Attitude Determination And Control

AERO0025 – Satellite Engineering

tjorven.delabie@kuleuven.be

OVERVIEW

- Introduction
- Rationale
- Attitude Requirements and Errors
- Governing Equations
- Attitude Parameterization
- Disturbance Torques
- Passive Control
- Active Control
- Going Further
- I am interested, what now?

INTRODUCTION

What is Attitude Determination and Control?

INTRODUCTION

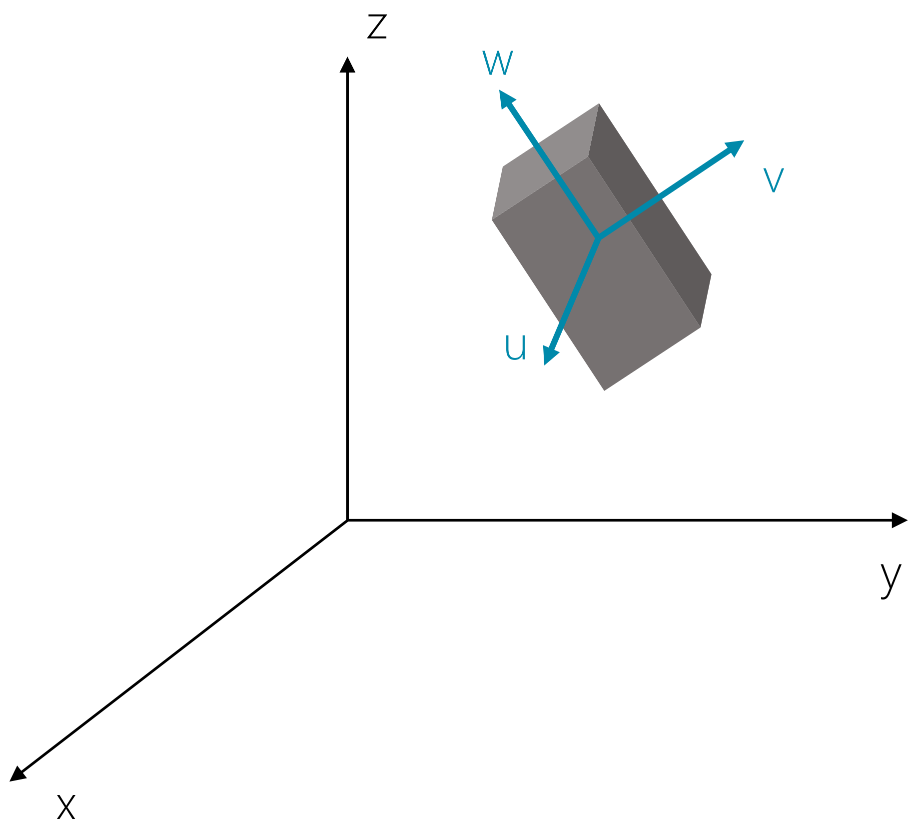
What is attitude?

"The word around the office is that you have an attitude problem. ..."

INTRODUCTION
What is attitude?

The orientation of a spacecraft in space is called its attitude.

The angular orientation of a body-fixed coordinate frame with respect to an external frame

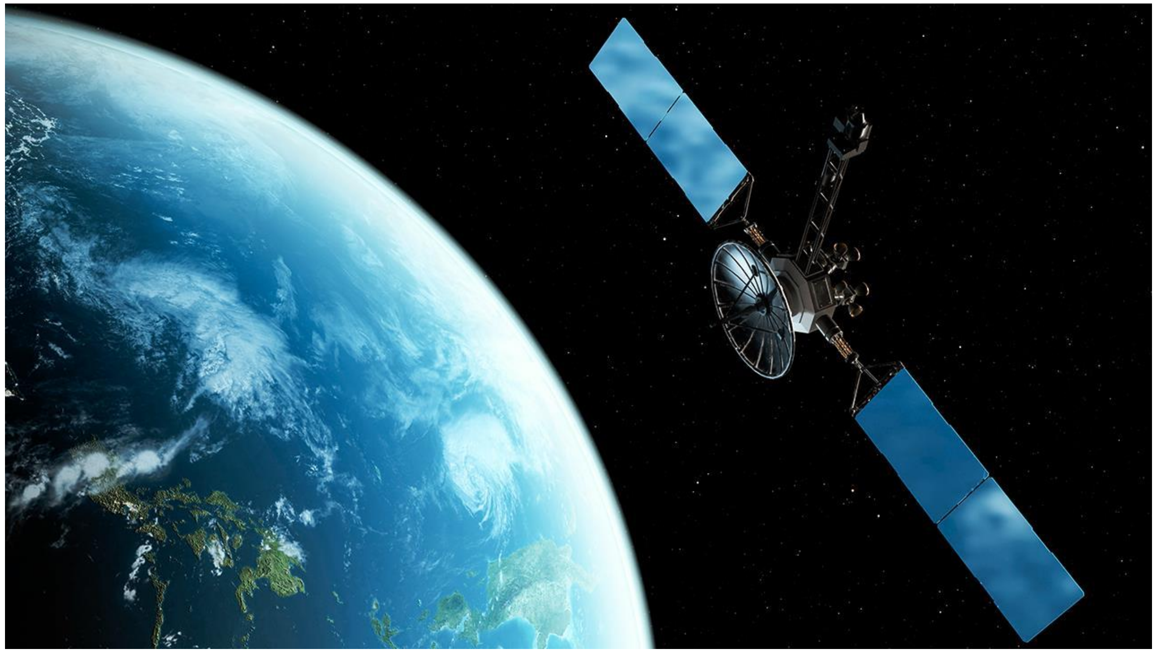


Reference frame (can be an inertial frame)
Satellite body frame

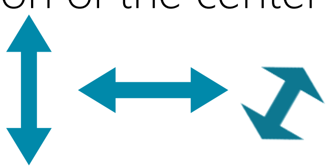
INTRODUCTION

Attitude Determination and Control

A rigid body satellite in space has 6 Degrees of Freedom



- Translation
- Linear momentum
- Motion of the center of mass



- Rotation
- Angular momentum
- Motion relative to the center of mass

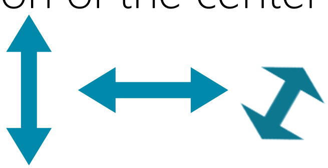
INTRODUCTION

Attitude Determination and Control

AOCS: Attitude and Orbit and Control System

ADCS: Attitude Determination and Control System

- Translation
- Linear momentum
- Motion of the center of mass

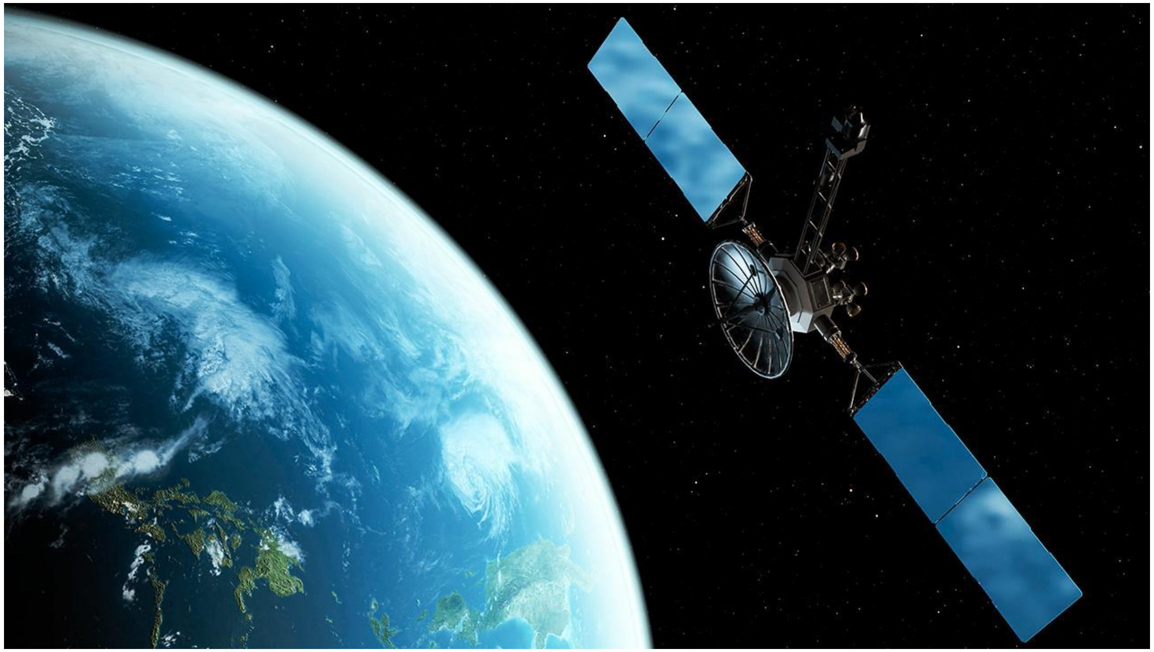


- Rotation
- Angular momentum
- Motion relative to the center of mass

INTRODUCTION

Attitude Determination and Control

A rigid body satellite in space has 6 Degrees of Freedom



During this lecture, we will not care about the position of the spacecraft, but about its orientation

- Rotation
- Angular momentum
- Motion relative to the center of mass

OUR FOCUS

INTRODUCTION

Side note about interdependency of attitude and orbit

For example

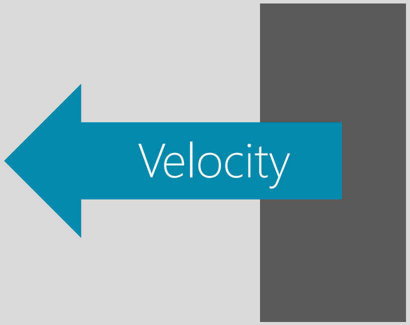
1. In LEO, the attitude will affect the atmospheric drag which will affect the orbit

2. The orbit determines the spacecraft position which determines both the atmospheric density and the magnetic field strength, which will, in turn, affect the attitude

But this dynamic coupling is often ignored, and the time history of the spacecraft position is assumed to be known and to be an input for ADCS

This coupling can even be used on purpose: (Limited) orbit control using differential drag.

Less drag



More drag

OVERVIEW

- Introduction
- Rationale
- Attitude Requirements and Errors
- Governing Equations
- Attitude Parameterization
- Disturbance Torques
- Passive Control
- Active Control
- Going Further
- I am interested, what now?

RATIONALE

Why do we need Attitude Determination and Control?

RATIONALE

Usages for attitude determination and control

Almost all spacecraft missions require attitude determination and control.

Point Antennas

The antenna needs to be pointing towards the ground station.

Higher accuracy →
More data

Point Solar Panels

The solar panels needs to be pointing towards the Sun.

Higher accuracy →
More power

Point Payloads

The payload needs to be pointing towards the point of interest.

Higher accuracy →
Better results

OVERVIEW

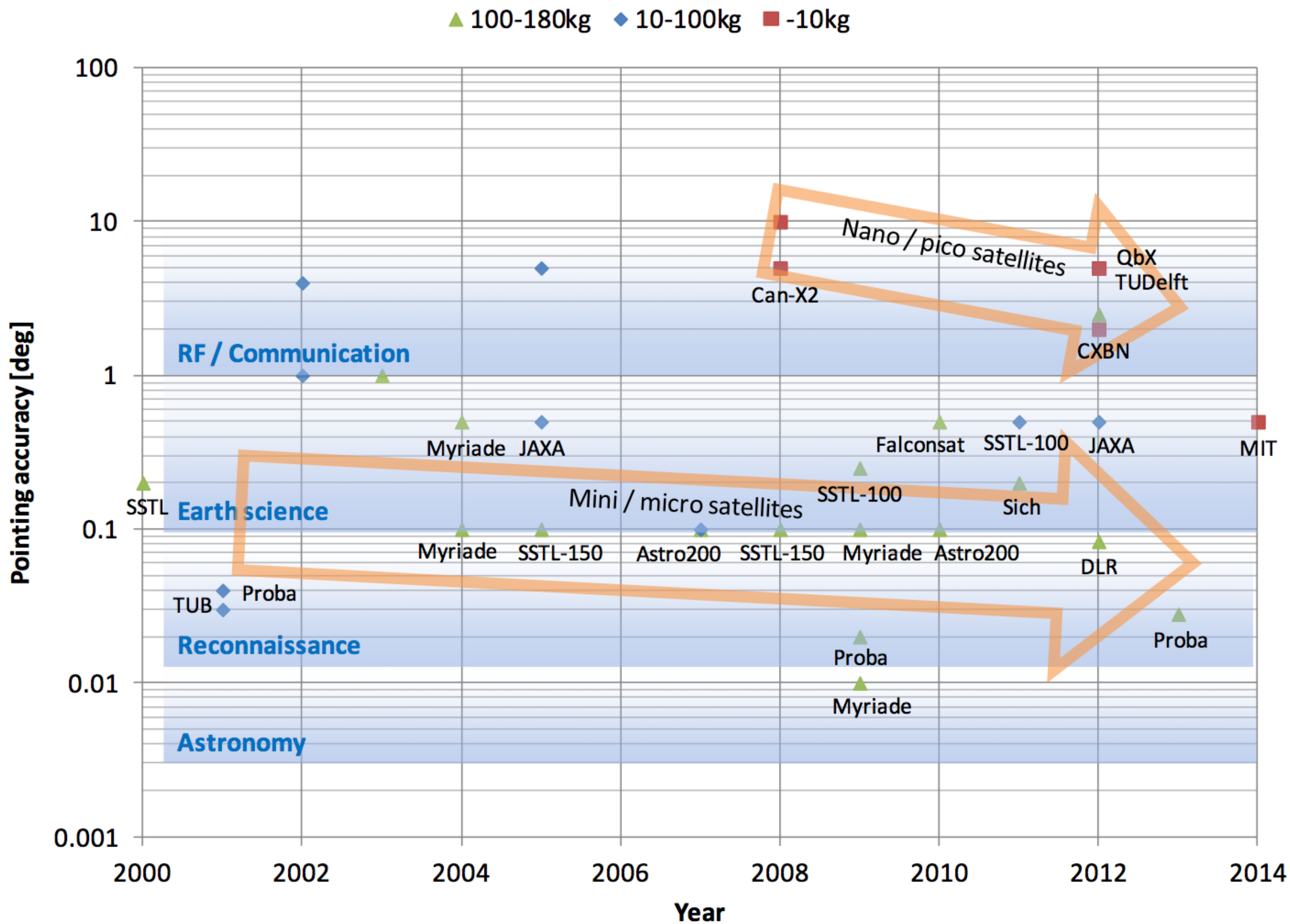
- Introduction
- Rationale
- Attitude Requirements and Errors
- Governing Equations
- Attitude Parameterization
- Disturbance Torques
- Passive Control
- Active Control
- Going Further
- I am interested, what now?

ATTITUDE REQUIREMENTS AND ERRORS

What pointing requirements do missions have and how do we define them?

