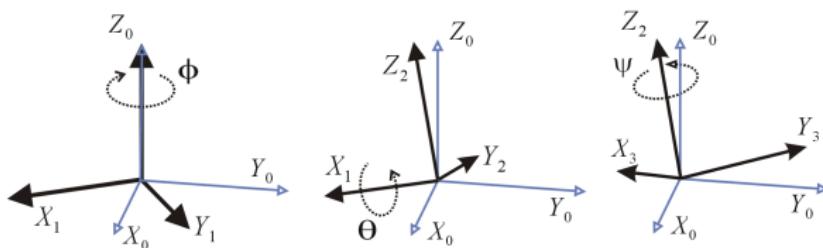
Figure: Cold Gas Thruster

Mechanisms for Control

Thrusters

Thrusters may alter orientation and angular velocity.

- e.g. Through rotation matrices



Only two sets of thrusters are needed to achieve any orientation (Euler Angles).

1. Rotate about \hat{b}_3 until \hat{b}_1 lines in $\hat{a}_2 - \hat{a}_1$ plane.
2. Rotate about \hat{b}_1 until \hat{b}_2 lines in $\hat{a}_2 - \hat{a}_1$ plane.
3. Rotate about \hat{b}_3 until $\hat{b}_1 = \hat{a}_1$ and $\hat{b}_2 = \hat{a}_2$.

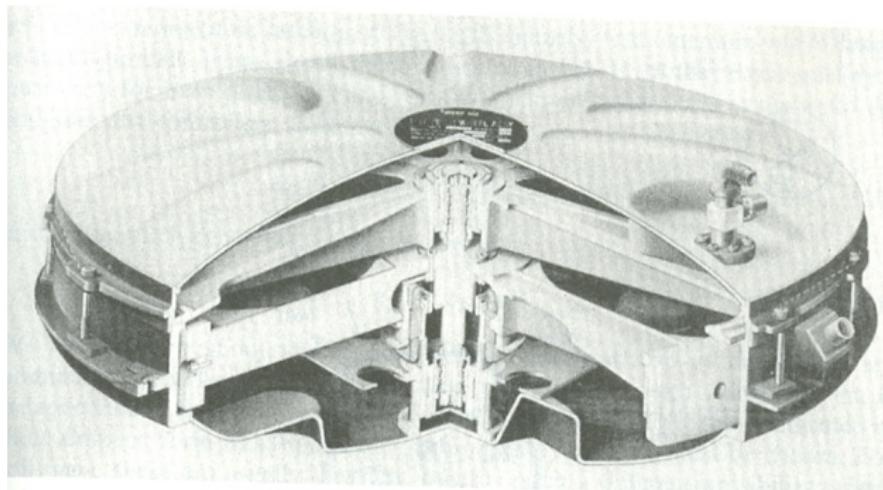
Usually better to have 3 sets of thrusters to minimize fuel

- Otherwise small changes can lead to big rotations.

Mechanisms for Control

Reaction wheels (Momentum Exchange Device)

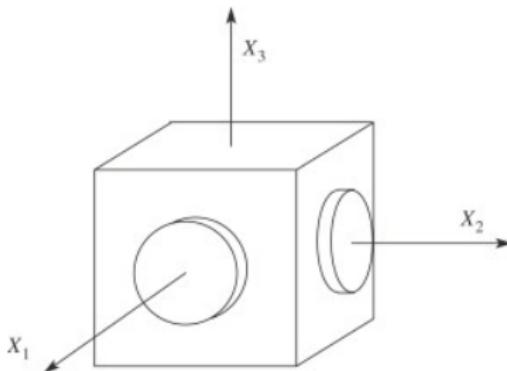
Because thrusters are not extremely accurate, they are rarely used to control the finer motions of attitude.



Reaction wheels: A momentum exchange device uses torque to spin up a wheel. An equal and opposite amount of torque is imparted to the spacecraft. The resulting angular momentum of the wheel and craft are then equal in magnitude and opposite in direction.

Mechanisms for Control

Reaction wheels



Dynamics: Consider rotation about the x -axis.

- Let J_x be the moment of inertia of the Spacecraft about the x -axis.
- Let I_x be the moment of inertia of the flywheel.
- By conservation of angular momentum:

$$I_x(\omega_f + \omega_s) + J_x\omega_s = 0$$

- ▶ ω_s is the angular velocity of the the craft in inertial space.
- ▶ ω_f is the angular velocity of flywheel w/r to the craft.