ATTITUDE REQUIREMENTS AND ERRORS

Mission attitude requirements

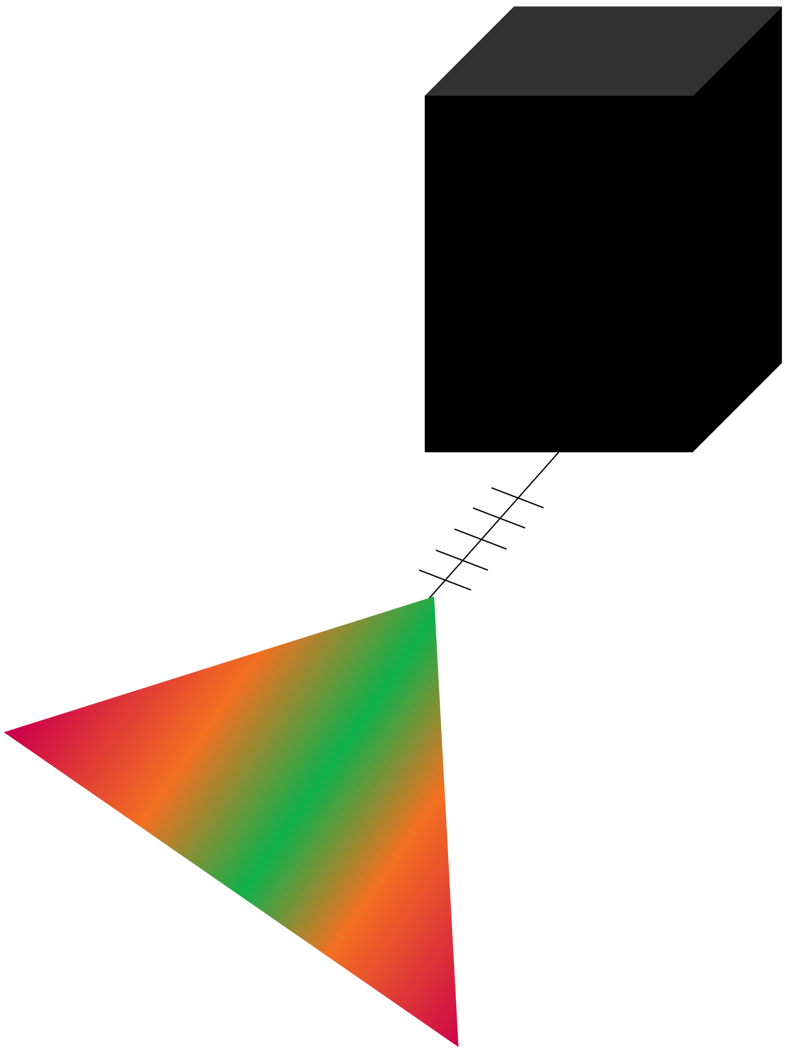


ATTITUDE REQUIREMENTS AND ERRORS

Communications

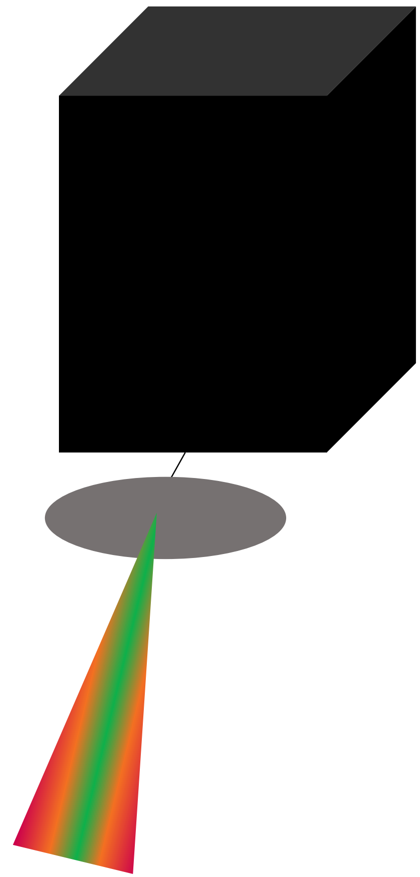
Wide beam low gain

Requirement: Several degrees



Narrow beam high gain

Requirement: <= 1 degree



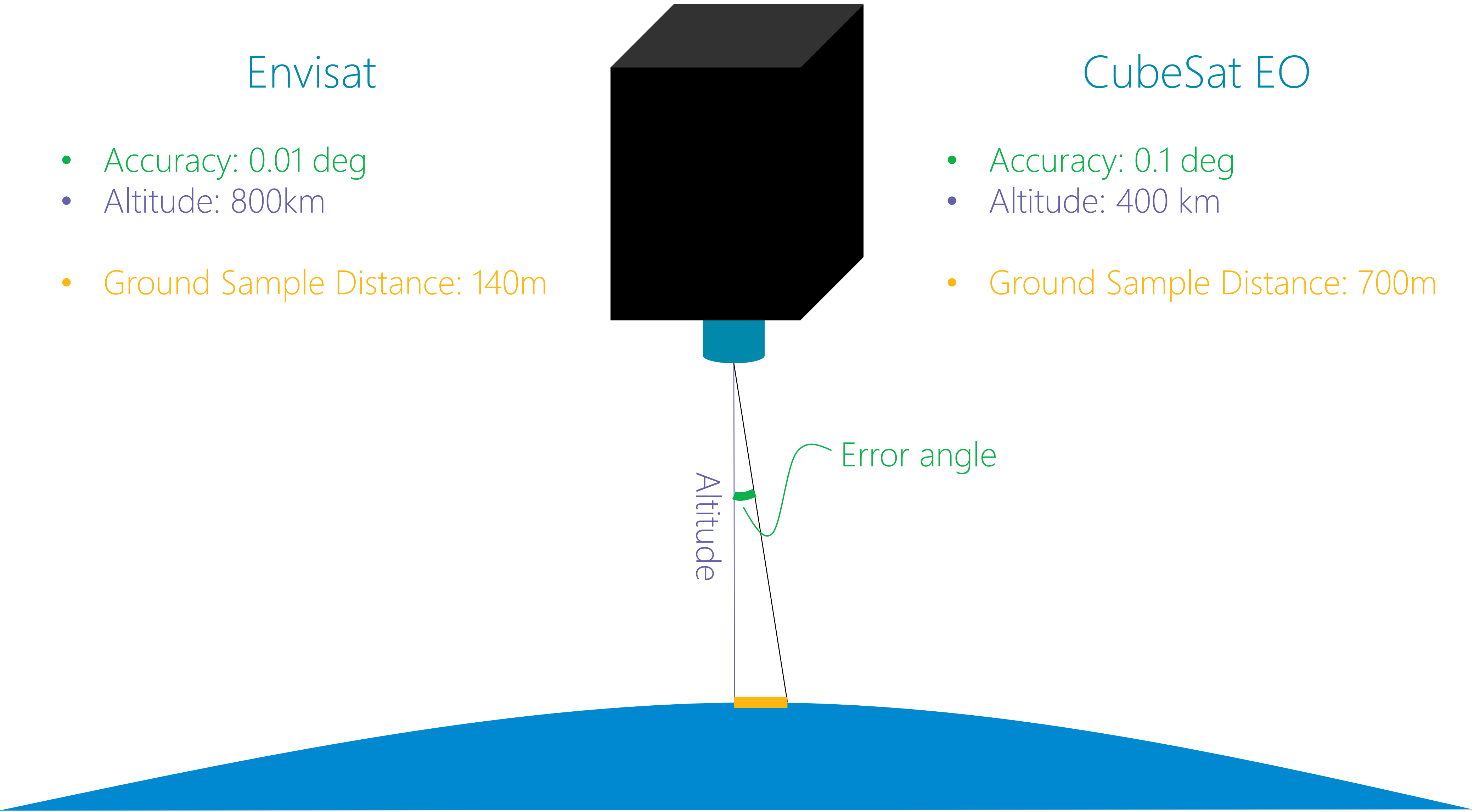
ATTITUDE REQUIREMENTS AND ERRORS

Earth Science

Envisat

- Accuracy: 0.01 deg
- Altitude: 800km

- Ground Sample Distance: 140m



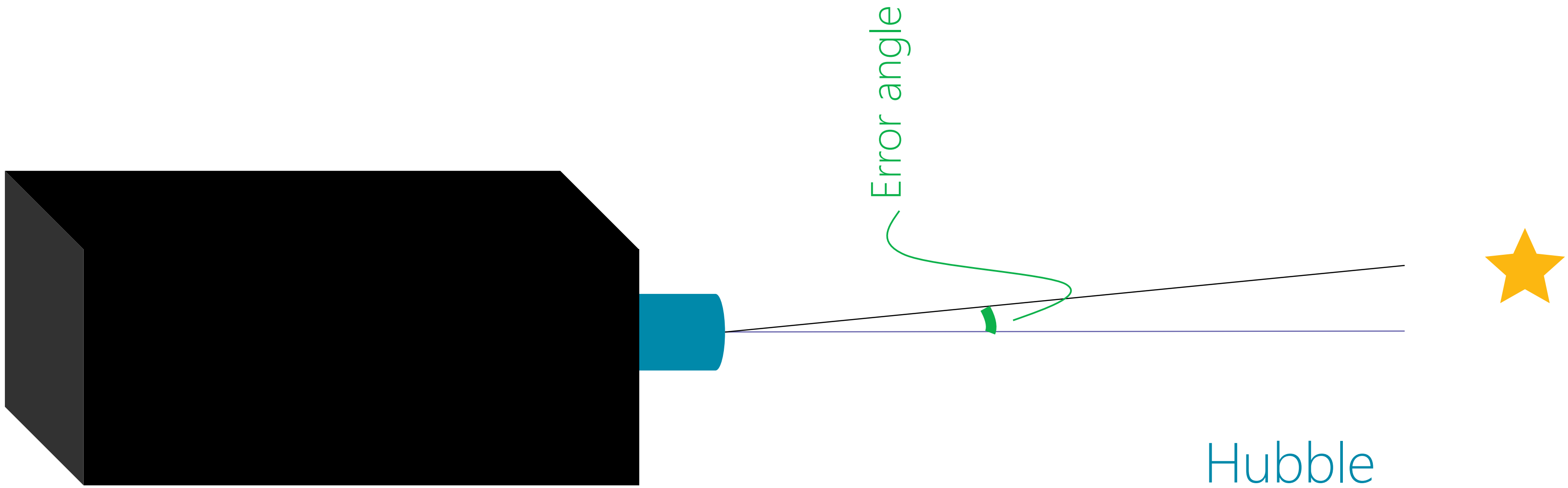
CubeSat EO

- Accuracy: 0.1 deg
- Altitude: 400 km

- Ground Sample Distance: 700m

ATTITUDE REQUIREMENTS AND ERRORS

Astronomy



Hubble

- Accuracy: 0.1 arc second

If you would give Hubble a laser pointer, it could hit the center of an archery target from 250 km away.

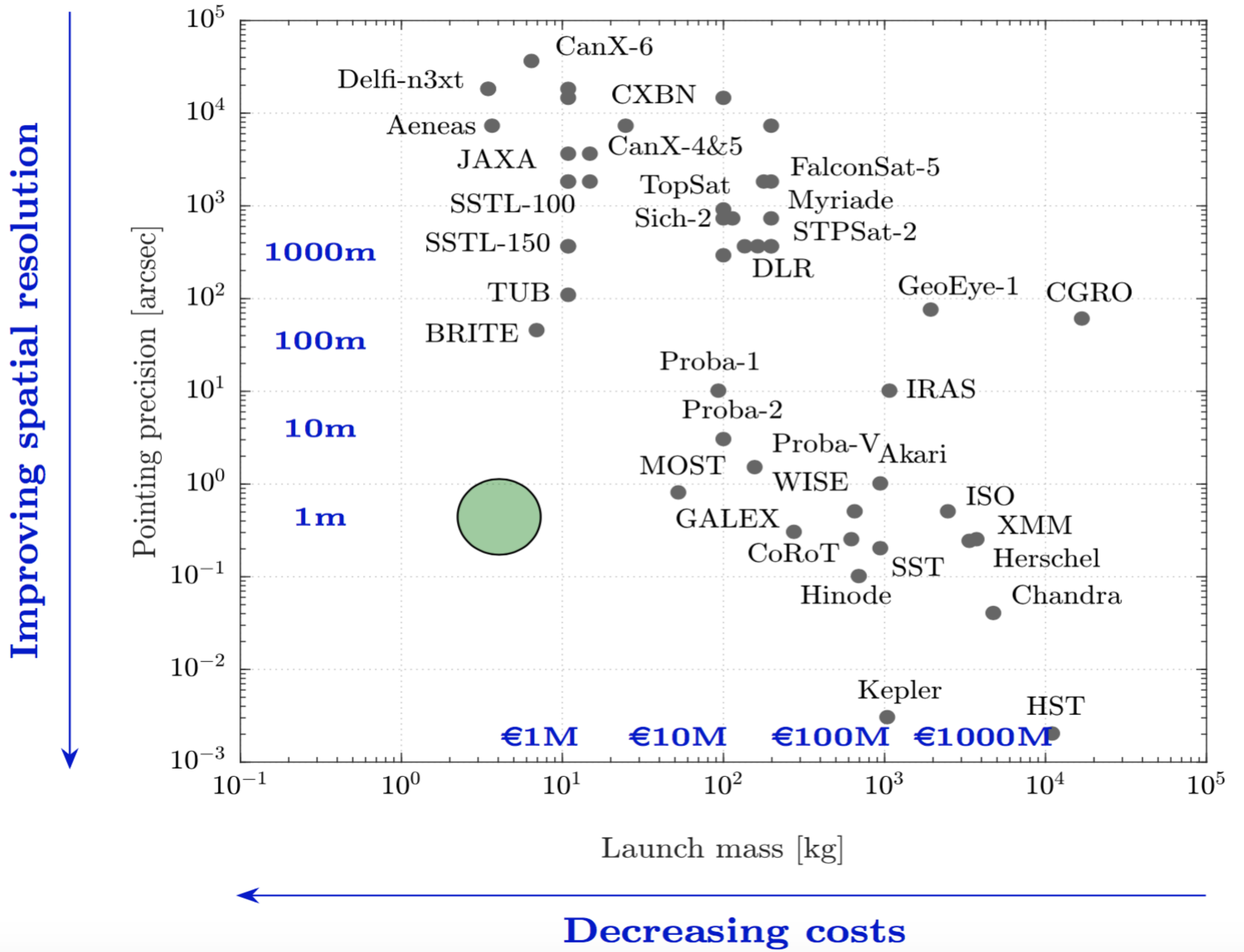
One arc second is 1/3600th of a degree.

- If a cake is split in pieces with an angle of 60 degrees, you have six pieces.
- If a cake is split in pieces with an angle of one arc second, you have 1.296.000 pieces.

Every inhabitant of the province of Liege could get a piece.

ATTITUDE REQUIREMENTS AND ERRORS

Pointing accuracy state of the art



ATTITUDE REQUIREMENTS AND ERRORS

Pointing Errors

Absolute Pointing Error (APE) → Accuracy

Dark black line

The actual pointing error at a given time t.

Windowed mean over period T

Horizontal black line

The mean of the pointing error over a period T.

Relative Pointing Error (RPE) → Jitter

The pointing error relative to the windowed mean.

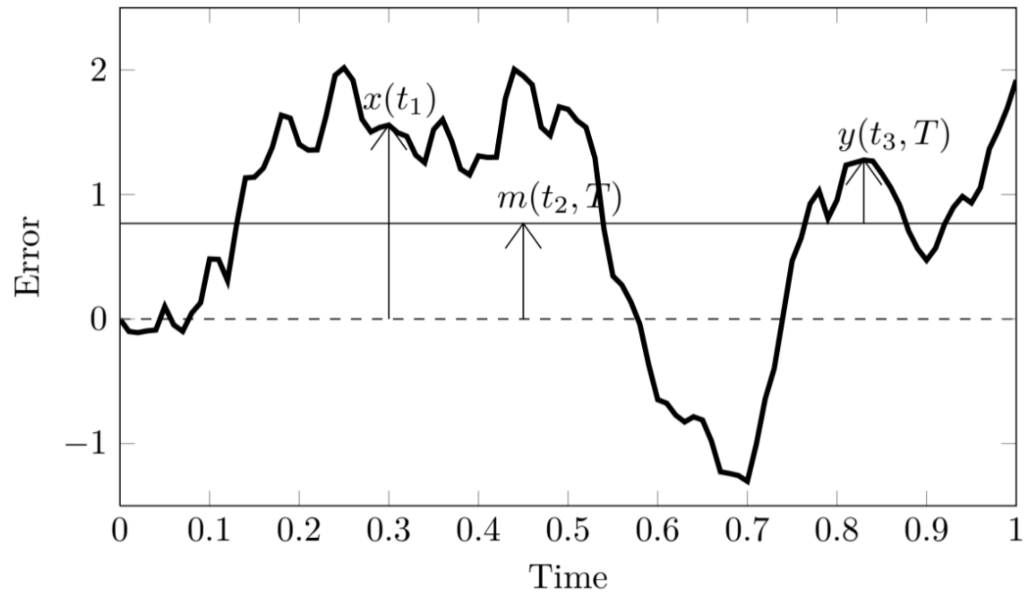


Illustration of the different performance metrics as seen within one window with length *T [1]*

[1] J. Vandersteen, "Observation and Estimation for Space Applications," KU Leuven, 2012

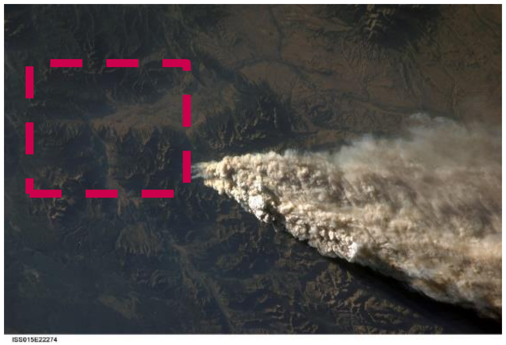
ATTITUDE REQUIREMENTS AND ERRORS

Pointing Errors Example: Disaster Monitoring

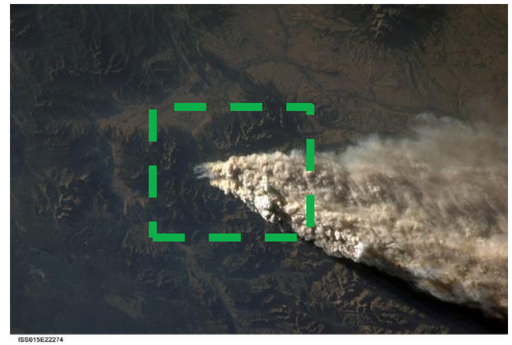
Absolute Pointing Error (APE) → Accuracy

The APE needs to be low enough, otherwise we are not looking at the correct scene.

High APE



Low APE



Relative Pointing Error (RPE) → Jitter

The RPE during the observation time (e.g. 1 second) needs to be low enough to get a stable picture.

High RPE

Low RPE

OVERVIEW

- Introduction
- Rationale
- Attitude Requirements and Errors
- Governing Equations
- Attitude Parameterization
- Disturbance Torques
- Passive Control
- Active Control
- Going Further
- I am interested, what now?

GOVERNING EQUATIONS

What equations describe the spacecraft attitude?

GOVERNING EQUATIONS

Key Concept: Angular Momentum

Fundamental quantity in rotational dynamics.

Moment of the linear momentum about a defined origin

$$\vec{H} = \sum_{i=1}^{n} \vec{H}_i = \sum_{i=1}^{n} \vec{r}_i \times m_i \vec{v}_i$$

The angular momentum of a particle referred to an inertially fixed point is only changed if the forces on it have a moment M about this fixed point.

$$\frac{d\vec{H}}{dt} = \vec{T}$$

GOVERNING EQUATIONS

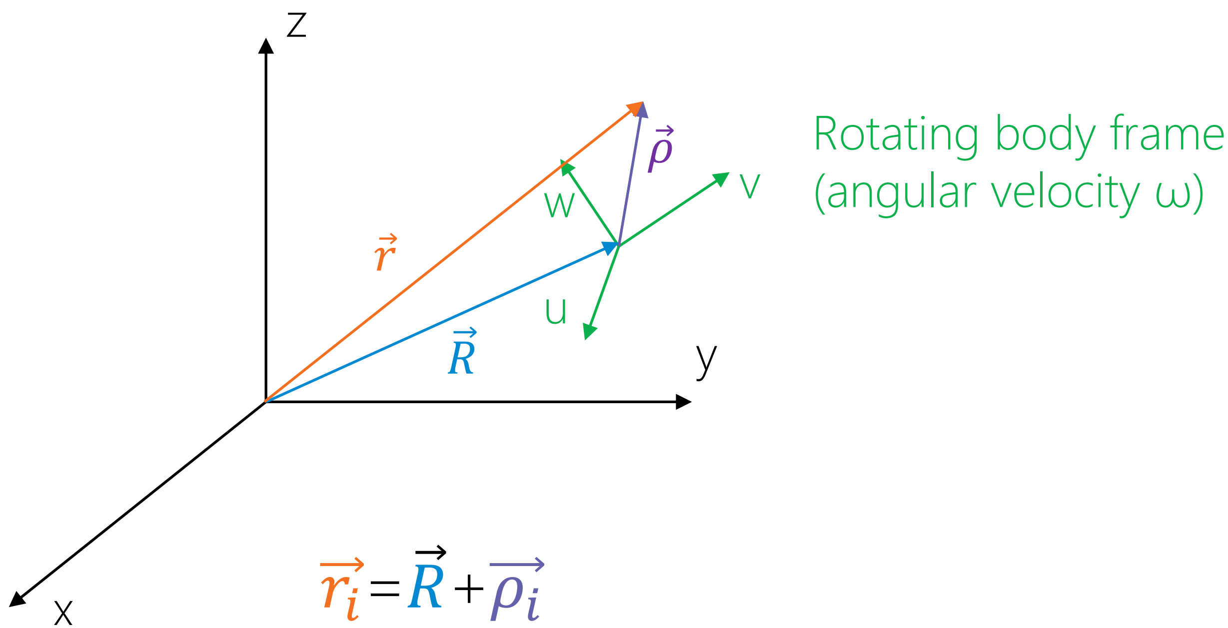
Key Concept: Angular Momentum

In the absence of an external torque, the angular momentum is preserved.

What happens to the angular momentum when the spacecraft deploys its solar panels?

GOVERNING EQUATIONS

Time Differentiation in a Rotating Frame



$$\vec{r_i} = \vec{R} + \vec{\rho_i}$$

$$\vec{v_i} = \frac{d\vec{r_i}}{dt} = \frac{d\vec{R}}{dt} + \left(\frac{d\vec{\rho_i}}{dt}\right)_{body} + \vec{\omega} \times \vec{\rho}_i$$

$$\vec{a_i} = \frac{d^2\vec{R}}{dt^2} + \left(\frac{d^2\vec{\rho_i}}{dt^2}\right)_{body} + 2\vec{\omega} \times \left(\frac{d\vec{\rho_i}}{dt}\right)_{body} + \frac{d\vec{\omega}}{dt} \times \vec{\rho}_i + \vec{\omega} \times (\vec{\omega} \times \vec{\rho}_i)$$

GOVERNING EQUATIONS

Total Angular Momentum

$$\overrightarrow{H_t} = \sum_{i=1}^{n} \vec{H}_i = \sum_{i=1}^{n} \vec{r}_i \times m_i \vec{v}_i$$

$$\overrightarrow{r_i} = \vec{R} + \overrightarrow{\rho_i}$$

$$\overrightarrow{v_i} = \frac{d\overrightarrow{r_i}}{dt} = \frac{d\vec{R}}{dt} + \vec{\omega} \times \vec{\rho}_i$$

$$\left(\frac{d\overrightarrow{\rho_i}}{dt}\right)_{body} = 0\ [Rigid\ Body]$$

Rotating frame at the center of mass

$$\overrightarrow{H_t} = \sum_{i=1}^{n} m_i \vec{R} \times \frac{d\vec{R}}{dt} + \sum_{i=1}^{n} m_i \vec{\rho}_i \times (\vec{\omega} \times \overrightarrow{\rho_i})$$

$$\vec{\vec{I}} = \sum_{i=1}^{n} m_i \left(\rho_i^2 \overrightarrow{\overrightarrow{E_3}} - \vec{\rho}_i \vec{\rho}_i\right)$$

$$\vec{a} \times \left(\vec{b} \times \vec{c}\right) =$$
$$\vec{b}(\vec{a}.\vec{c}) - \vec{c}\left(\vec{a}.\vec{b}\right) =$$
$$\vec{b}(\vec{a}.\vec{c}) - \vec{b}(\vec{c}.\vec{a}^T\ ) = \vec{b}\left(\overrightarrow{\overrightarrow{E_3}}\vec{a}.\vec{c} - \vec{c}.\vec{a}^T\right)$$

$$\overrightarrow{H_t} = \sum_{i=1}^{n} m_i \vec{R} \times \vec{V} + \vec{\vec{I}}\vec{\omega}$$

GOVERNING EQUATIONS

Total Angular Momentum

$$\overrightarrow{H_t} = \underbrace{\sum_{i=1}^{n} m_i \vec{R} \times \vec{V}}_{\overrightarrow{H_{orbit}}} + \underbrace{\vec{\vec{I}}\vec{\omega}}_{\overrightarrow{H_{s/c}}}$$

The angular momentum is equivalent to the linear momentum for rotational dynamics ($m \rightarrow I$, $v \rightarrow \omega$)

For a rigid spacecraft, the spin angular momentum can be decoupled from the orbital angular momentum.