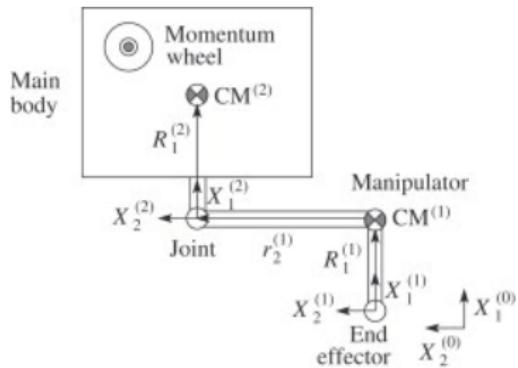
Mechanisms for Control

Reaction wheels

Figure: Spacecraft rotation via 3-1-3 Euler Angles

Mechanisms for Control

Reaction Wheels



So if the craft has some velocity ω_s in the \hat{b}_1 -direction and the reaction wheel is aligned with this axis, we can null out the velocity by spinning up to

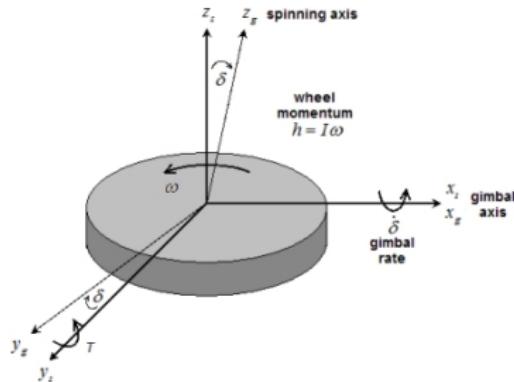
$$\omega_f = -\frac{J_x \omega_s + I_x \omega_s}{I_x} = -\frac{J_x + I_x}{I_x} \omega_s.$$

If we have reaction wheels in the \hat{b}_2 and \hat{b}_3 directions, we can create any angular velocity vector.

- Flywheels can be used to correct for small deviations (Telescopes).
 - ▶ However, accumulated momentum may cause the flywheels to spin too fast.
 - ▶ Will need to eventually find a way to dump momentum.

Mechanisms for Control

Control Moment Gyros (CMGs)



Control Moment Gyros are different from reaction wheels in that they have a fixed rate of rotation (ω_{CMG})

- Thus the magnitude of the angular momentum vector, $\|\vec{h}\|$ will be fixed.
- The direction of the angular momentum vector will vary, however.

Single Gimbal Control is achieved by rotation of the gyroscope through an angle δ .

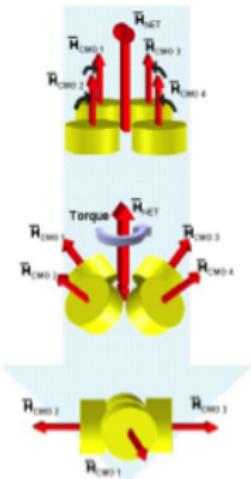
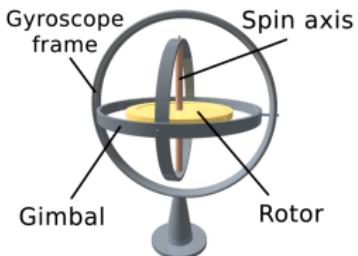
- This can only be used for 2-axis stabilization

Single-Gimbal Control Moment Gyro

Figure: Effect of Single Control Moment Gyro

Dual-Gimbal Control Moment Gyro

Alternatively, a dual-gimbal CMG may be used



Suppose

- The initial angular momentum vector of the CMG is \bar{h}
- The desired angular momentum vector of the spacecraft is \bar{h}_d
- The final position vector of the CMG is $R_3(\theta_3)R_1(\theta_2)R_3(\theta_1)\bar{h}$

By conservation of angular momentum

$$\bar{h} = \bar{h}_d + R_3(\theta_3)R_1(\theta_2)R_3(\theta_1)\bar{h}$$

└ Dual-Gimbal Control Moment Gyro

Dual-Gimbal Control Moment Gyro

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- The final position vector of the CMG is $R_3(\theta_3)R_1(\theta_1)R_2(\theta_2)R_3(\theta_3)\vec{h}$

By conservation of angular momentum

$$\vec{h} = \vec{h}_d + R_3(\theta_3)R_1(\theta_1)R_2(\theta_2)R_3(\theta_3)\vec{h}$$

If ω is rotation vector of the craft, T_{ext} is external torque

$$\dot{H}_s + \omega \times H_s = T_{ext}$$

and H_s is total angular momentum (To be derived in next lecture). Then if J is the inertia tensor of the craft

$$H_s = J\omega + h$$

where h is the CMG angular momentum. If u is the internal torque applied to the CMG, then

$$J\dot{\omega} + \omega \times J\omega = u + T_{ext}, \quad \dot{h} + \omega \times h = -u$$

Dual-Gimbal Control Moment Gyro

Definition 1.

Given \bar{h} , the **Momentum Envelope** is set of solutions of

$$\bar{h}_d = (I - R_3(\theta_3)R_1(\theta_2)R_3(\theta_1))\bar{h}$$

for some set of Euler rotations, $\theta_1, \theta_2, \theta_3$.