Choose principal axes of inertia! In practice, asymmetries and misalignments lead to coupling, which leads to unwanted disturbances to be removed by the control system

GOVERNING EQUATIONS

External Torques

$$\vec{T_i} = \vec{\rho_i} \times \vec{F_i}$$

A force applied to the spacecraft produces a torque about the center of mass

$$\overrightarrow{T_{total}} = \vec{T} = \sum_{i=1}^{n} \vec{\rho_i} \times \vec{F_i} = \sum_{i=1}^{n} \vec{\rho_i} \times m_i \frac{d^2\vec{r_i}}{dt^2}$$

$$\vec{a_i} = \frac{d^2\vec{R}}{dt^2} + \left(\frac{d^2\vec{\rho_i}}{dt^2}\right)_{body} + 2\vec{\omega} \times \left(\frac{d\vec{\rho_i}}{dt}\right)_{body} + \frac{d\vec{\omega}}{dt} \times \vec{\rho}_i + \vec{\omega} \times (\vec{\omega} \times \vec{\rho}_i)$$

$$\overrightarrow{H_{s/c}} = \vec{\vec{I}}\vec{\omega}$$

$$\vec{T} = \frac{d\vec{H}}{dt} = \left(\frac{d\vec{H}_{s/c}}{dt}\right)_{body} + \vec{\omega} \times \vec{H}_{s/c} = \vec{\vec{I}}\left(\frac{d\vec{\omega}}{dt}\right)_{body} + \vec{\omega} \times \vec{\vec{I}}\vec{\omega}$$

Fundamental equation for attitude dynamics
(Newton's second law for rotating rigid bodies)

GOVERNING EQUATIONS

Equation Governing Attitude Dynamics

$$\vec{T} \Leftrightarrow \vec{\omega}$$

$$\vec{T} = \vec{\vec{I}}\left(\frac{d\vec{\omega}}{dt}\right)_{body} + \underbrace{\vec{\omega} \times \vec{\vec{I}}\vec{\omega}}_{\text{Gyroscopic coupling}}$$

Principal axes

$$\dot{H}_x = I_x\dot{\omega}_x = T_x + (I_y - I_z)\omega_y\omega_z$$
$$\dot{H}_y = I_y\dot{\omega}_y = T_y + (I_z - I_x)\omega_x\omega_z$$
$$\dot{H}_z = I_z\dot{\omega}_z = T_z + (I_x - I_y)\omega_x\omega_y$$

Nonlinear equations with no general solution → computer simulations

GOVERNING EQUATIONS

Simplification

For quick calculations, we may choose to simplify and make our life easier:

$$T_x \approx I_x \dot{\omega}_x = I_x \alpha_x$$
$$T_y \approx I_y \dot{\omega}_y = I_y \alpha_y$$
$$T_z \approx I_z \dot{\omega}_z = I_z \alpha_z$$

If the gyroscopic effect becomes more important, this gets less accurate!

GOVERNING EQUATIONS

Spinning Rigid Spacecraft

$$\omega_x, \omega_y \ll \omega_z = \Omega$$

$$I_x\dot{\omega}_x = T_x + (I_y - I_z)\omega_y\omega_z$$
$$I_y\dot{\omega}_y = T_y + (I_z - I_x)\omega_x\omega_z$$
$$I_z\dot{\omega}_z = T_z + (I_x - I_y)\omega_x\omega_y$$

Free response

$$\dot{\omega}_x = \frac{(I_y - I_z)}{I_x}\Omega\omega_y$$
$$\dot{\omega}_y = \frac{(I_z - I_x)}{I_y}\Omega\omega_x$$
$$\dot{\omega}_z = 0$$

$$\omega_x = f_1(\omega_n t)$$
$$\omega_y = f_2(\omega_n t)$$

Nutation frequency $$\omega_n^2 = \frac{(I_z - I_y)}{I_x}\frac{(I_z - I_x)}{I_y}\Omega^2$$

GOVERNING EQUATIONS

Spinning Rigid Spacecraft

What happens if the spin axis inertia I_z is intermediate between I_x and I_y ?

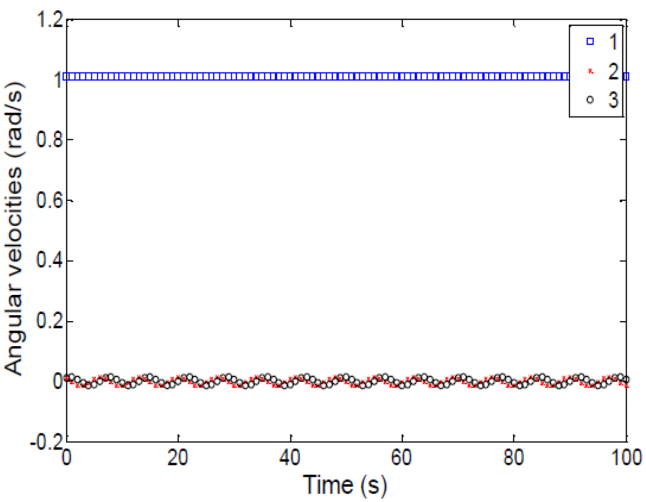
The nutation frequency is imaginary. Any perturbing torque will result in the growth of the nutation angle until the body is spinning about either the maximum or minimum inertia axis, depending on initial condition.

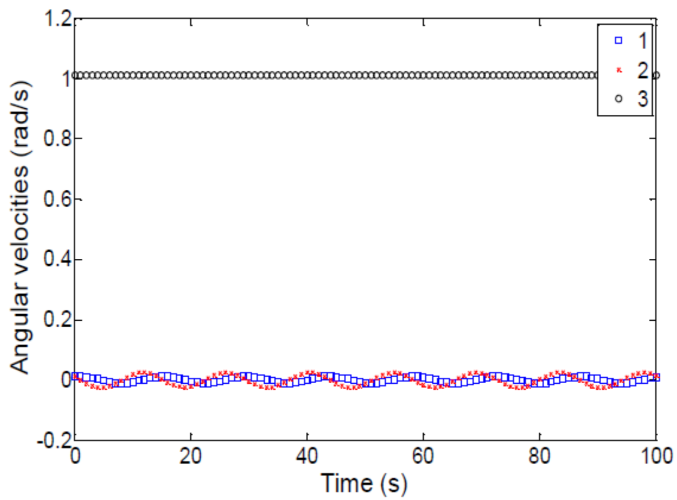
A rigid body can rotate about its extreme inertia axis,
but not the intermediate axis

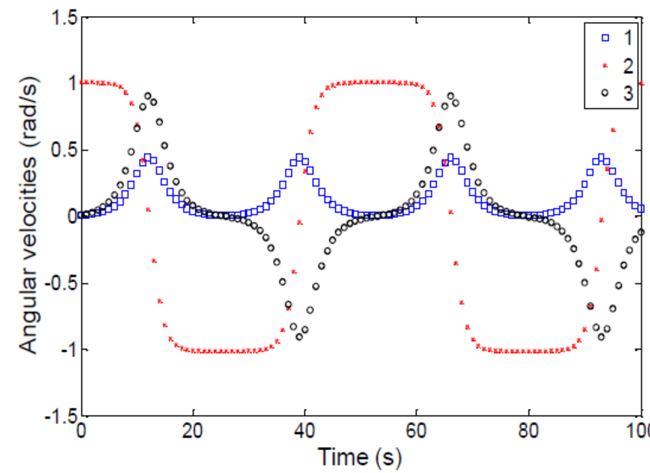
GOVERNING EQUATIONS

Spinning Rigid Spacecraft

What happens if the spin axis inertia I_z is intermediate between I_x and I_y ?







$$I_1 > I_2 > I_3$$

OVERVIEW

- Introduction
- Rationale
- Attitude Requirements and Errors
- Governing Equations
- Attitude Parameterization
- Disturbance Torques
- Passive Control
- Active Control
- Going Further
- I am interested, what now?

ATTITUDE PARAMETERIZATION

How do we describe the attitude of a spacecraft?

ATTITUDE PARAMETERIZATION

Introduction

The attitude – or orientation – of the spacecraft needs to be described in an unambiguous way. There are several ways of doing this:

- Direction Cosine Matrix
- Euler Angles
- Quaternion
- Others that will not be described here.

Each of these has its advantages and disadvantages and are used for different reasons.

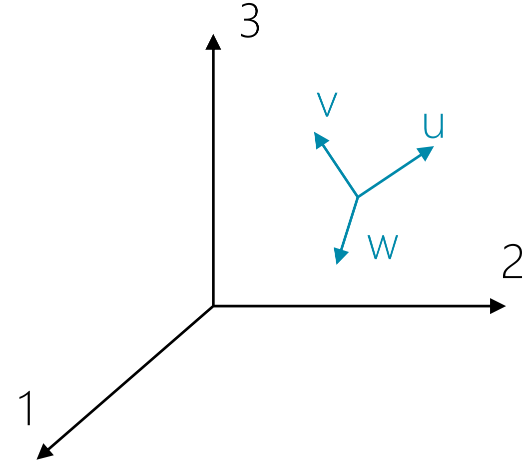
ATTITUDE PARAMETERIZATION

Direction Cosine Matrix

Assume an orthogonal, right handed triad of unit vectors.
(E.g. the body frame of a spacecraft.)

Specifying the components of these unit vectors in the coordinate frame 1-2-3 fixes the orientation completely.

$$A = \begin{bmatrix} u_1 & u_2 & u_3 \\ v_1 & v_2 & v_3 \\ w_1 & w_2 & w_3 \end{bmatrix}$$



ATTITUDE PARAMETERIZATION

Direction Cosine Matrix

$$A = \begin{bmatrix} u_1 & u_2 & u_3 \\ v_1 & v_2 & v_3 \\ w_1 & w_2 & w_3 \end{bmatrix}$$

Each of the elements of the matrix corresponds with the cosine of the angle between a body unit vector and a reference axis. E.g. u_1 is the cosine of the angle between $\boldsymbol{u}$ and the $\mathit{1}$-axis.

A is therefore often called the Direction Cosine Matrix.

The Direction Cosine Matrix maps vectors from the reference frame to the body frame.

$$\begin{bmatrix} a_u \\ a_v \\ a_w \end{bmatrix} = \begin{bmatrix} u_1 & u_2 & u_3 \\ v_1 & v_2 & v_3 \\ w_1 & w_2 & w_3 \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \\ a_3 \end{bmatrix}$$

ATTITUDE PARAMETERIZATION

Euler Angles

By Jakob Emanuel Handmann - Kunstmuseum Basel, Public Domain, https://commons.wikimedia.org/w/index.php?curid=893656

Swiss mathematician, physicist, astronomer, logician and engineer, who published around 800 pages per year.

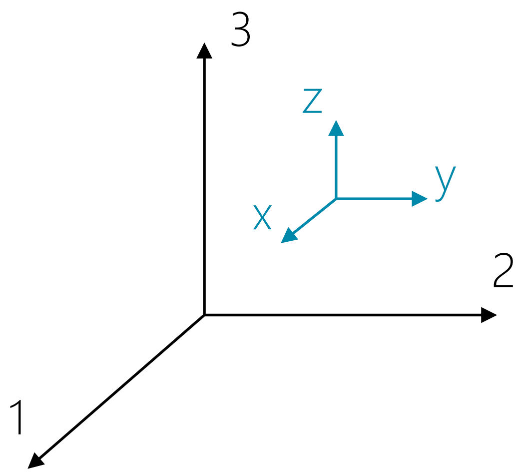
He produced, on average, one mathematical paper every week in the year 1775, while being almost blind.

ATTITUDE PARAMETERIZATION

Euler Angles

To define the Euler Angles, consider four orthogonal, right handed triads of unit vectors:

$$[x \quad y \quad z]$$
$$[x' \quad y' \quad z']$$
$$[x'' \quad y'' \quad z'']$$
$$[u \quad v \quad w]$$



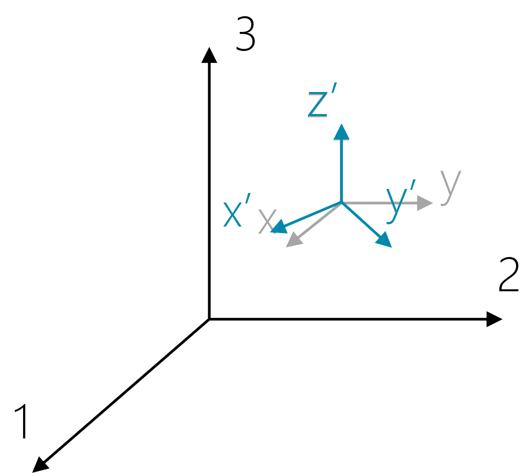
$[x \quad y \quad z]$ is parallel to the reference frame axes.

ATTITUDE PARAMETERIZATION

Euler Angles

To define the Euler Angles, consider four orthogonal, right handed triads of unit vectors:

$$[x \quad y \quad z]$$
$$[x' \quad y' \quad z']$$
$$[x'' \quad y'' \quad z'']$$
$$[u \quad v \quad w]$$



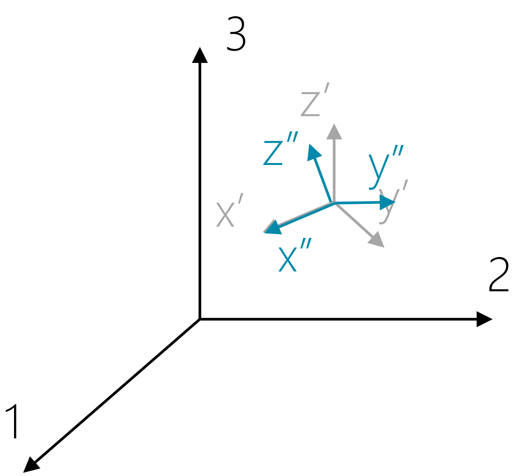
$[x \quad y \quad z]$ is parallel to the reference frame axes.
$[x' \quad y' \quad z']$ is rotated as opposed to $[x \quad y \quad z]$ with an angle Φ around an axis i (let's assume the z-axis).

ATTITUDE PARAMETERIZATION

Euler Angles

To define the Euler Angles, consider four orthogonal, right handed triads of unit vectors:

$$[x \quad y \quad z]$$
$$[x' \quad y' \quad z']$$
$$[x'' \quad y'' \quad z'']$$
$$[u \quad v \quad w]$$



$[x \quad y \quad z]$ is parallel to the reference frame axes.

$[x' \quad y' \quad z']$ is rotated as opposed to $[x \quad y \quad z]$ with an angle Φ around an axis i (let's assume the z-axis).

$[x'' \quad y'' \quad z'']$ is rotated as opposed to $[x' \quad y' \quad z']$ with an angle θ around an axis j (let's assume the x-axis).

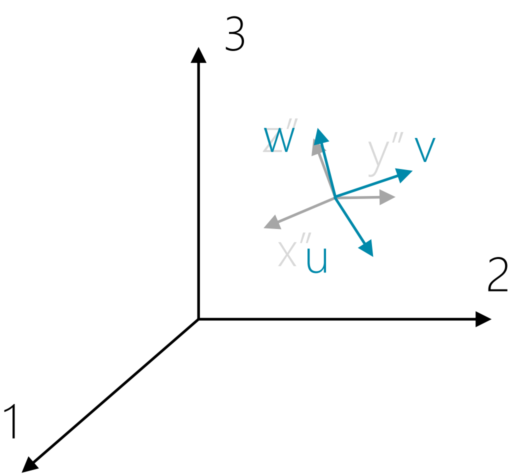
j cannot be equal to i, otherwise we are just rotating further or back from the previous step.

ATTITUDE PARAMETERIZATION

Euler Angles

To define the Euler Angles, consider four orthogonal, right handed triads of unit vectors:

$$[x \quad y \quad z]$$
$$[x' \quad y' \quad z']$$
$$[x" \quad y" \quad z"]$$
$$[u \quad v \quad w]$$



$[x \quad y \quad z]$ is parallel to the reference frame axes.
$[x' \quad y' \quad z']$ is rotated as opposed to $[x \quad y \quad z]$ with an angle Φ around an axis i (let's assume the z-axis).
$[x" \quad y" \quad z"]$ is rotated as opposed to $[x' \quad y' \quad z']$ with an angle θ around an axis j (let's assume the x'-axis).
$[u \quad v \quad w]$ is rotated as opposed to $[x" \quad y" \quad z"]$ with an angle ψ around an axis k (let's assume the z″-axis).

k cannot be equal to j, otherwise we are just rotating further or back from the previous step.

ATTITUDE PARAMETERIZATION

Euler Angles

The three rotation angles (Φ, θ, ψ), together with the axis order (3-1-3 in this case), define the attitude.

There are 12 different axis sequences:

313, 212, 121, 323, 232, 131, 312, 213, 123, 321, 231, 132

It is of course possible to convert Euler Angles to a Direction Cosine Matrix.
e.g. for a 313 sequence

$$A_{313}(\Phi, \theta, \psi) =$$

$$A_3(\Phi) A_1(\theta) A_3(\psi) =$$

$$\begin{bmatrix} \cos\psi\cos\Phi - \cos\theta\sin\psi\sin\Phi & \cos\psi\sin\Phi + \cos\theta\sin\psi\cos\Phi & \sin\theta\sin\psi \\ -\sin\psi\cos\Phi - \cos\theta\cos\psi\sin\Phi & -\sin\psi\sin\Phi + \cos\theta\cos\psi\cos\Phi & \sin\theta\cos\psi \\ \sin\theta\sin\Phi & -\sin\theta\cos\Phi & \cos\theta \end{bmatrix}$$

ATTITUDE PARAMETERIZATION

Quaternions

Sir William Rowan Hamilton knew that complex numbers could be interpreted as points in a plane, and he was looking for a way to do the same for points in three-dimensional space.

As he walked along the towpath of the Royal Canal with his wife, the concepts behind quaternions were taking shape in his mind. When the answer dawned on him, Hamilton could not resist the urge to carve the formula for the quaternions. [1]

By Wisher at English Wikipedia - Transferred from en.wikipedia to Commons by Premeditated Chaos using CommonsHelper., Public Domain, https://commons.wikimedia.org/w/index.php?curid=18674771

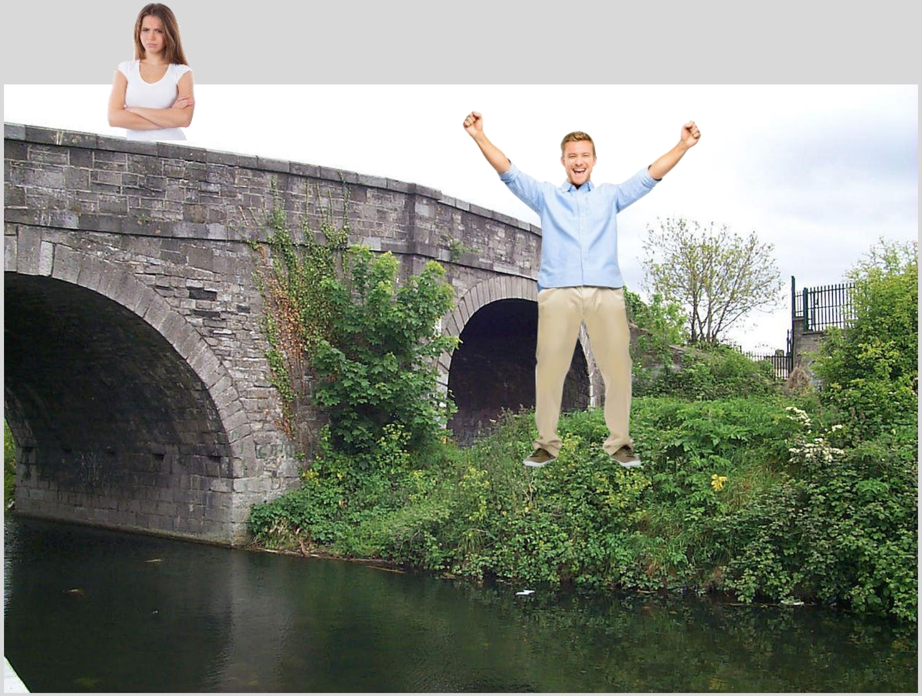
[1] https://en.wikipedia.org/wiki/Quaternion

ATTITUDE PARAMETERIZATION

Quaternions

Sir William Rowan Hamilton knew that complex numbers could be interpreted as points in a plane, and he was looking for a way to do the same for points in three-dimensional space.

As he walked along the towpath of the Royal Canal with his wife, the concepts behind quaternions were taking shape in his mind. When the answer dawned on him, Hamilton could not resist the urge to carve the formula for the quaternions. [1]



By Wisher at English Wikipedia - Transferred from en.wikipedia to Commons by Premeditated Chaos using CommonsHelper., Public Domain, https://commons.wikimedia.org/w/index.php?curid=18674771

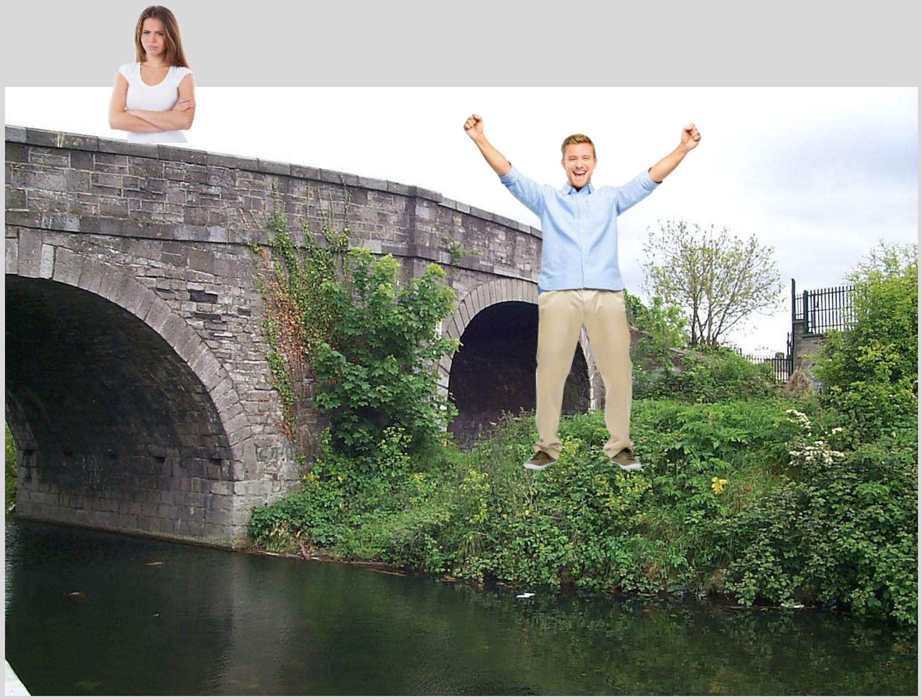
[1] https://en.wikipedia.org/wiki/Quaternion

ATTITUDE PARAMETERIZATION

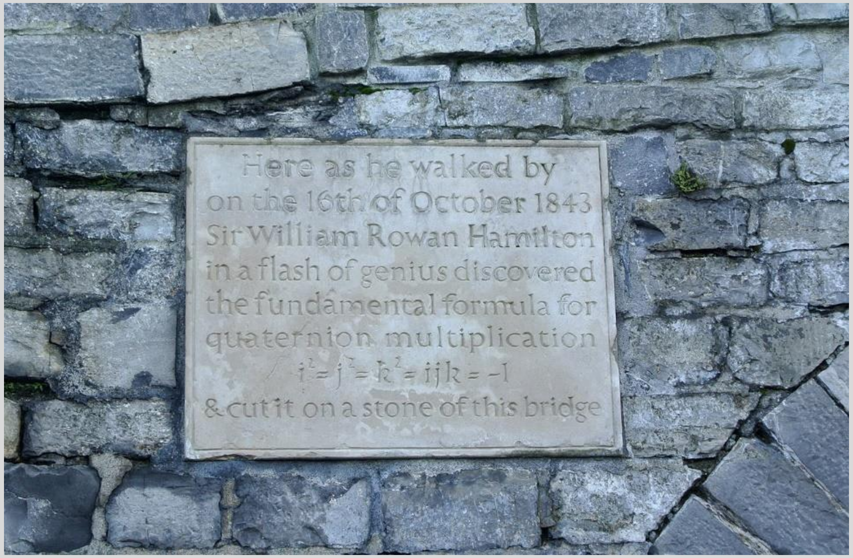
Quaternions

Sir William Rowan Hamilton knew that complex numbers could be interpreted as points in a plane, and he was looking for a way to do the same for points in three-dimensional space.

As he walked along the towpath of the Royal Canal with his wife, the concepts behind quaternions were taking shape in his mind. When the answer dawned on him, Hamilton could not resist the urge to carve the formula for the quaternions. [1]



By Wisher at English Wikipedia - Transferred from en.wikipedia to Commons by Premeditated Chaos using CommonsHelper., Public Domain, https://commons.wikimedia.org/w/index.php?curid=18674771



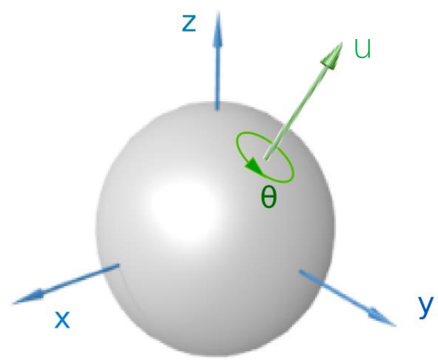
By Cone83 - Own work, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=64867702

[1] https://en.wikipedia.org/wiki/Quaternion

ATTITUDE PARAMETERIZATION

Quaternions

Any rotation or sequence of rotations of a rigid body or coordinate system about a fixed point is equivalent to a single rotation by a given angle θ about a fixed axis (called the *Euler axis*) that runs through the fixed point.[1]



$$q = e^{\frac{\theta}{2}(u_x i + u_y j + u_z k)} = \cos\frac{\theta}{2} + (u_x i + u_y j + u_z k)\sin\frac{\theta}{2}$$

$$q = \begin{bmatrix} q_w \\ q_x \\ q_y \\ q_z \end{bmatrix} \begin{matrix} \} \text{ Scalar part} \\ \left.\begin{matrix} \\ \\ \\ \end{matrix}\right\} \text{ Vector part} \end{matrix}$$

[1] https://en.wikipedia.org/wiki/Quaternions_and_spatial_rotation

ATTITUDE PARAMETERIZATION

Quaternions

A quaternion can again be converted to a Direction Cosine Matrix.

$$A(q) = \begin{bmatrix} q_x^2 - q_y^2 - q_z^2 + q_w^2 & 2(q_x q_y + q_z q_w) & 2(q_x q_z - q_y q_w) \\ 2(q_z q_y - q_z q_w) & -q_x^w + q_y^2 - q_z^2 + q_w^2 & 2(q_y q_z + q_x q_w) \\ 2(q_x q_z + q_y q_w) & 2(q_y q_z - q_x q_w) & -q_x^2 - q_y^2 + q_z^2 + q_w^2 \end{bmatrix}$$

There are no trigonometric functions in this equation.

ATTITUDE PARAMETERIZATION

Overview

Parameterization	Advantages	Disadvantages	Common Applications
Direction Cosine Matrix	• No Singularities • No trigonometric functions • Convenient product rule for successive rotations	• Six redundant parameters	In analysis, to transform vectors from one reference frame to another
Euler Angles	• No redundant parameters • Physical interpretation is clear in some cases	• Trigonometric functions • Singularity possible • No convenient product rule for successive rotations	Analytical studies and as input/output for human manipulation
Quaternion	• No singularities • No trigonometric functions • Convenient product rule for successive rotations	• One redundant parameter • No obvious physical interpretation	• Onboard the spacecraft, in the control laws.

OVERVIEW

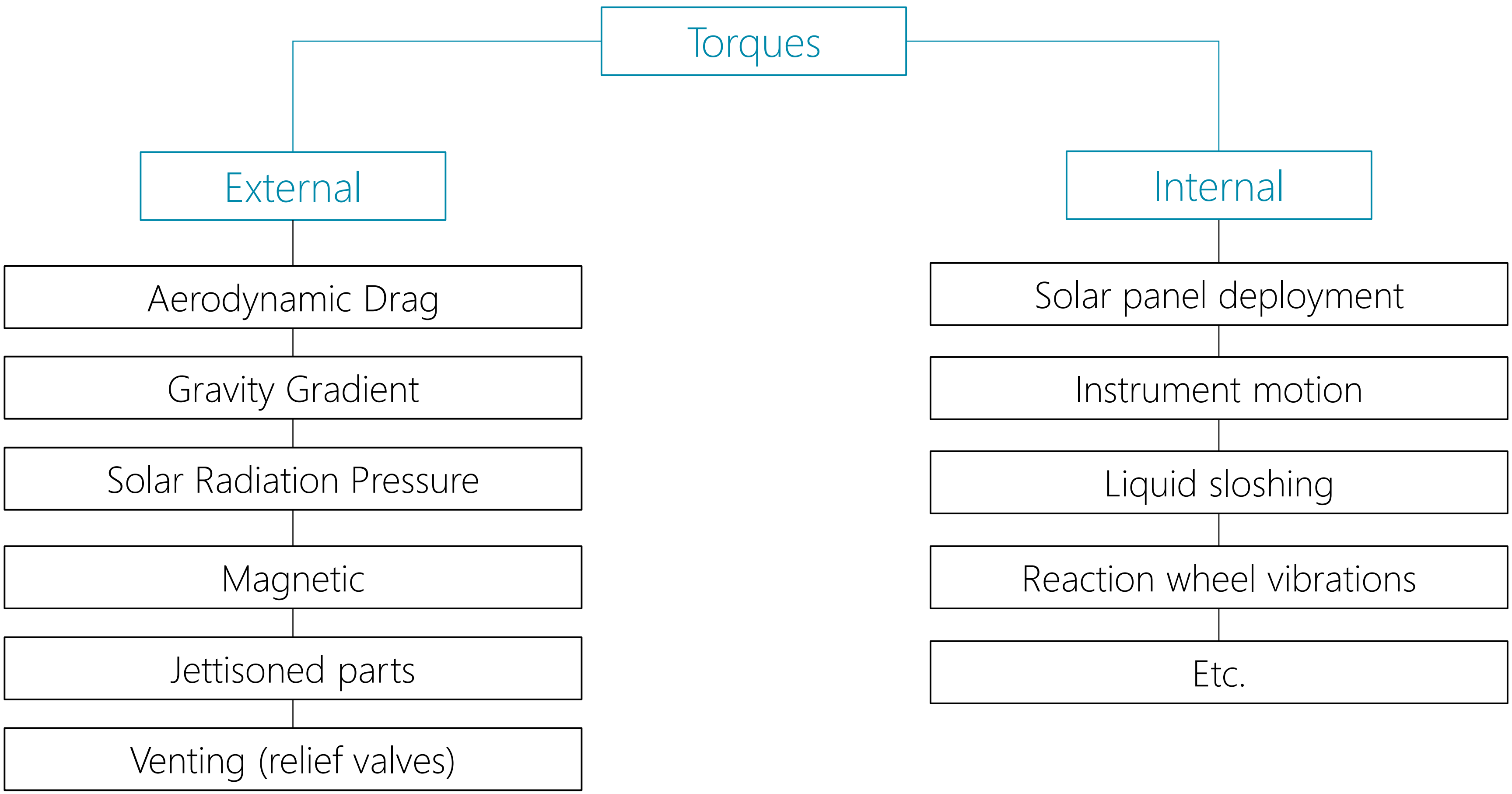
- Introduction
- Rationale
- Attitude Requirements and Errors
- Governing Equations
- Attitude Parameterization
- Disturbance Torques
- Passive Control
- Active Control
- Going Further
- I am interested, what now?

DISTURBANCE TORQUES

Which torques are disturbing the spacecraft attitude?

DISTURBANCE TORQUES

Different Sources



Affect the total angular momentum

Total angular momentum conserved but influence spacecraft orientation

DISTURBANCE TORQUES
Aerodynamic Drag Torque

The drag force produces a disturbance torque on the spacecraft due to any offset that exists between the aerodynamic center of pressure and the center of mass

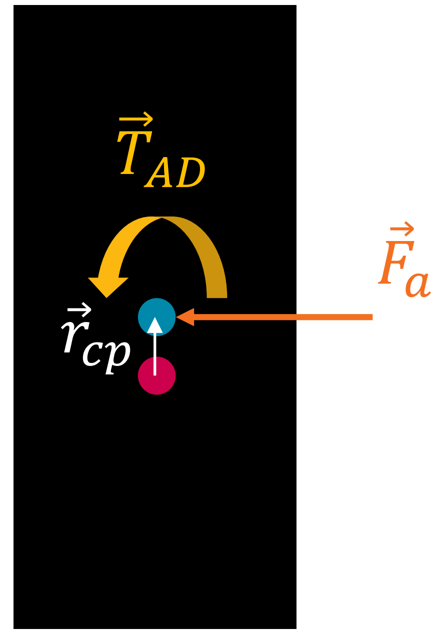
$$\vec{T}_{AD} = \vec{r}_{cp} \times \vec{F}_a$$

Center of Pressure vector relative to the Center of Mass

$$\vec{F}_a = \frac{1}{2}\rho V^2 S C_D \frac{\vec{V}}{V}$$

Frontal Area

~2 for free-molecular flow



Center of Mass

Center of Pressure

DISTURBANCE TORQUES

Aerodynamic Drag Torque

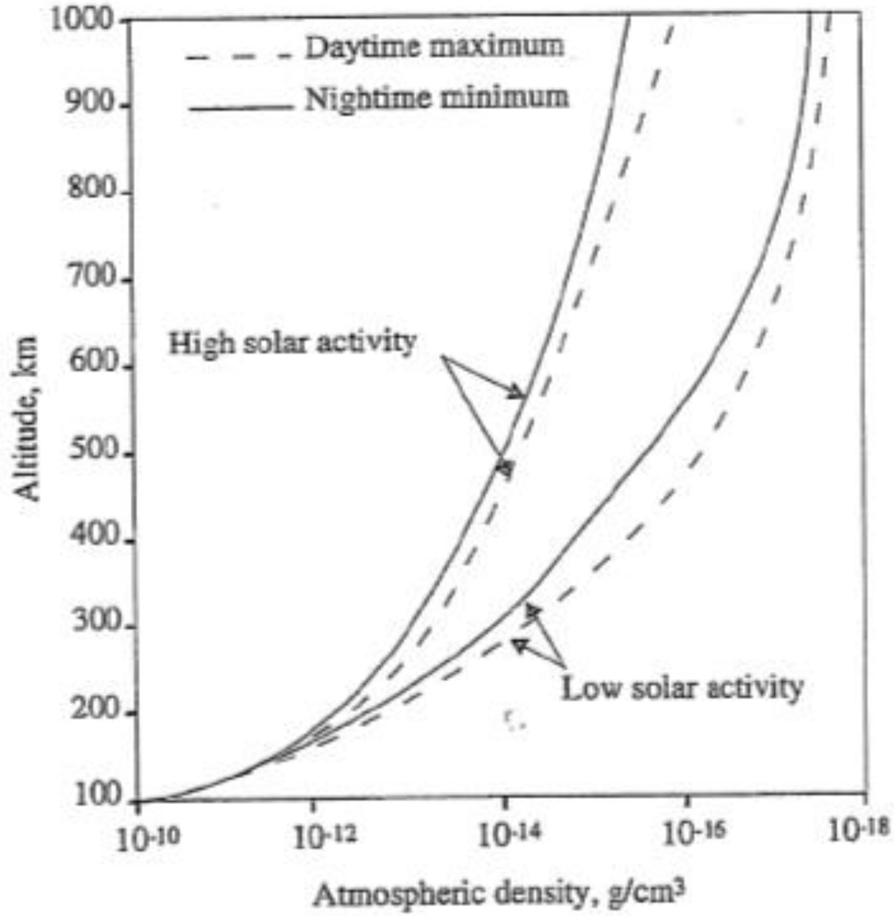
Above 200km altitude, the mean free path is significantly greater than the dimensions of most space vehicles

- Aerodynamics must be based upon free molecular flow
- Heat exchange solely due to radiation (no convection)

Table 2.3 Mean free path λ_0 as a function of altitude

Altitude (km)	λ_0 (m)	Altitude (km)	λ_0 (m)
100	0.142	300	2.6×10^3
120	3.31	400	16×10^3
140	18	500	77×10^3
160	53	600	280×10^3
180	120	700	730×10^3
200	240	800	1400×10^3

DISTURBANCE TORQUES
Aerodynamic Drag Torque



July 15, 2000: a strong solar flare heated the Earth's atmosphere, increasing the air density to a value 100 times greater than that for which its ADCS had been designed to cope. The magnetorquers were unable to compensate and the satellite was lost.

DISTURBANCE TORQUES

Aerodynamic Drag Torque: Example

$$S = 5\ m^2$$

$$C_D = 2$$

$$h = 400\ km \ \rightarrow \ \rho = 4 \times 10^{-12} \frac{kg}{m^3}$$

$$r_{CP} = 0.01m$$

$$\boxed{T = 1.2 \times 10^{-5} \text{Nm}}$$

$$For\ I = 1000\ kgm^2$$

$$T = \frac{dH}{dt} = I\frac{d\omega}{dt} = I\frac{d^2\omega}{dt^2}$$

$$\theta(0) = 0$$

$$\dot{\theta}(0) = 0$$

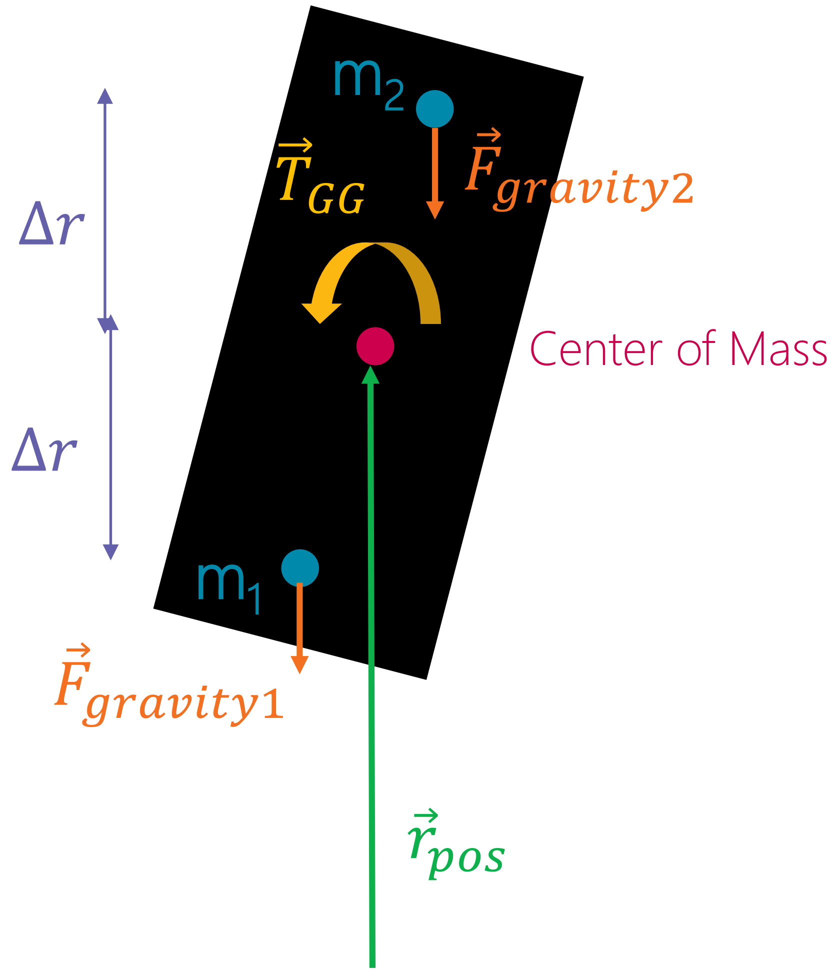
$$\theta(t) = \frac{T}{I}t^2 = 1.2 \times 10^{-8} s^{-2} t^2$$

Drift of 57deg after
2 orbits (around 10.000 s) !!!
Unacceptable.