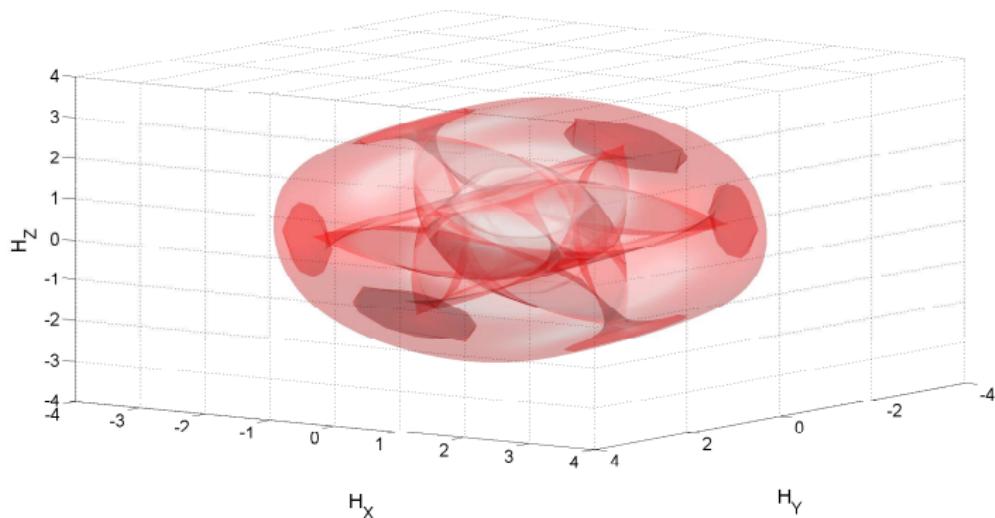
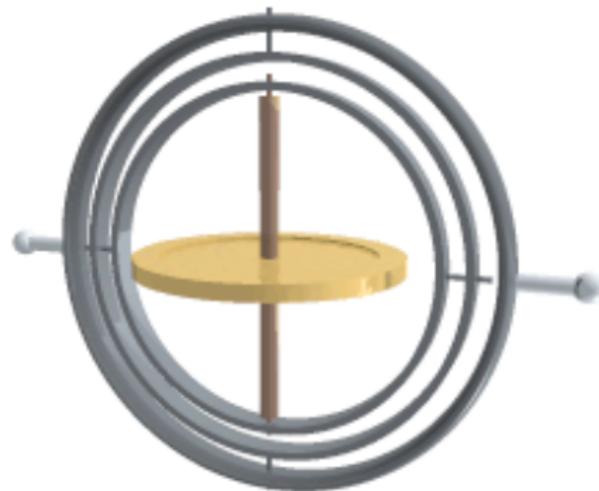
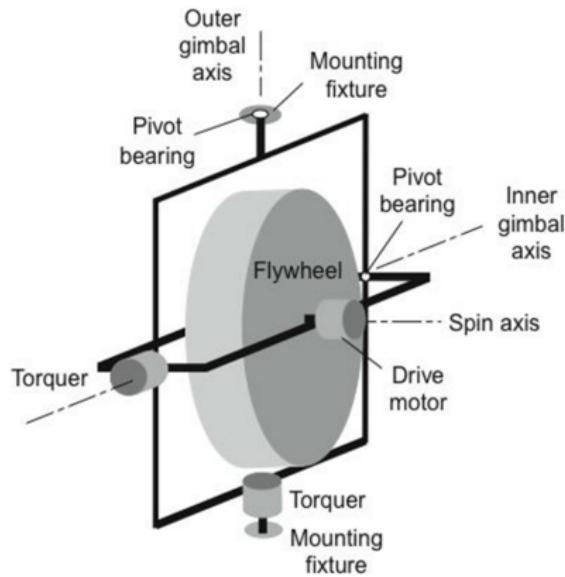


Figure: Momentum Envelope for a pyramidal 4-CMG array. Note the singularities.

Dual-Gimbal Control Moment Gyro

The effect of the singularities is most easily understood as **Gimbal Lock**

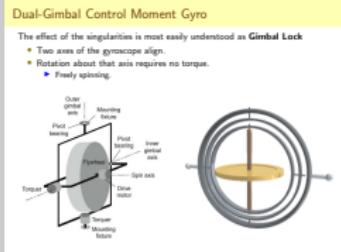
- Two axes of the gyroscope align.
- Rotation about that axis requires no torque.
 - ▶ Freely spinning.



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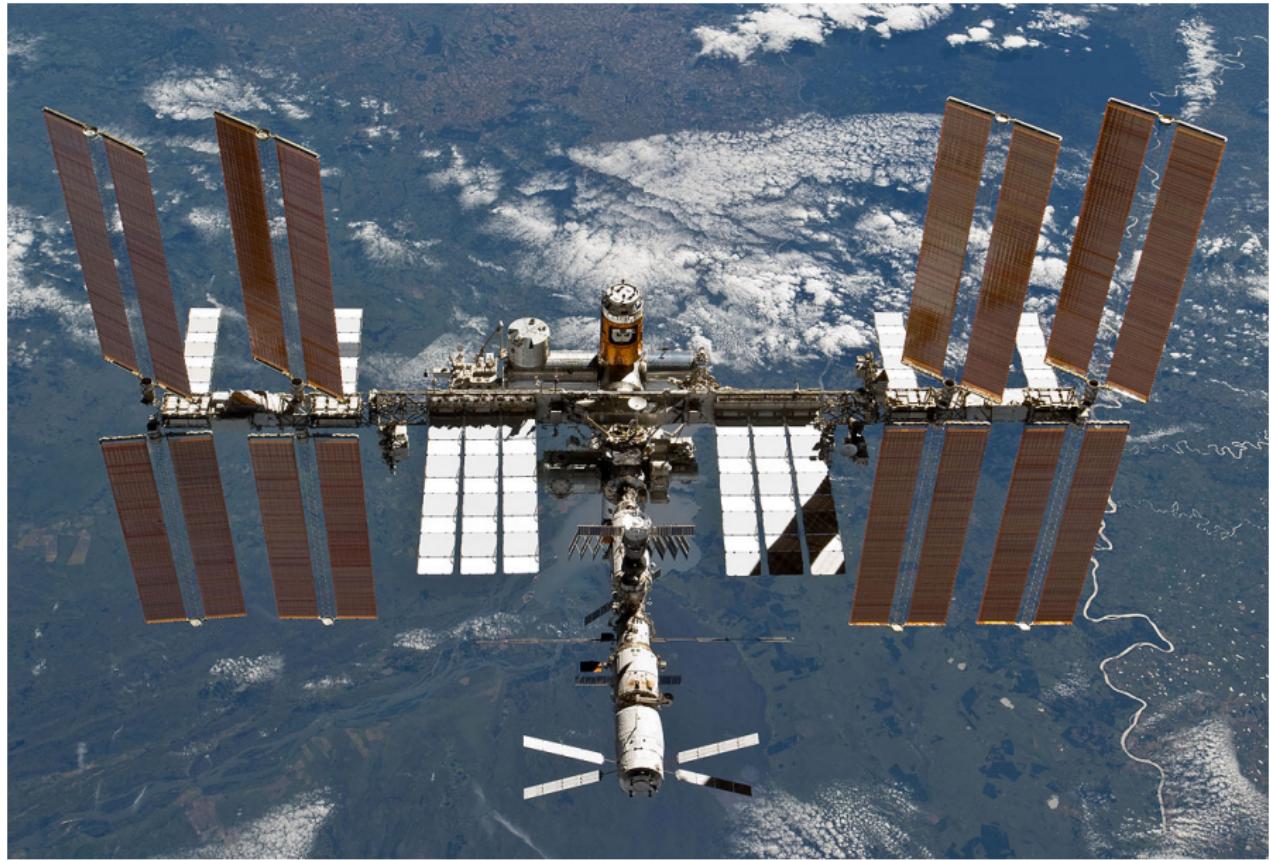
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└ Dual-Gimbal Control Moment Gyro



Youtube video on Gimbal Lock (See minute 4:20)

Control Moment Gyros on the International Space Station



Control Moment Gyros on the International Space Station

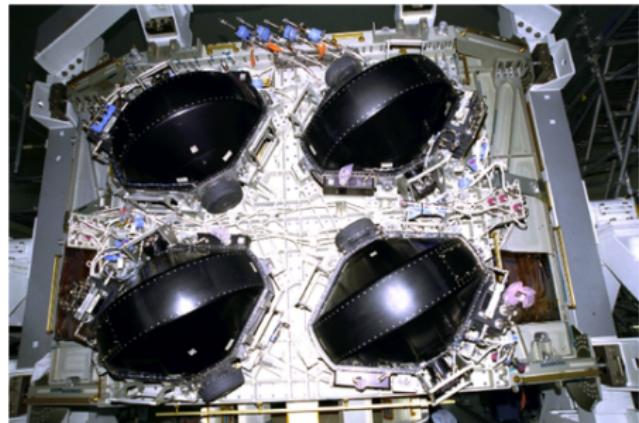


Figure: ISS Z1 truss with 4-CMG array

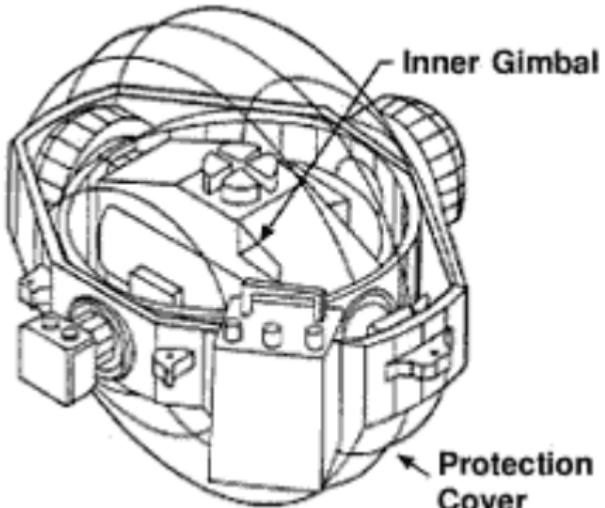


Figure: Cutaway of ISS CMG

The CMGs are double-gimbal, so hardware orientation is not important.