DISTURBANCE TORQUES

Gravity Gradient Torque

Gravitational fields decrease with distance from the center of the planet → a spacecraft in orbit experiences a stronger attraction on its “lower” side than its “upper” side.

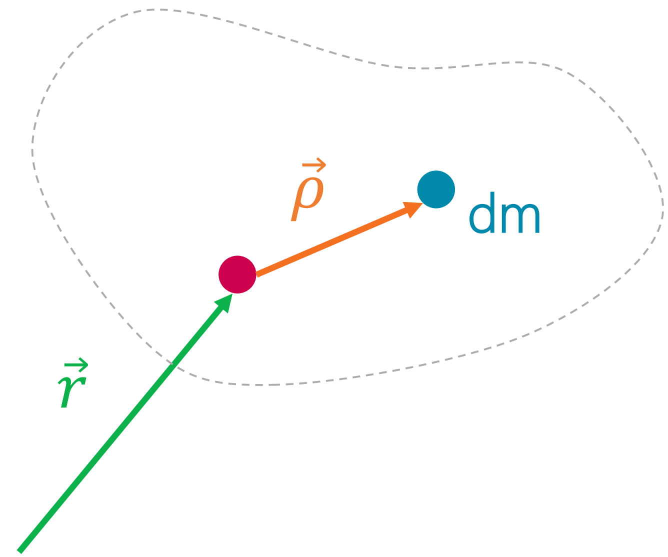


DISTURBANCE TORQUES

Gravity Gradient Torque

$$d\vec{F} = -\mu \frac{\vec{\rho} + \vec{r}}{|\vec{\rho} + \vec{r}|^3} dm$$

Gravitational constant
(for Earth: 3.986 x 10^{14} m^3/s^2)



$$d\vec{T} = \vec{\rho} \times d\vec{F} \rightarrow \vec{T} = \int \vec{\rho} \times \left(-\mu \frac{\vec{\rho} + \vec{r}}{|\vec{\rho} + \vec{r}|^3}\right) dm$$

DISTURBANCE TORQUES

Gravity Gradient Torque

$$\vec{\rho} \ll \vec{r} \rightarrow \frac{1}{|\vec{\rho}+\vec{r}|^3} \approx r^{-3}\left[1 - 3\frac{\vec{r}}{r^2}\vec{\rho}\right]$$

$$\vec{T} = \int \vec{\rho} \times \left[\frac{-\mu}{r^3}\left(1 - 3\frac{\vec{r}}{r^2}\vec{\rho}\right)\vec{r}\right] dm \qquad \int \vec{\rho}\, dm = 0, \hat{r} = \frac{\vec{r}}{r}$$

$$\vec{T} = \frac{3\mu}{r^3}\left(\int \vec{\rho}.\vec{\rho} dm\right)\hat{r} \times \hat{r} \Rightarrow \boxed{\vec{T} = \frac{3\mu}{r^3}\hat{r} \times \vec{\vec{I}}\hat{r}}$$

Perpendicular to Earth-spacecraft vector

DISTURBANCE TORQUES

Gravity Gradient Torque: Example

Further derivation leads to the following equation we can use to calculate the gravity gradient torque around one axis:

$$\vec{T}_{GG} = \frac{3\mu}{2r^3}\left|I_z - I_y\right| \sin(2\theta)$$

- *R is the* orbit radius (m)
- θ is the maximum deviation of the Z-axis from local vertical in radians
- I_z and I_y *are* moments of inertia about z and *y*
- (or *x*, if smaller) axes in kgm^2.

Altitude = 700km
Inertia moment difference = 30 kgm^2
Θ = 1 deg

$$\vec{T}_{GG} = \frac{3 \times 3.986 \times 10^{14}}{2 \times (7{,}078 \times 10^6)^3} 30 \sin(2deg) = 1.8 \times 10^{-6} Nm$$

J.R. Wertz, Space Mission Analysis and Design, 3rd ed. Hawthorne, CA and New York NY: Microcosm Press and Springer, 1999

DISTURBANCE TORQUES

Solar Radiation Pressure Torque

Solar radiation pressure produces a disturbance torque on the spacecraft, which depends upon the distance from the sun. It is independent of spacecraft position and velocity and is perpendicular to the sun line.

Solar radiation is NOT related to solar wind, which is a continuous stream of particles emanating from the sun. The momentum flux in the solar wind is small compared with that due to solar radiation.

Solar radiation (photons)	$\neq$	Solar wind (particles)

DISTURBANCE TORQUES

Solar Radiation Pressure Torque

$$\vec{T}_{SP} = \vec{r}_{CP} \times \vec{F}_s$$

Vector from the center of mass to the center of solar pressure

$$\vec{F}_s = (1 + K) p_S A_p$$

Projected area normal to sun vector

Surface reflectivity

$$\frac{1360 \, {}^{W}/_{m^2}}{3 \times 10^8 \, {}^{m}/_{s}}$$

$A_p = 5m^2, K = 0.5, r = 0.1m$ ⇒ $\vec{T}_{SP} = 3.5 \times 10^{-6} Nm$

DISTURBANCE TORQUES

Magnetic Torque

The magnetic field generated by a spacecraft interacts with the local field from the Earth.

$$\vec{T}_{MA} = \vec{M} \times \vec{B}$$

Spacecraft magnetic dipole moment (current loops+residual magnetic moment). E.g., residual moment in the magnetorquers of PROBA 2=0.03 Am^2

Earth magnetic field vector in spacecraft coordinates (proportional to $1/r^3$ with r the distance of the center of Earth to the spacecraft.)

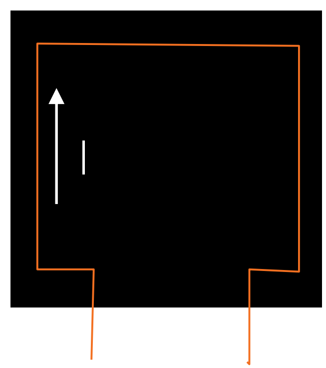
Current through the loop

$$M = nIS$$

Number of turns

Surface area of the loop

Current loop through solar panels



How can we reduce the “disturbance” magnetic moment generated by the current loops in the solar panels?

DISTURBANCE TORQUES

Magnetic Torque

The magnetic field generated by a spacecraft interacts with the local field from the Earth.

$$\vec{T}_{MA} = \vec{M} \times \vec{B}$$

Spacecraft magnetic dipole moment (current loops+residual magnetic moment). E.g., residual moment in the magnetorquers of PROBA 2=0.03 Am^2

Earth magnetic field vector in spacecraft coordinates (proportional to $1/r^3$ with r the distance of the center of Earth to the spacecraft.)

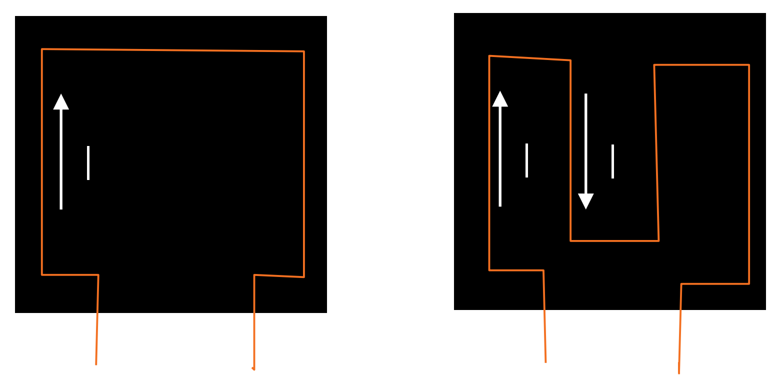
Current through the loop

$$M = nIS$$

Number of turns

Surface area of the loop

Counteracting current loop through solar panels



DISTURBANCE TORQUES

Magnetic Torque: Example

$$\vec{T}_{MA} = \vec{M} \times \vec{B}$$

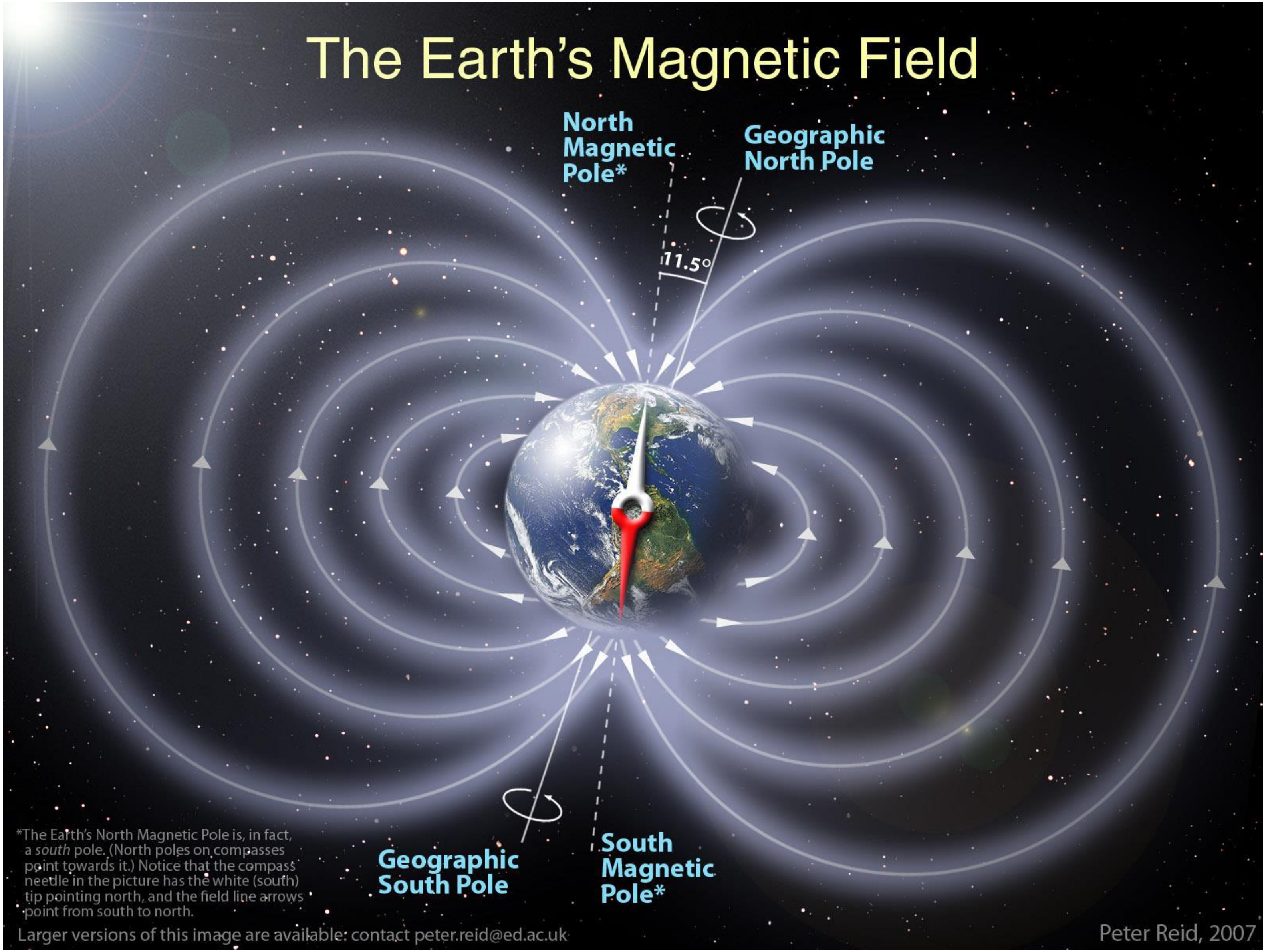
$$B \text{ @ } 700km\ altitude = \frac{2M_{Earth}}{R^3} = \frac{2 \times 7.96 \times 10^{15}}{(6378 + 700)^3} \approx 4.5 \times 10^{-5} Tesla$$

$$M\ (Small\ spacecraft) \approx 0.1 Am^2$$

$$\vec{T}_{MA} = 4.5 \times 10^{-6} Nm$$

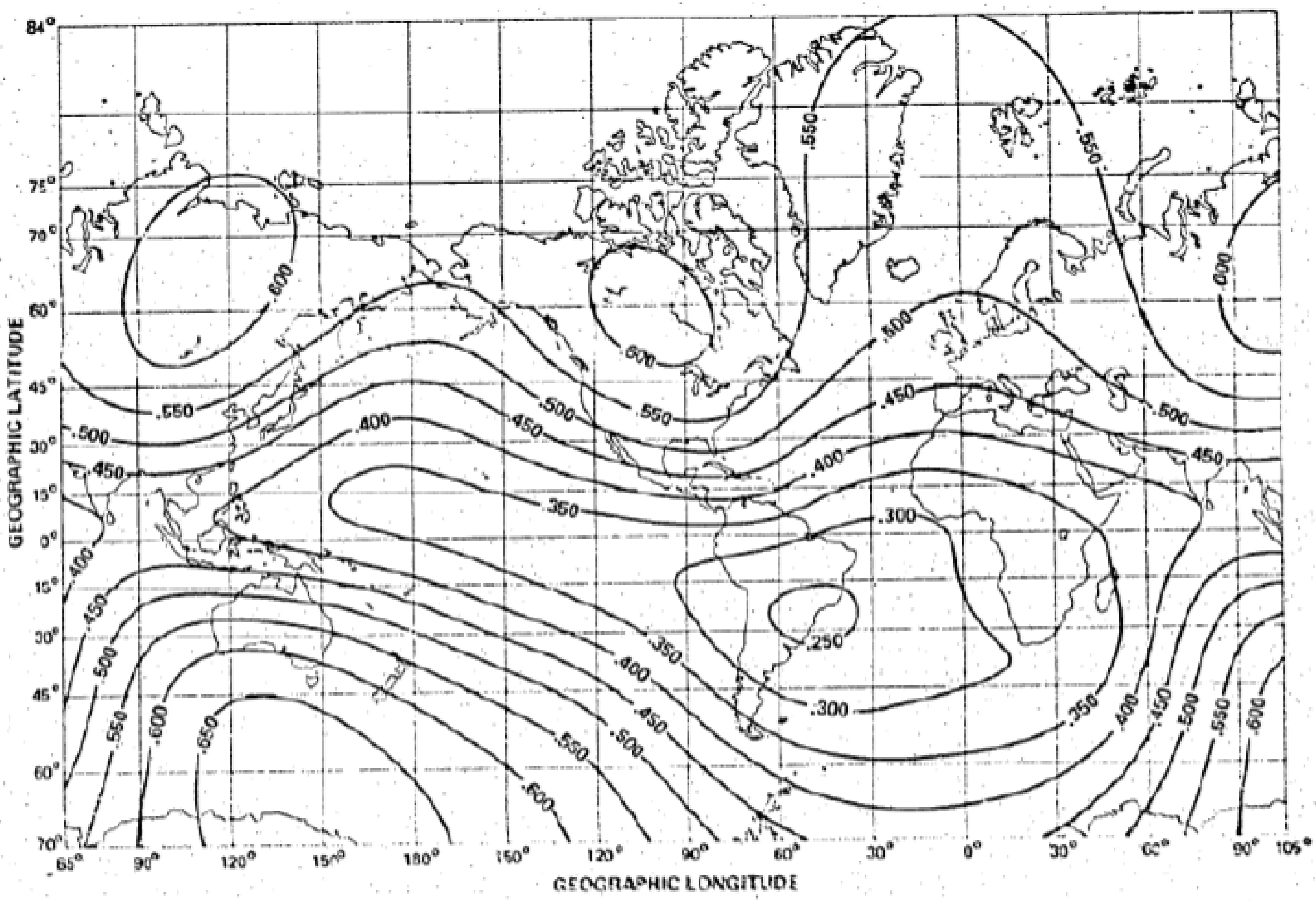
DISTURBANCE TORQUES

Earth's Magnetic field



DISTURBANCE TORQUES

Earth's Magnetic field



Total magnetic field intensity at Earth's surface in Gauss (=0.0001 Tesla) in 1965

DISTURBANCE TORQUES

Overview

Disturbance	Dependence on the distance to the Earth
Aerodynamic	e^{-ar} *Strong dependence on solar activity and also day/night*
Gravity Gradient	$\frac{1}{r^3}$
Solar Radiation Pressure	Independent *Almost no dependence on solar activity but care for eclipse !*
Magnetic	$\frac{1}{r^3}$

The effect of disturbance torques generally decreases when the orbit is higher.

DISTURBANCE TORQUES

Dominant Disturbance Torques

Interplanetary

Solar radiation pressure

GEO

Solar radiation pressure can be the primary source of disturbance torque. The lifetime of a GEO satellite is often controlled by the mass budget available for stationkeeping and attitude control fuel. Designers must avoid center-of-mass to center-of-pressure offsets.

1000 km

Different disturbance torques must be considered.

300-400 km

The aerodynamic torque is dominant

OVERVIEW

- Introduction
- Rationale
- Attitude Requirements and Errors
- Governing Equations
- Attitude Parameterization
- Disturbance Torques
- Passive Control
- Active Control
- Going Further
- I am interested, what now?

PASSIVE CONTROL

How can the spacecraft attitude be controlled* passively?

* Kept stable

OVERVIEW

- Introduction
- Rationale
- Attitude Requirements and Errors
- Governing Equations
- Attitude Parameterization
- Disturbance Torques
- Passive Control
- Active Control
- Going Further
- I am interested, what now?