└ Control Moment Gyros on the International Space Station

Control Moment Gyros on the International Space Station



Figure: ISS Z1 truss with 4-CMG array

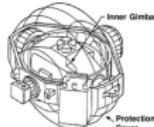
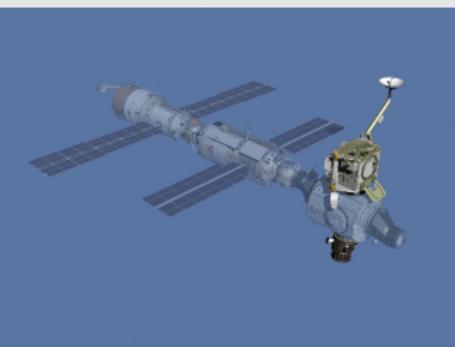


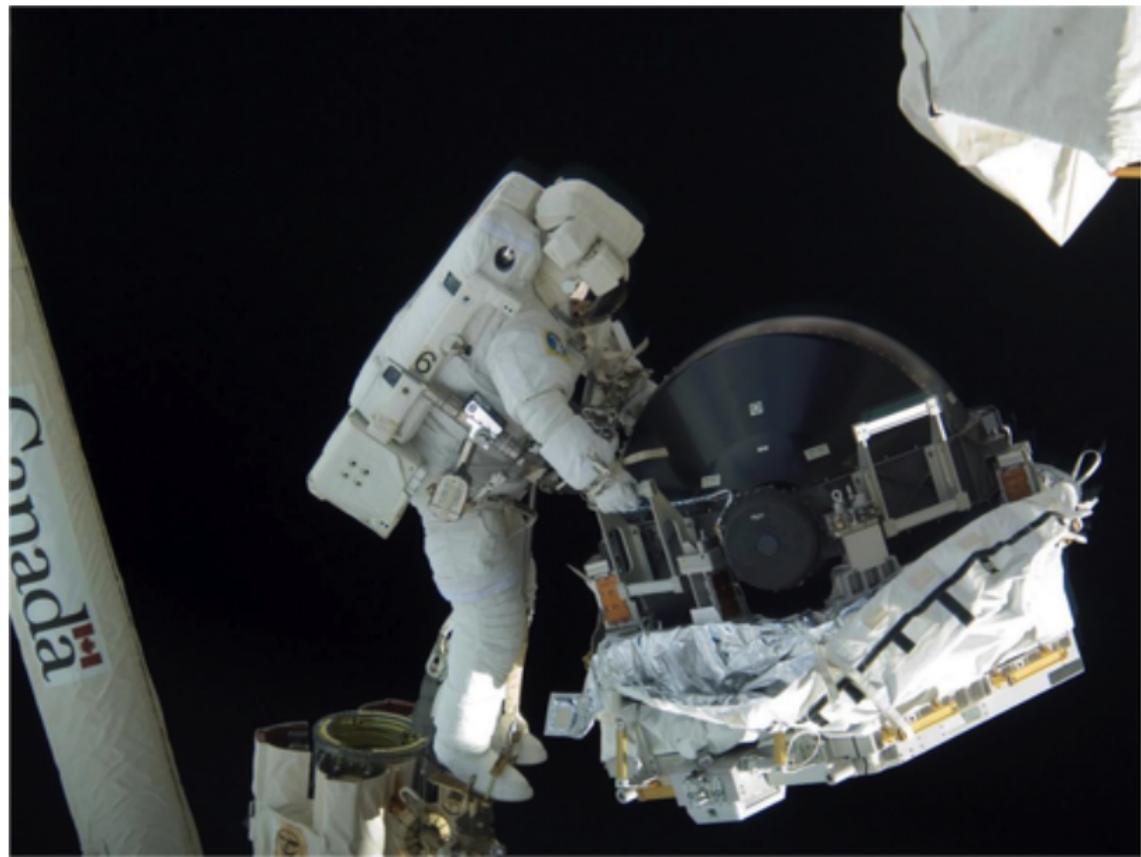
Figure: Cutaway of ISS CMG

The CMGs are double-gimbal, so hardware orientation is not important

- CMGs are located on Z1 truss.
- CMGs launched with Z1 truss in Oct. 2001.
- Activated Feb 2001 (previously thrusters were used for attitude)
- CMG1 failed June, 2002 - Replaced Aug, 2005
- Oct. 2006, CMG3 failed (sensor failure?) - replaced Aug. 2007
- Failure possibly due to large gimbal rates during desaturation. Bearing failure.



Replacement of CMG on the International Space Station



Control Moment Gyros on the International Space Station

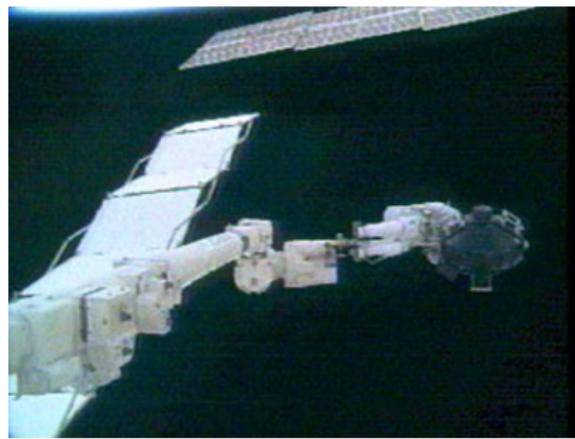


Figure: Replacement of CMG on ISS in 2005 (STS-114)