PASSIVE CONTROL

Principle

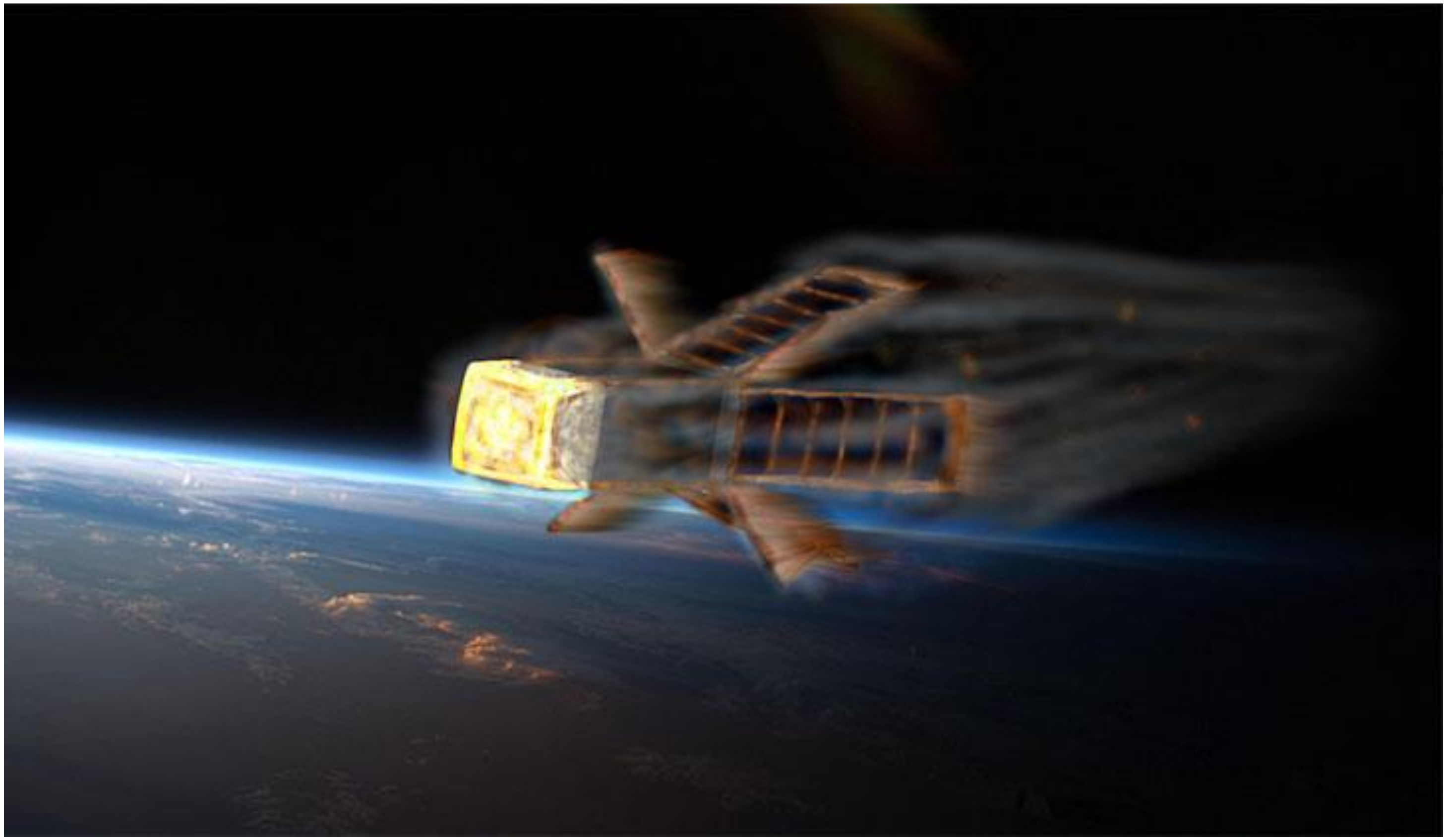
The disturbance torques can be used to our advantage to keep the spacecraft stable.

Passive control is not really control, in the sense that we can command the spacecraft to take a certain attitude. It rather allows to keep the spacecraft stable.

PASSIVE CONTROL

Aerodynamic stabilization

At Low Earth Orbits, the aerodynamic drag can be high enough to align the most aerodynamic side of the spacecraft with the velocity vector.

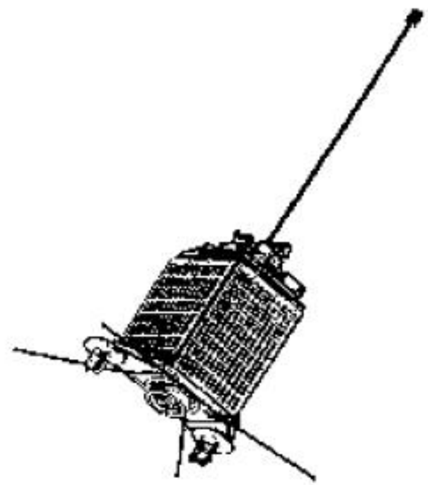


e.g. The Belgian CubeSat QARMAN will rely on its aerodynamic properties to maintain a stable attitude during re-entry.

PASSIVE CONTROL

Gravity Gradient stabilization

Gravity Gradient stabilization uses the inertial properties of the spacecraft to align the spacecraft longitudinal axis to the Earth's center. This does not influence the yaw angle of the spacecraft.



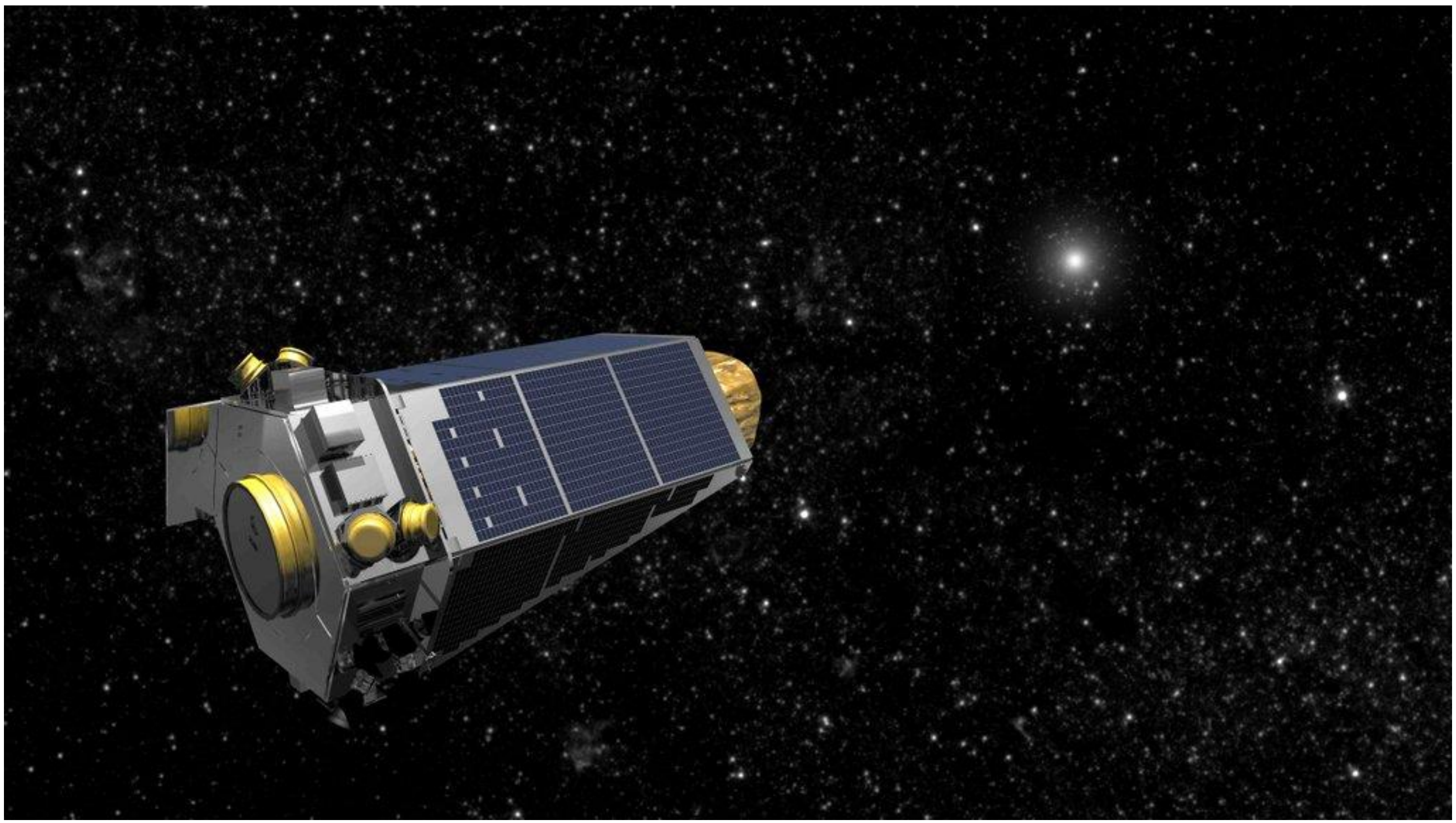
Long booms with weights are used to achieve the desired inertias and to have sufficient stabilization.

PASSIVE CONTROL

Solar Radiation Pressure stabilization

Solar Radiation Pressure stabilization is not as common.

When the second of four reaction wheels of Kepler failed, Kepler mission and Ball Aerospace engineers developed an innovative way of recovering pointing stability by maneuvering the spacecraft so that the solar pressure is evenly distributed across the surfaces of the spacecraft.

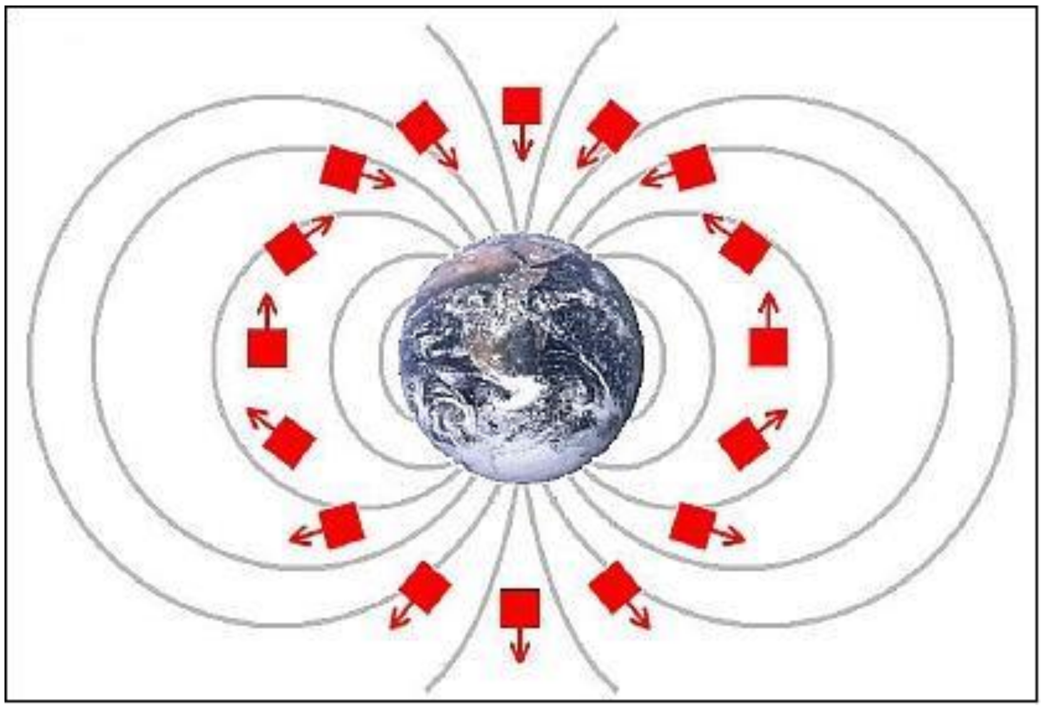


PASSIVE CONTROL

Magnetic stabilization

Magnetic stabilization uses permanent magnets on board of the spacecraft to align it with the Earth's magnetic field.

This is most effected in near-equatorial orbits where the field orientation stays almost constant for an Earth-pointing spacecraft.



J.R. Wertz, Space Mission Analysis and Design, 3rd ed. Hawthorne, CA and New York NY: Microcosm Press and Springer, 1999

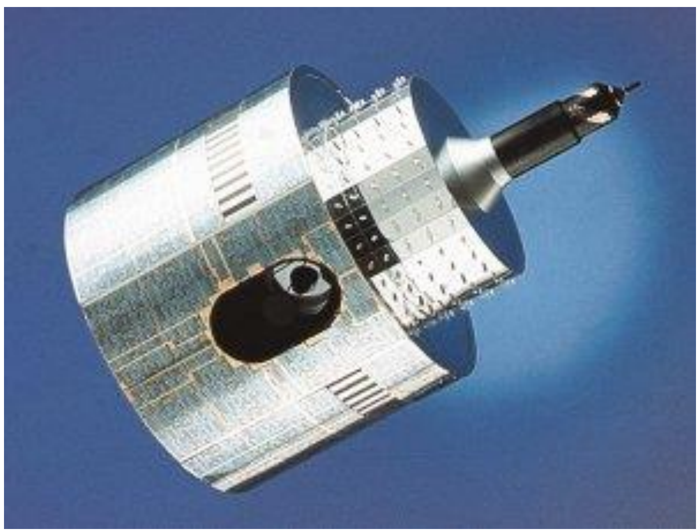
PASSIVE CONTROL

Spin Stabilization

The intrinsic gyroscopic stiffness of a spinning body is used to maintain its orientation in inertial space

Unlike the other types of stabilization, we maintain here the orientation in an inertial space (conservation of angular momentum)

The advantage of spinning a spacecraft is that the thermal environment improves (more equal exposure for components). For scanning payloads, a spin can be even required.



Meteosat
Spin stabilized with nutation damper

A real (therefore flexible) body can spin stably only about the axis of maximum moment of inertia

→ The vehicle must be a “wheel” rather than a “pencil”

PASSIVE CONTROL
Spin Stabilization

NO SPIN

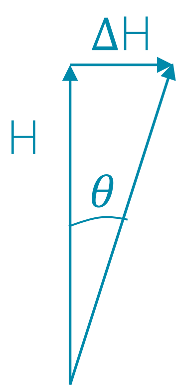
$$T = I\ddot{\theta}$$

Constant disturbing torque,
along one axis

$$\theta = \frac{1}{2}\frac{T}{I}t^2$$

Small disturbance torque can lead to large deviation angle. Quadratic growth

SPIN STABILIZED



Constant disturbing torque,
Perpendicular to the angular momentum

$$\vec{T} = \frac{\Delta\vec{H}}{\Delta t}, \theta \approx \frac{\Delta H}{H} = \frac{T\Delta t}{H}$$

Linear growth inversely proportional to H and hence to the angular velocity
(Faster spin rate → Less effect of disturbances)

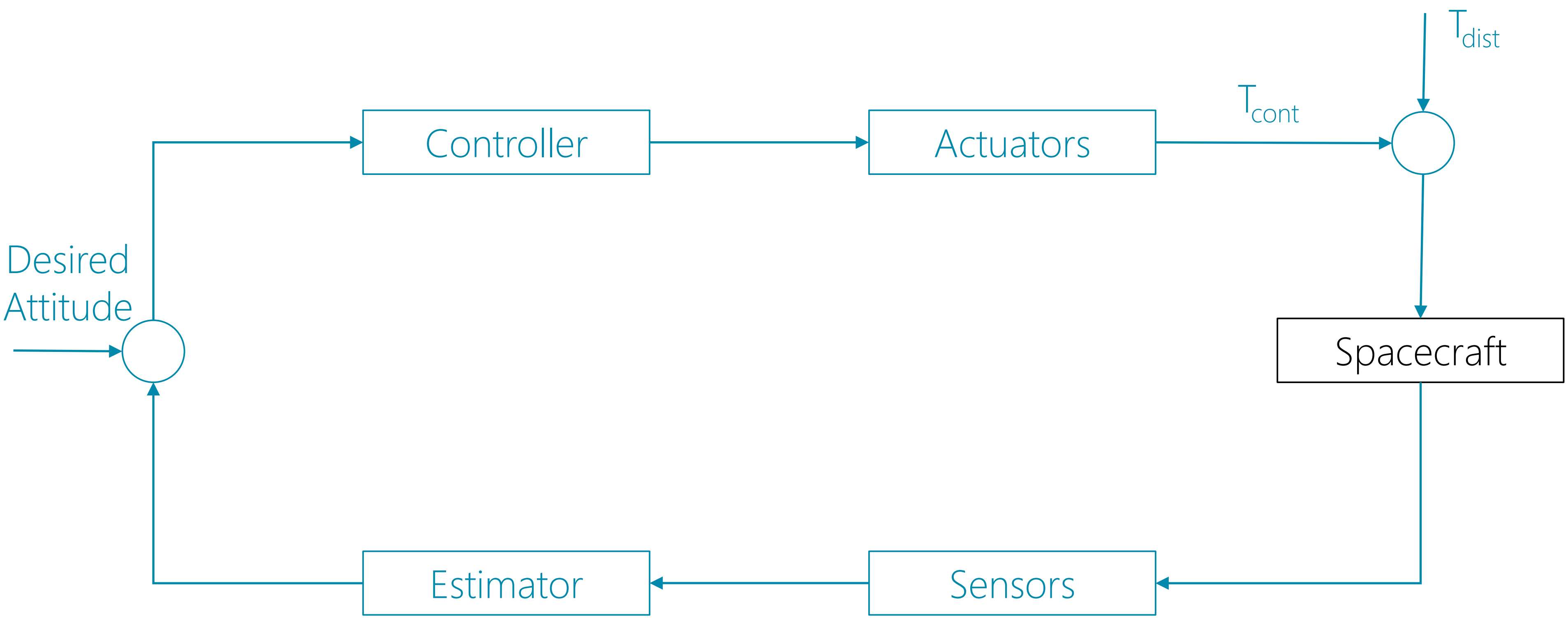
ACTIVE CONTROL

How can the spacecraft attitude be controlled actively?

ACTIVE CONTROL

Feedback loop for active control

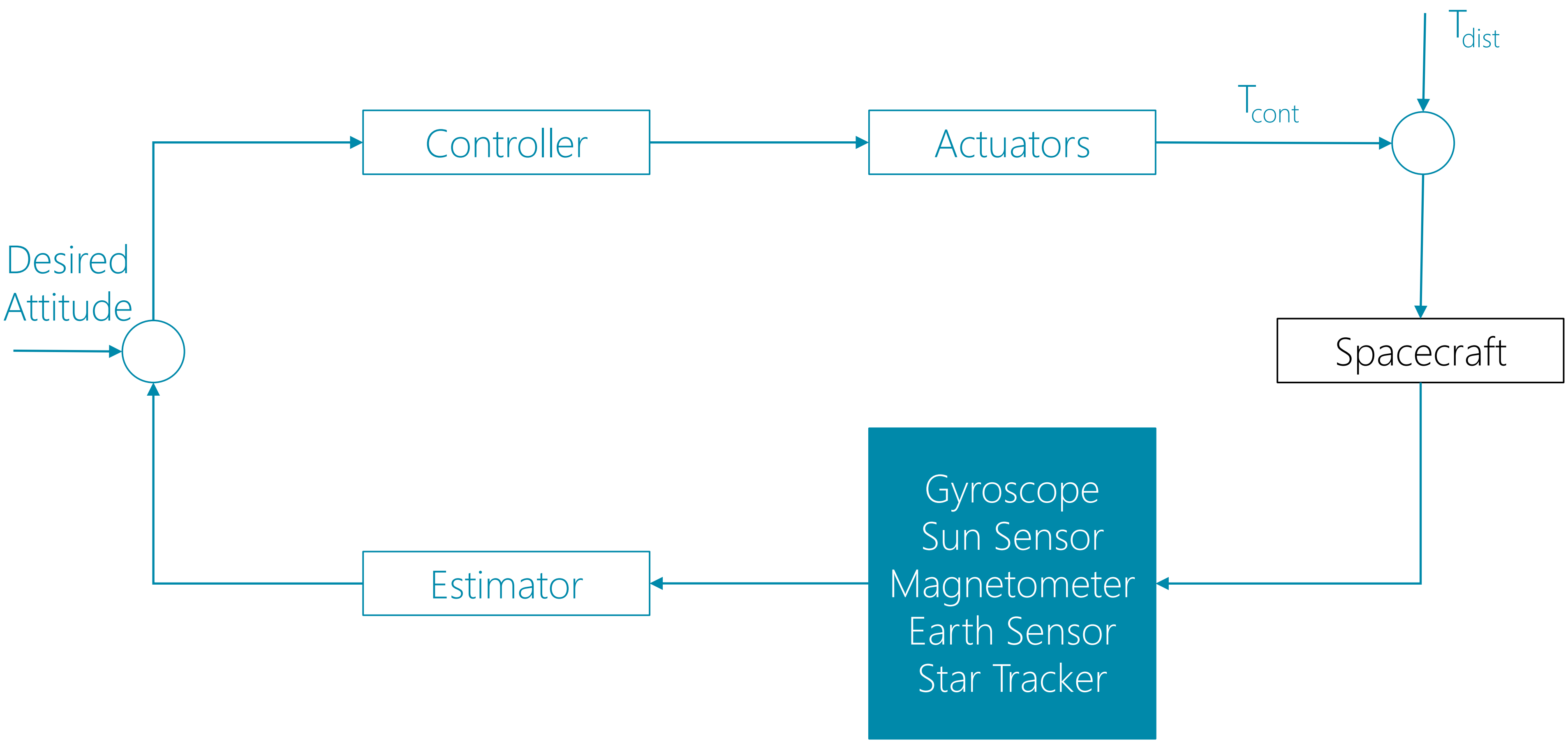
With active attitude control, we estimate the spacecraft attitude and control actuators to actively change it to a desired attitude.



ACTIVE CONTROL

Feedback loop for active control

With active attitude control, we estimate the spacecraft attitude and control actuators to actively change it to a desired attitude.



ACTIVE CONTROL

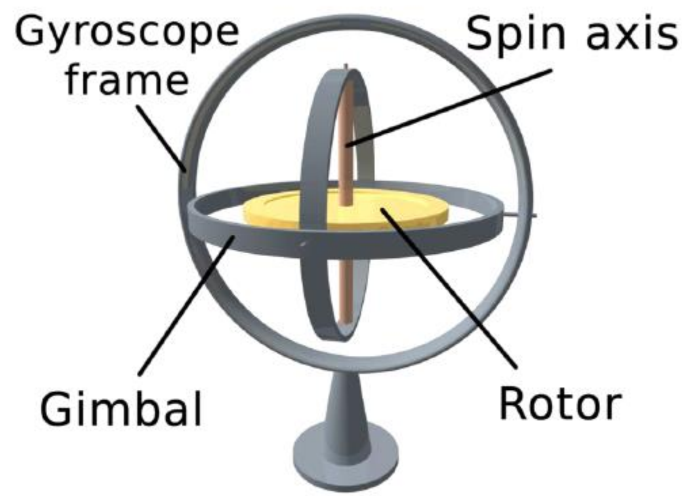
Gyroscope

The gyroscope is a special case among the sensors, in the sense that it does not measure the absolute attitude of the spacecraft, but rather the change in attitude (the rotational rate).

A gyroscope can therefore only propagate the attitude.

A set of three orthogonal gyroscopes measures the three components of the spacecraft angular velocity.

MEMS gyroscopes: Cheap, but low accuracy
Laser ring gyroscopes: Expensive, but high accuracy



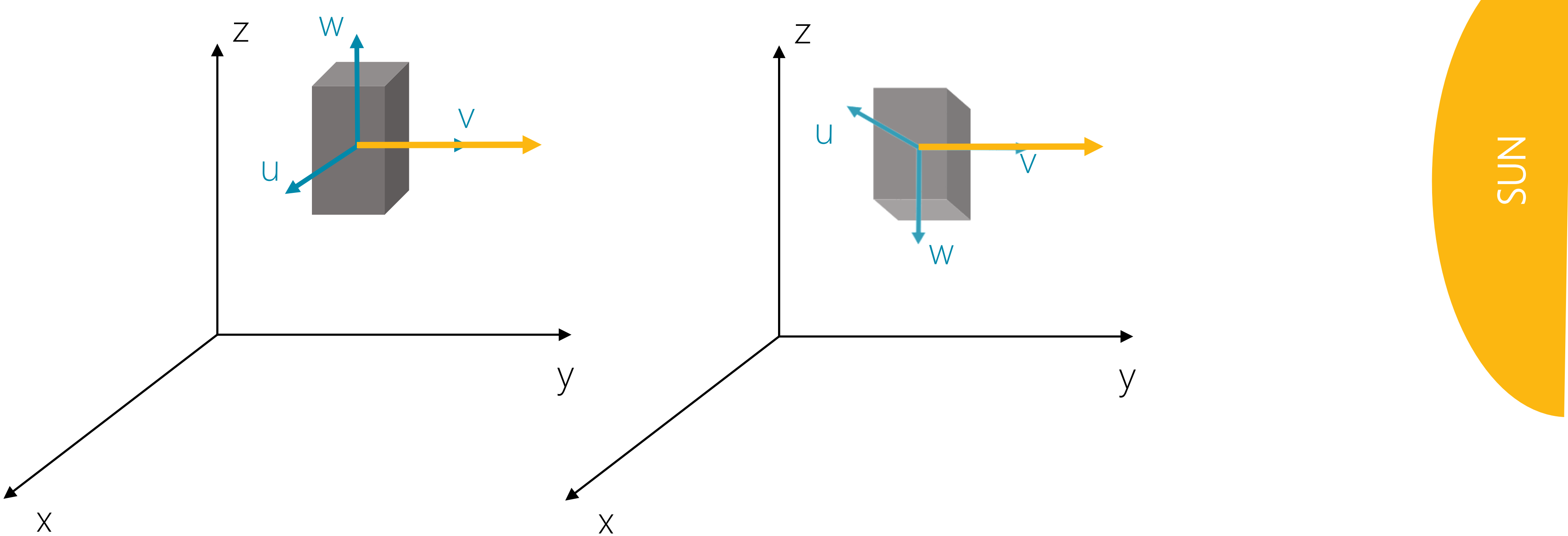
ACTIVE CONTROL

Sun Sensor

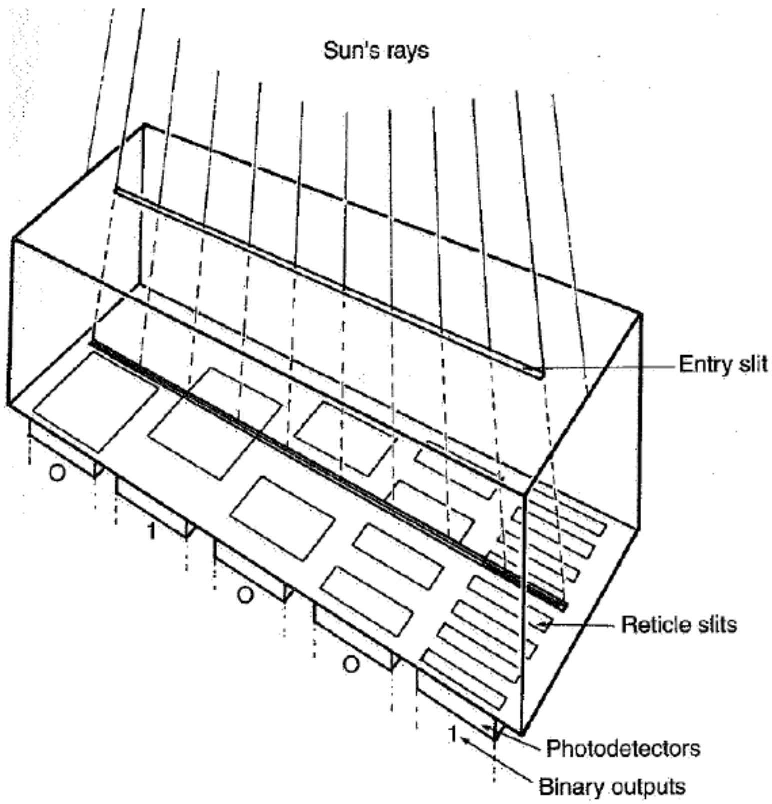
The sun sensors measures the position of the sun, relative to the spacecraft.

If we know the vector towards the sun in the body frame (measured by the sun sensor) and we know the vector towards the sun in the inertial frame (calculated based on the known spacecraft position and the time), we have obtained knowledge about the spacecraft attitude.

→ However: One vector is not enough to know the attitude!
(The spacecraft can still be rotated around the known vector) → A second vector is needed



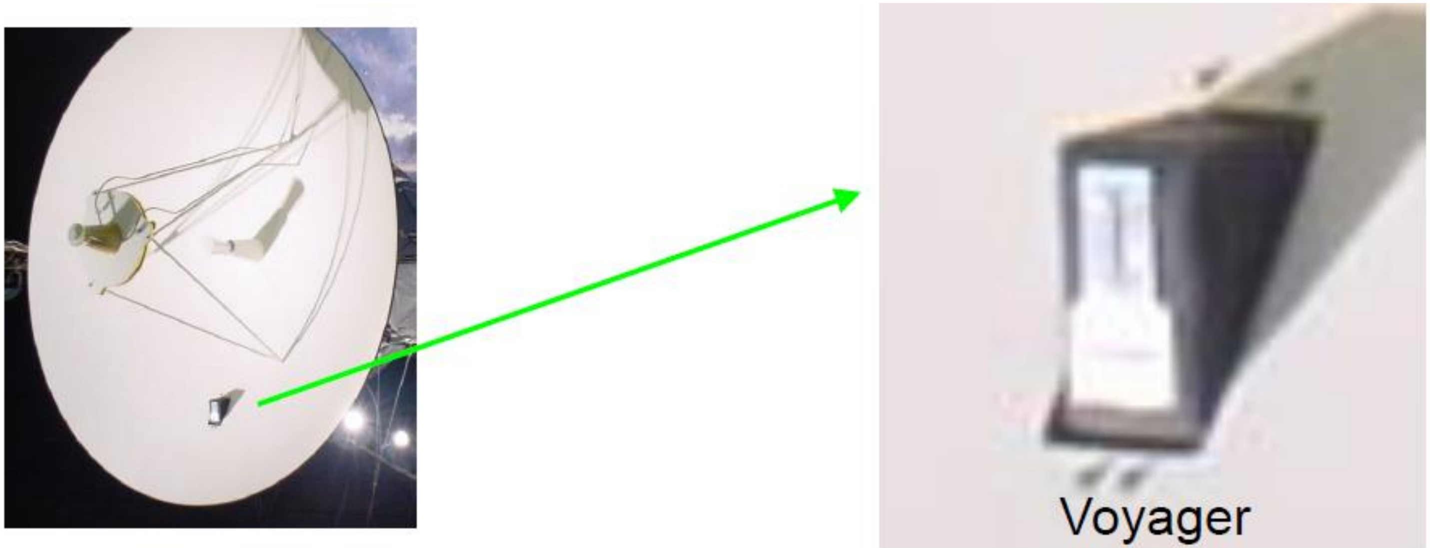
ACTIVE CONTROL
Sun Sensor



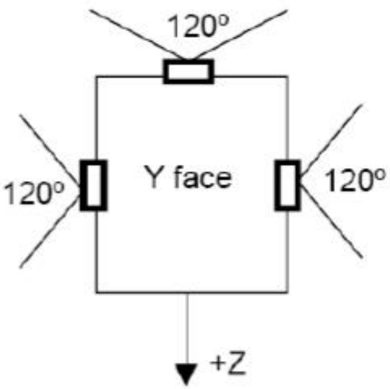
The digital output of this sensor allows to determine the plane in which the sun lies.

Two such detectors mounted orthogonally can determine the spacecraft to Sun vector in the body frame.

ACTIVE CONTROL
Sun Sensor



Field of View	120° x 120°
Output	2-axis, 16 bit data word per axis, through CAN interface
Accuracy	0.02° (95% probability)
Noise Equivalent Angle	0.01°
Resolution	0.01°
Data processing	In AOCS system
Operating temperature	-50°C to +80°C
Mass	250g
Power consumption	<1W
Supply Voltage	5 Volts DC (±0.25 VDC, 135 mV ripple)



ESEO

ACTIVE CONTROL

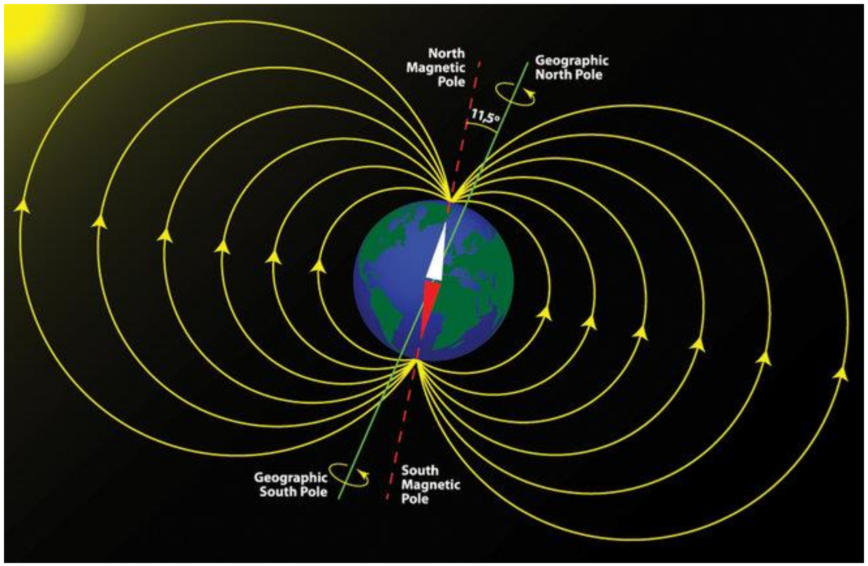
Magnetometer

The magnetometer measures the direction of the magnetic field, relative to the spacecraft.

With three orthogonal magnetometers, the magnetic field vector can be measured.

If we know the vector along the magnetic field in the body frame (measured by the magnetometer) and we know the vector along the magnetic field in the inertial frame (calculated based on the known spacecraft position and a magnetic field model), we have obtained knowledge about the spacecraft attitude.

One vector is not enough to know the attitude!



ACTIVE CONTROL

Earth Sensor

The Earth sensor measures the direction towards the Earth, relative to the spacecraft.

If we know the vector towards the Earth in the body frame (measured by the Earth sensor) and we know the vector towards the Earth in the inertial frame (calculated based on the known spacecraft position), we have obtained knowledge about the spacecraft attitude.

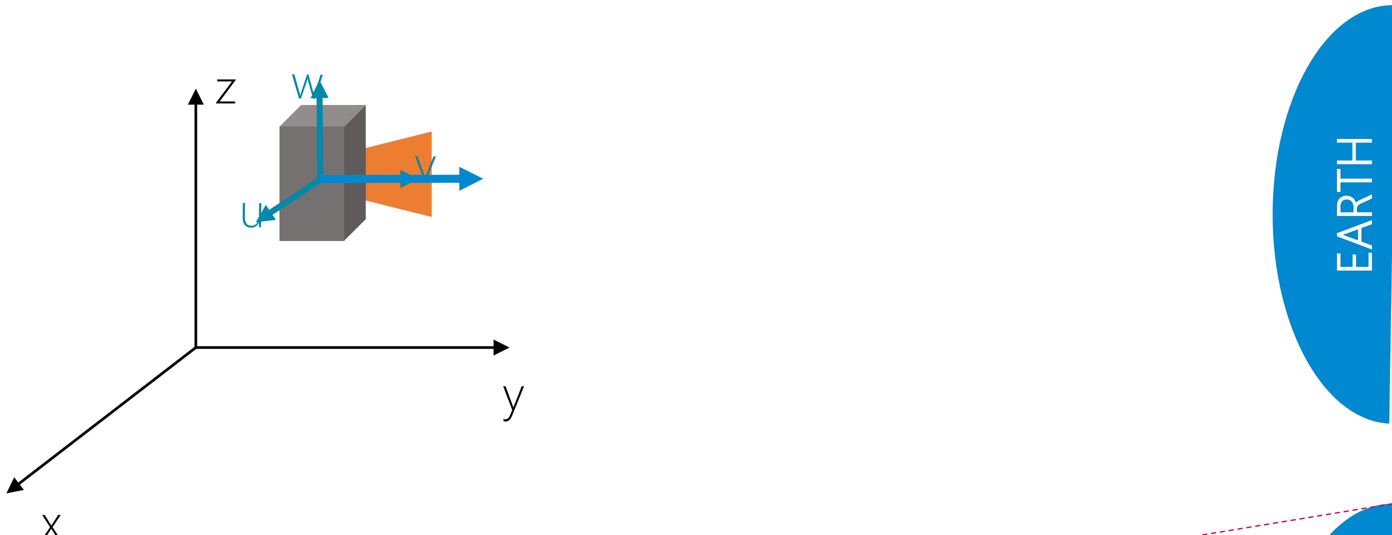
One vector is not enough to know the attitude!

ACTIVE CONTROL

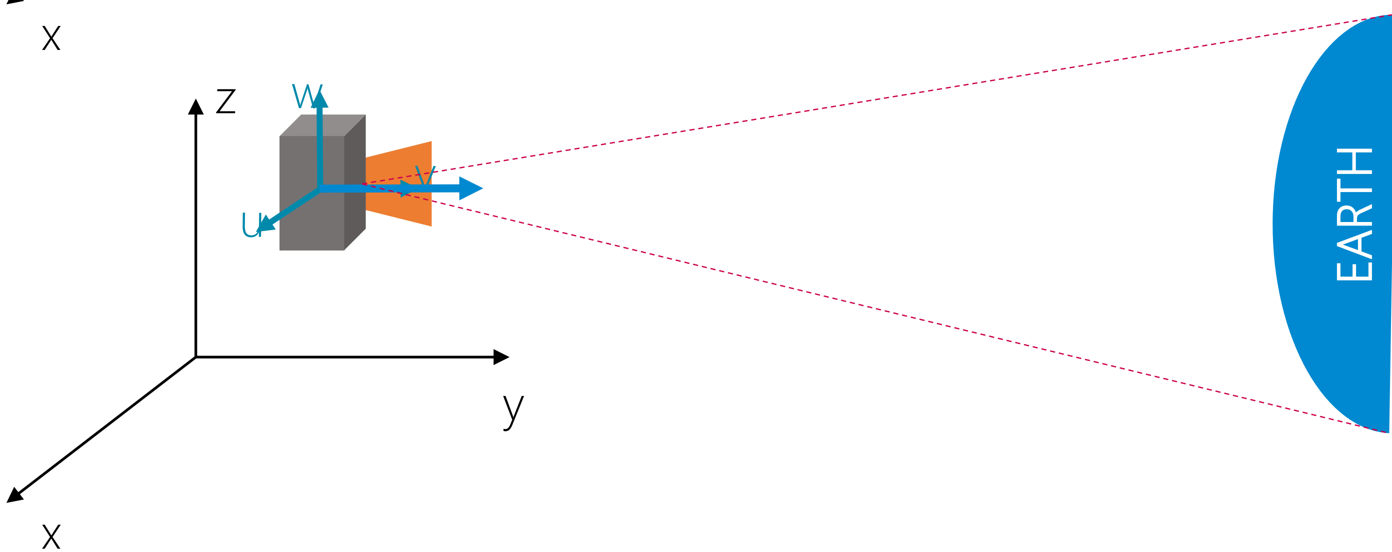
Earth Sensor

Earth sensors can determine the vector towards the center of the Earth by:

Taking an image of the Earth and performing image processing.



Sensing the horizon of the Earth (typically in infrared).
→ Works in eclipse



ACTIVE CONTROL

Star Tracker

The star tracker determines the attitude based on an image of the stars.