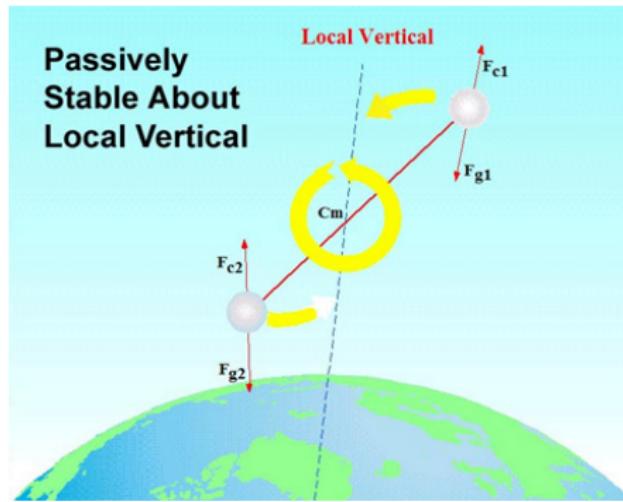
Mechanisms for Control

Gravity Gradient Stabilization

Gravitational attraction varies as

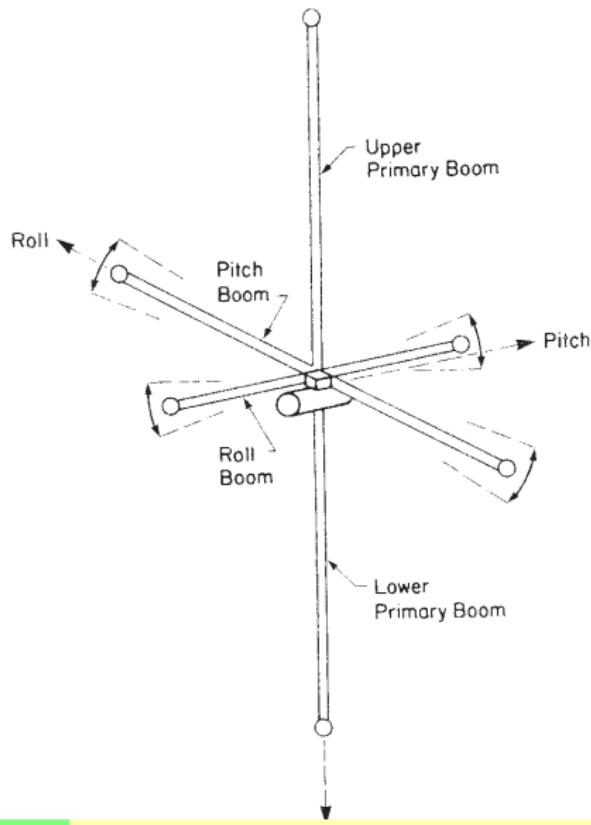
$$\|F\| = \frac{\mu m}{r^2}$$

For very long spacecraft, lower section will feel additional gravitational attraction.



Mechanisms for Control

Gravity Gradient Stabilization



Gravity Gradient Stabilization

Salyut 6



└ Gravity Gradient Stabilization



- Any spacecraft will tend to align its minimum moment of inertia axis with the radial vector.
- An extreme case is the use of space tethers (65N on TSS-1R).
 - Failure VERY common due to electrical discharge (TSS-1R), dynamic instabilities.
- ONR TiPS was a successful 4km tether, with lifetime of 10 years.
- TSS-1R failed at 19.7km and produced 15lb force

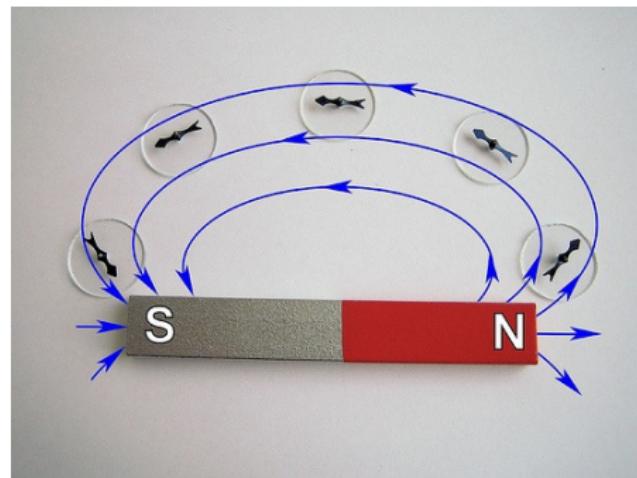
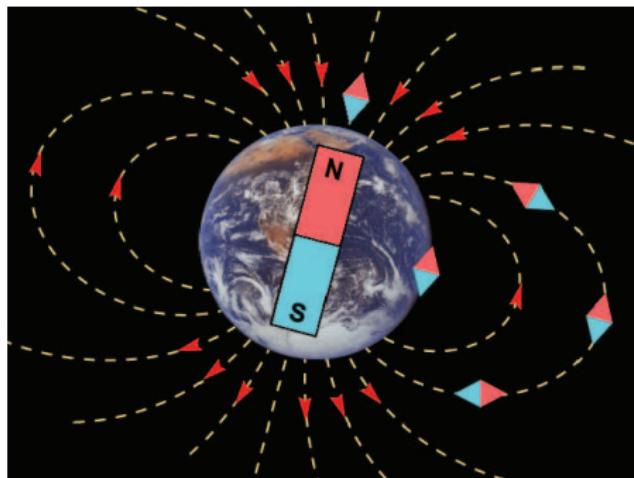


Magnetic Torquers

In addition to gravity, the **Magnetic Field** of the earth can be used to provide attitude control.

Idea: The earth has a magnetic field, $\vec{B}_e(x, y, z)$.

- the interaction of two magnets produces force



What if we put a magnet on the spacecraft?

- Turn it into a giant flying compass.

Magnetic Torquers

Instead of using fixed magnets, we use electromagnets to create an arbitrary magnetic dipole moment, \vec{M} for the spacecraft.

Maxwell's Equations lead us to

$$\vec{T} = \vec{M} \times \vec{\mathbf{B}}_e$$

Thus

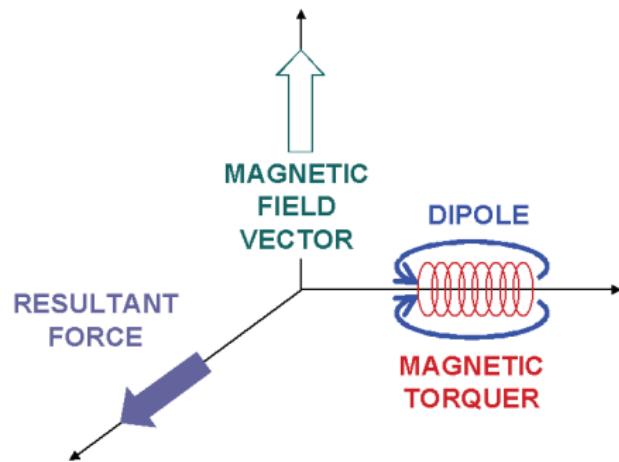
$$\begin{bmatrix} T_x \\ T_y \\ T_z \end{bmatrix} = \begin{bmatrix} 0 & B_z & -B_y \\ -B_z & 0 & B_x \\ B_y & -B_x & 0 \end{bmatrix} \begin{bmatrix} M_x \\ M_y \\ M_z \end{bmatrix}$$

Unfortunately,

$$\begin{bmatrix} 0 & B_z & -B_y \\ -B_z & 0 & B_x \\ B_y & -B_x & 0 \end{bmatrix}$$

is not invertible.

- Magnetic fields cannot rotate the spacecraft about a field-line.
- Pitch or Yaw forces - No Roll.
- Makes Control Difficult



Lecture 15

└ Magnetic Torquers

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Note how we represent the cross-product as matrix multiplication:

$$\vec{M} \times \vec{B}_e = \begin{bmatrix} 0 & B_z & -B_y \\ -B_z & 0 & B_x \\ B_y & -B_x & 0 \end{bmatrix} \begin{bmatrix} M_x \\ M_y \\ M_z \end{bmatrix}$$

Magnetic Torquers

The magnetic dipole moment is created by torque-rods.



Unfortunately the magnitude of the torque is limited by:

- The magnitude of earth's magnetic field is inversely proportional to radius.

$$\|\mathbf{B}_e\| \cong \frac{7.96 \cdot 10^{15} Wb - m}{r^3}$$

- The magnetic dipole of the torque rod ($\|M\| \cong 10Am^2 - 100Am^2$).
- The angle to the field line (α).

$$T = \|M\| \|B\| \sin \alpha$$

Magnetic Torquers

In a 400km orbit with a $100A - m^2$ dipole at 30° field orientation, we can obtain a torque of

$$T = \frac{7.96 \cdot 10^{15}}{6778000^3} \cdot 100 \cdot \sin(30^\circ) = 1.28 \cdot 10^{-3} N \cdot m$$



Magnetic Torque is not typically used for active attitude control.

- Used to dump angular momentum over time from
 - ▶ Reaction Wheels
 - ▶ CMGs
- Combined with momentum wheel for roll-control.

Lecture 15

2020-04-19

└ Magnetic Torquers

Magnetic Torquers

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Small Satellite ACDS kits:

<http://www.cubesatpointing.com/>

<https://www.cubesatshop.com/>

<https://www.clyde.space>

Solar Sail Stabilization

Multi-Functional Transport Satellite (MTSAT)

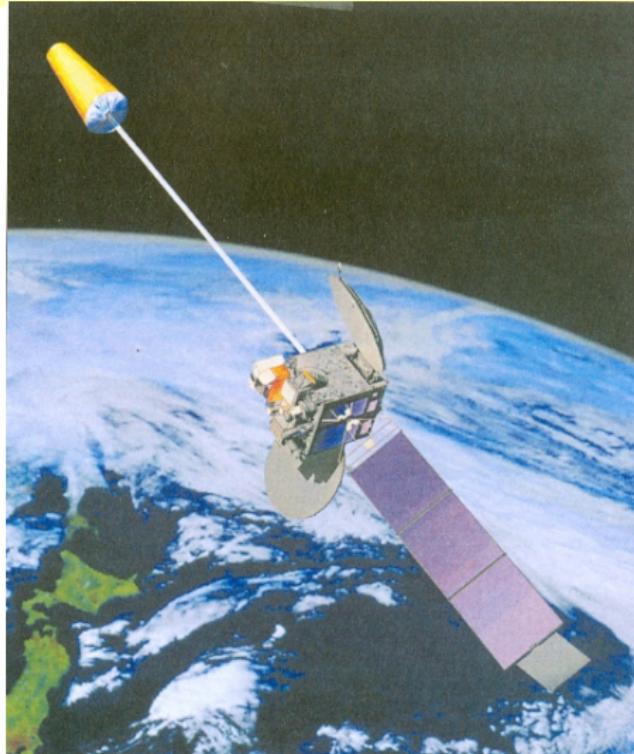


Figure: Japanese Air-traffic Control/Navigation/Meteorology Satellite MTSAT

Lecture 15

└ Solar Sail Stabilization



The rescue mission for the Kepler space telescope was based on combining solar sail (the body) with 2 functioning reaction wheels.

Mechanisms for Control

Spin Stabilization

Historically, the most common form of stabilization have been spin stabilization.

Idea: Give the craft an angular momentum vector which is fixed in the body-fixed axis.

- Think of rifles vs. muskets

Positives:

- By Newton's second Law: A large angular momentum vector requires large torques to change.
- Very little active maintenance required.

Negatives:

- Spin motion complicates communication, solar power, navigation, etc.
- Changing attitude after spin-up is very difficult.
- Angular momentum vector is not fixed in the body-axes!
 - ▶ We will study this issue in more detail.

Pioneer Venus Orbiter (1978-1992)



Mapping/Communication. Dual-Spin Stabilized. **Orbit:** Pericytherion: 181.6 km; Apocytherion: 66,630 km; inclination 105° ; 24hr period

Lecture 15

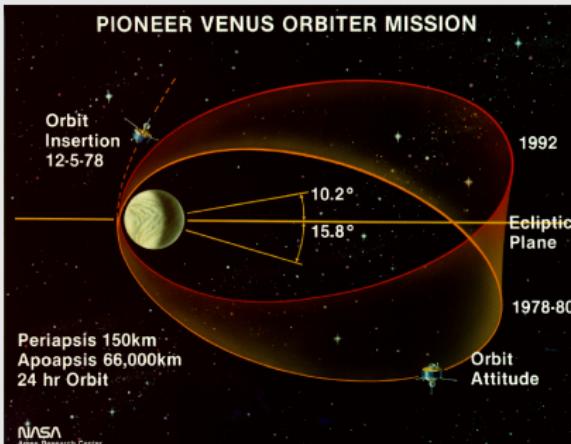
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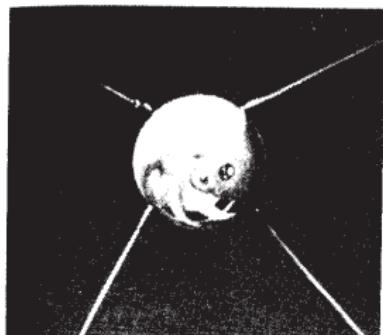
- Launch May 20, 1978
- Orbit insertion Dec 4, 1978
- Antenna dish was despun to allow contact with earth
- Periapse temporarily raised to 2300km
- Re-entry on Oct 22, 1992
- Orbit change on arrival of Magellan (to observe southern hemisphere)



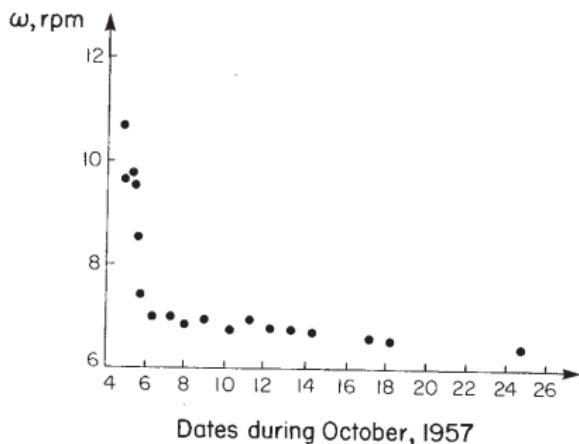
Mechanisms for Control

Spin Stabilization

Spin stabilization can decay.



(a) Sputnik 1



(b) Spin Rate Data, based on [Beletskii]

Figure: Decay in Spin Control of Sputnik I Satellite

Cause: Atmospheric Motoring

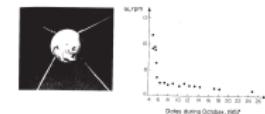
- See Also Explorer 20 and Alouette 1 data

Mechanisms for Control

Mechanisms for Control

Spin Stabilization

Spin stabilization can decay.



4.1.1 Sputnik 1

[1] Sam Newcomer, American [2] NASA]

Figure: Decay in Spin Control of Sputnik 1 Satellite

Cause: Atmospheric Motoring

• See Also Explorer 20 and Alouette 1 data

- In Modern spacecraft, spin stabilization is typically used at separation from upper stage.
- Spacecraft use yo-yo despin for transition to operational status.

Conclusion

In this lecture we have covered:

- Mission Requirements
- Forms of Attitude Control

Next Lecture:

Equations of Motion

- How to differentiate Vectors in Rotating Frames
- Derivation of the Nonlinear 6DOF Equations of Motion

Euler Angles

- Definition of Euler Angles
- Using Rotation Matrices to transform vectors
- Derivatives of the Euler angles
 - ▶ Relationship to p - q - r in Body-Fixed Frame