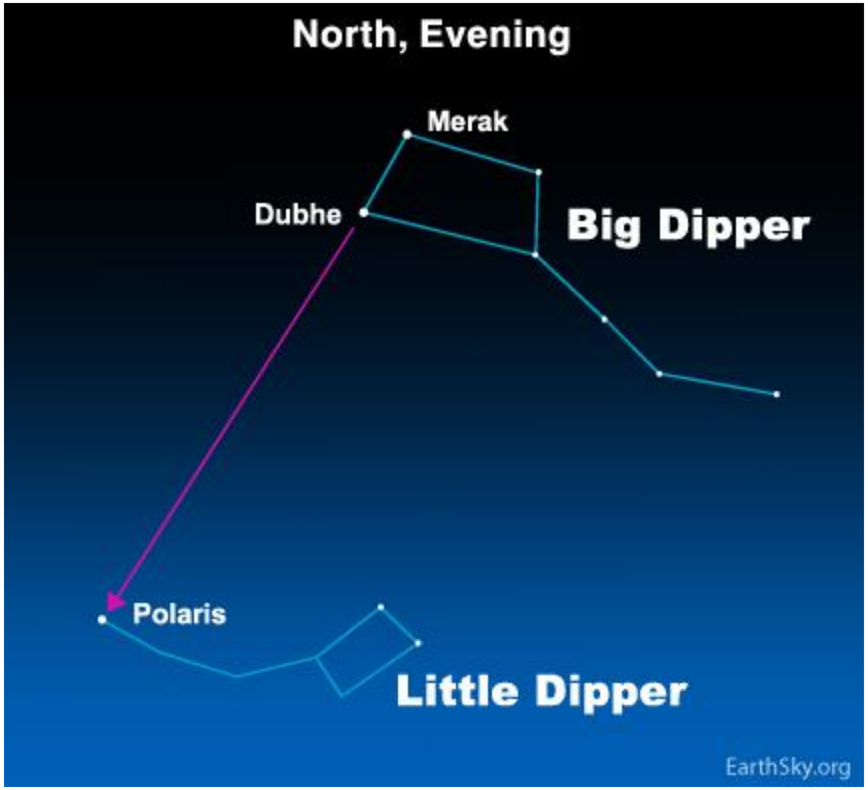
A star tracker can fully determine the spacecraft attitude (if there are at least two stars in the image).

Using the stars to determine your orientation and the direction in which you should travel has been done for centuries.

ACTIVE CONTROL

Star Tracker

How a star tracker works can be simply explained with an example that everyone knows.



Let's say we want to know where North is on a starry night.

1. We search for the Big Dipper and can recognize it based on its famous shape.

   Star Identification

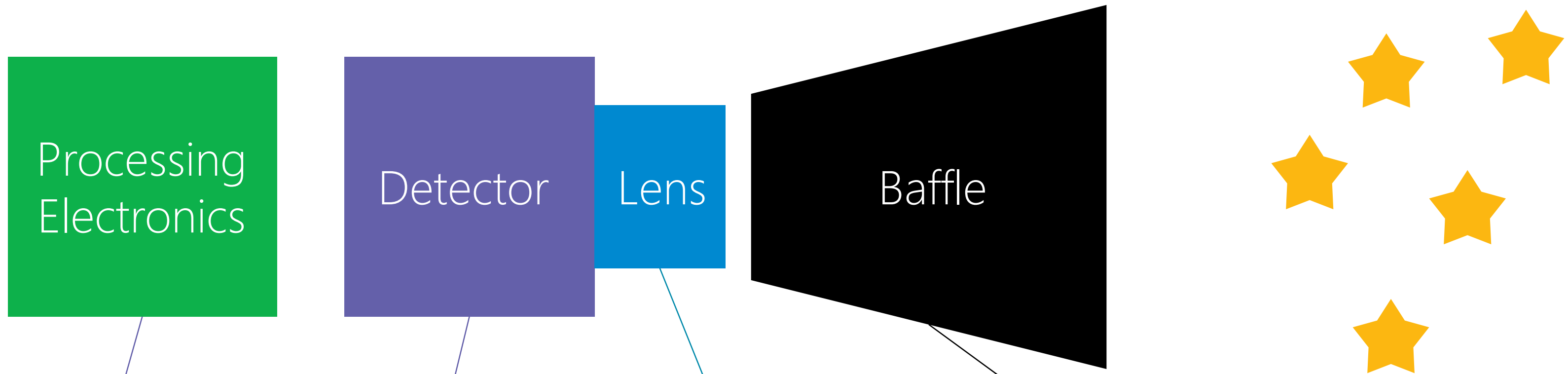
2. Based on this, we know where the North Star is. We know that if we look at it, we are looking North (knowledge on our orientation).

   Star Tracking

A star tracker follows the same principle, it recognizes stars in the image and matches it to their known position in the inertial frame. It does this for thousands of stars with high accuracy.

ACTIVE CONTROL

Star Tracker Hardware



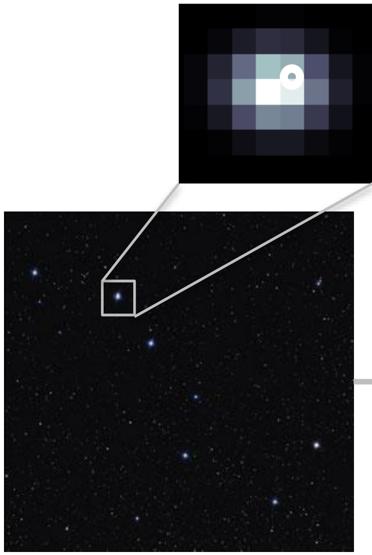
The detector actually takes the image. This used to be a CCD detector but more often, a CMOS is used.

The baffle shields the star tracker from light that comes from outside of the field of view (e.g. from the Sun, Moon or Earth).

The processing electronics determine the attitude based on the star image.

The lens focusses the light and determines the focal length, how much light enters, etc.

ACTIVE CONTROL
Star Tracker Software



Hipparcos Database

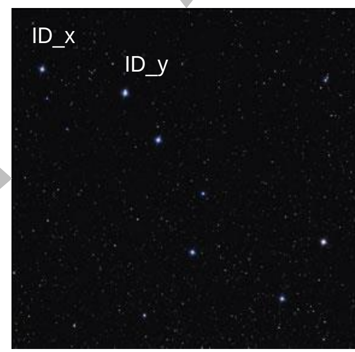


Image (body frame)

Star	x	y
ID_x	val	val
ID_y	-val	val
ID_...	...	...

Database (inertial frame)

Star	x	y	z
ID_x	value	value	value
ID_y	value	value	value
…	…	…	…

Attitude

Centroiding

Determine the centroids of stars

Lost-in-Space or Matching

Identify corresponding database stars

Tracking

Estimate the attitude

ACTIVE CONTROL

Sensor Overview

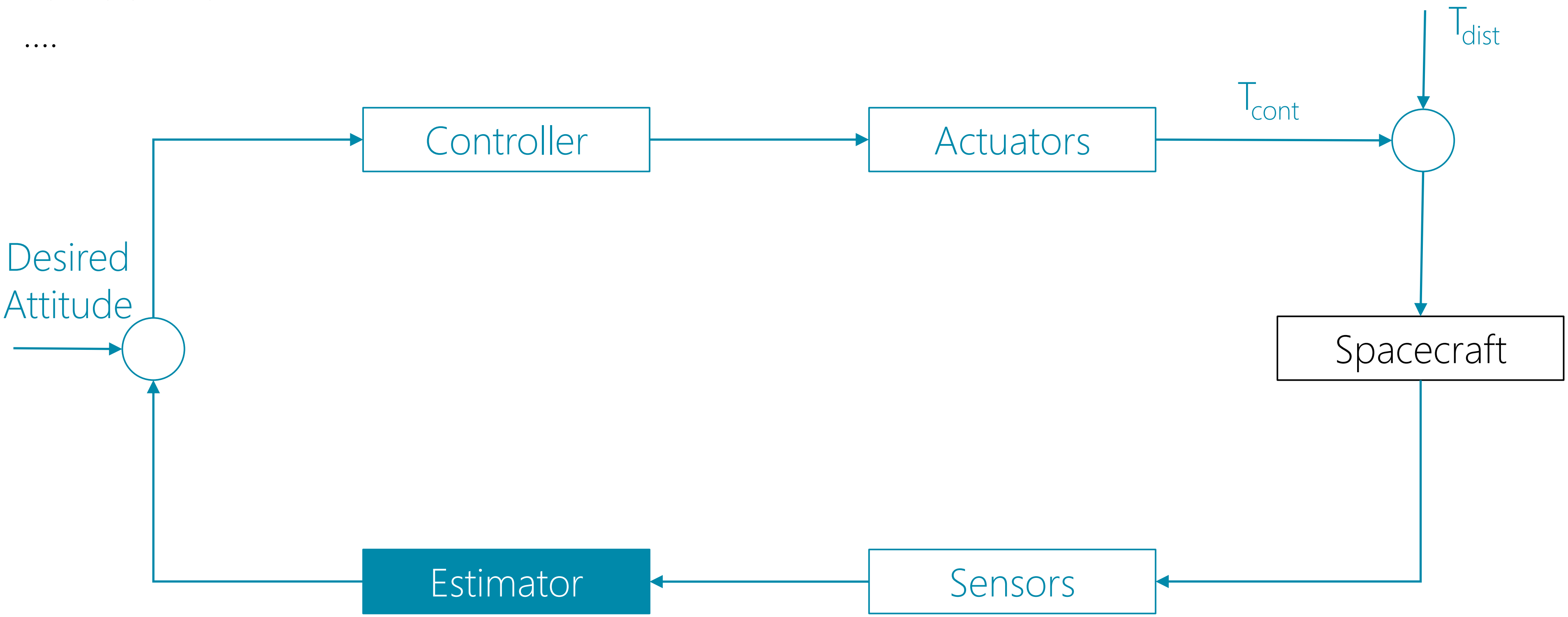
Sensor	Performance (deg)	Availability
Gyroscope	0.01/h (drift)	Continuous coverage
Sun Sensor	0.01-0.1 (angle that the sun subtends)	Outside of eclipse (intermittent use)
Magnetometer	1 (variability and uncertainty of the magnetic field)	Continuous coverage, but below 6000 km
Earth Sensor	0.02-0.03 (Earth oblateness + fuzziness of horizon)	Continuous coverage
Star Tracker	0.001	Not blocked by the Earth or Sun in the FOV (intermittent use)

ACTIVE CONTROL

Estimator

The estimator fuses the information of different sensors and can use a model of the spacecraft to obtain an accurate estimate of the spacecraft attitude and rotational rate.

- Extended Kalman Filter
- Unscented Kalman Filter
- Particle Filter
- ....

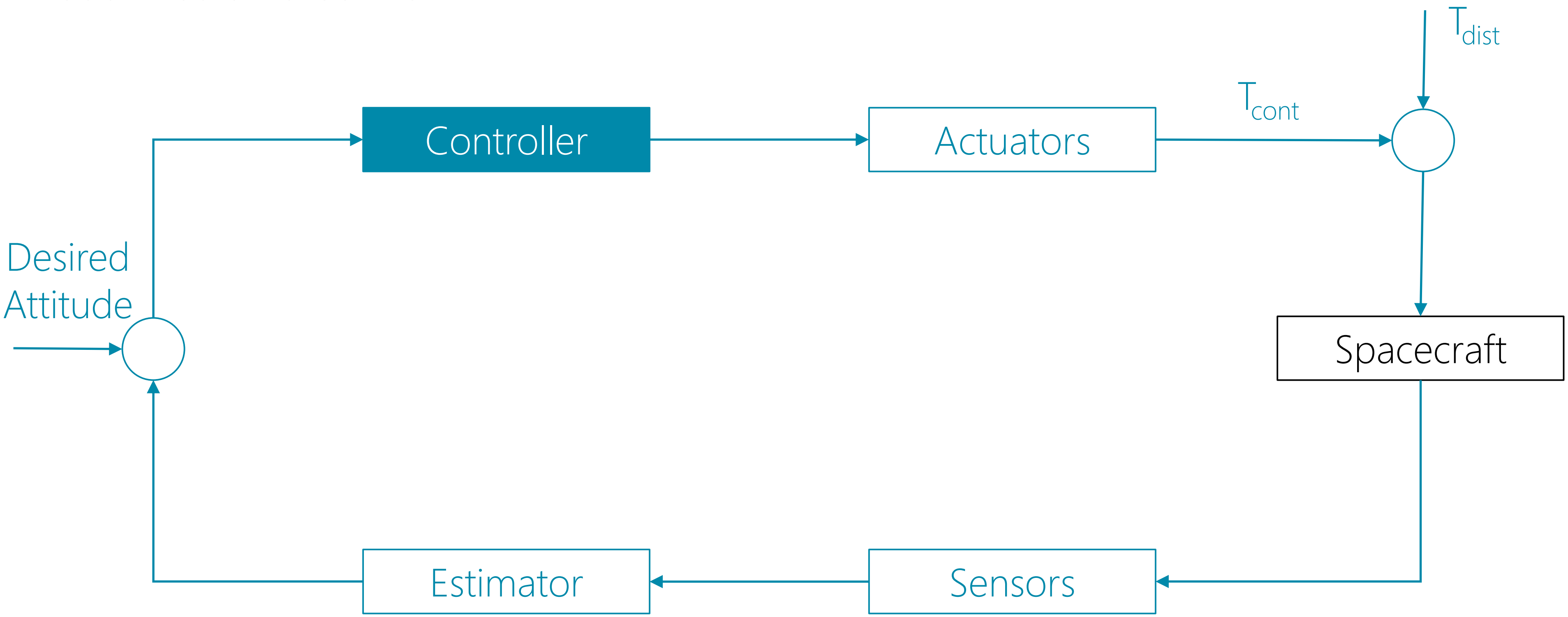


Important and interesting Control Theory problems, but not the focus of this lesson.

ACTIVE CONTROL
Controller

The controller determines the action of the actuators. A spacecraft typically has a set of controllers for different situations (e.g. to detumble from fast rates, for fine control, etc.)

- Detumble Bdot controller
- PID Controller
- Model Predictive Control

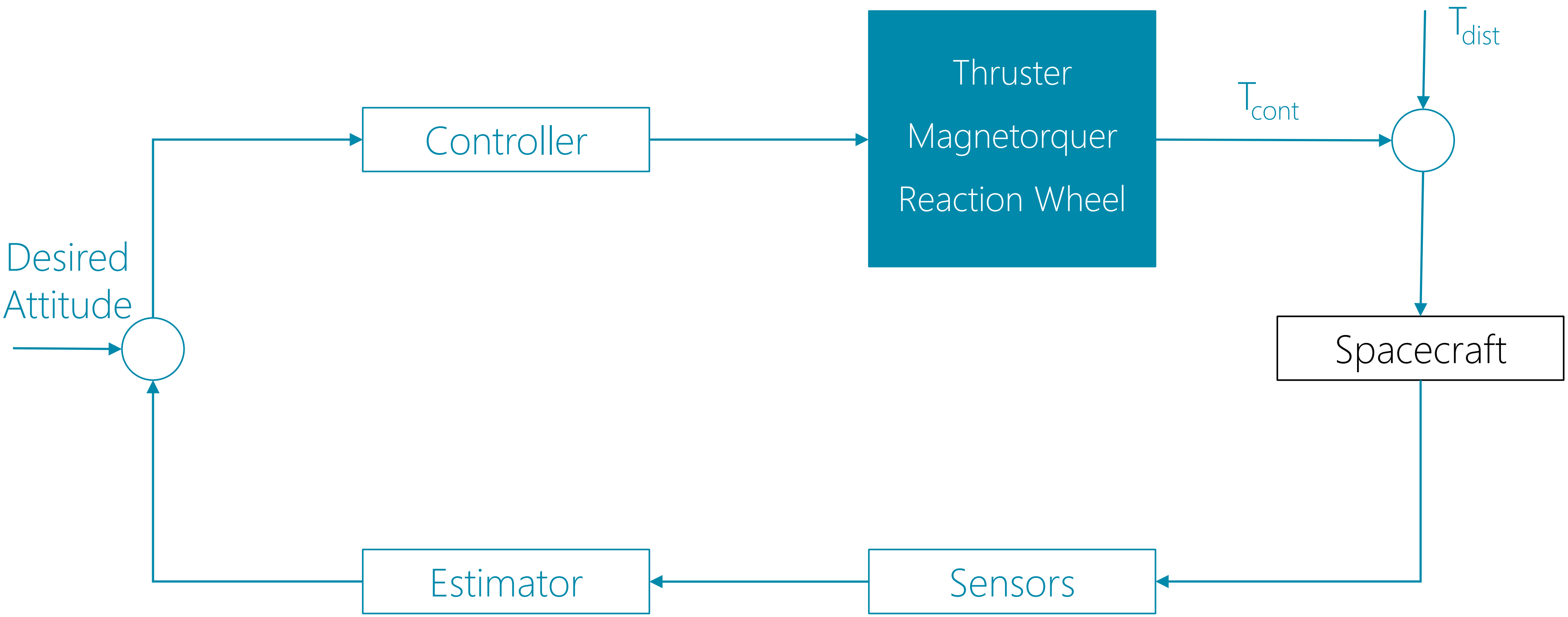


Important and interesting Control Theory problems, but not the focus of this lesson.

ACTIVE CONTROL

Actuators

The actuators change the orientation of the spacecraft



ACTIVE CONTROL

Actuators

- Torques
  - External
    - Thrusters
    - Magnetorquers
  - Internal
    - Reaction Wheel

Affect the total angular momentum

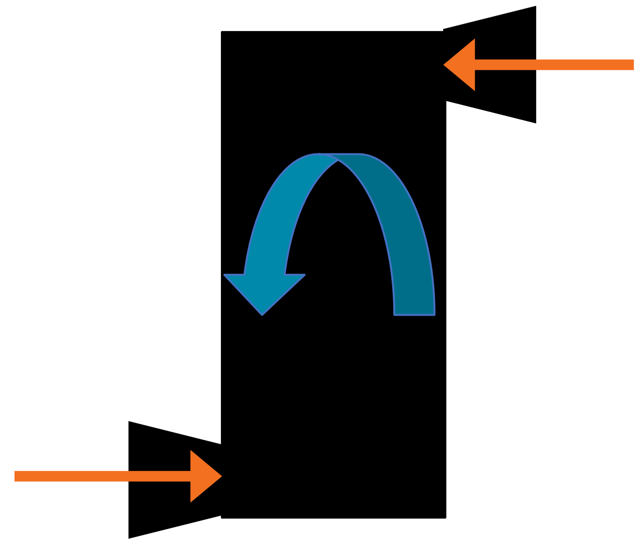
Necessary

Total angular momentum conserved but influence spacecraft orientation

Optional

ACTIVE CONTROL
Thrusters

- Common and effective means of providing spacecraft attitude control.
- Common on satellites intended to operate in relatively high orbit, where a magnetic field will not be available for angular momentum dumping.
- Potentially largest source of torque
- Usually a redundant set of thrusters
- Thrusters for orbit control may or may not be used as attitude thrusters as well



ACTIVE CONTROL

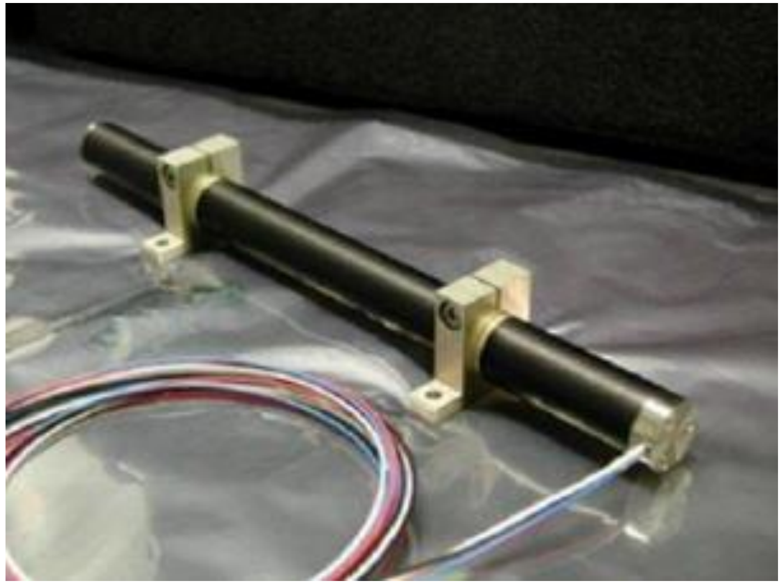
Magnetorquers

A magnetorquer is in essence an electrical coil that generates a magnetic moment m, that interacts with the Earth's magnetic field to generate a torque.

This leads to a torque:

$$\vec{T} = \vec{m} \times \vec{B}$$

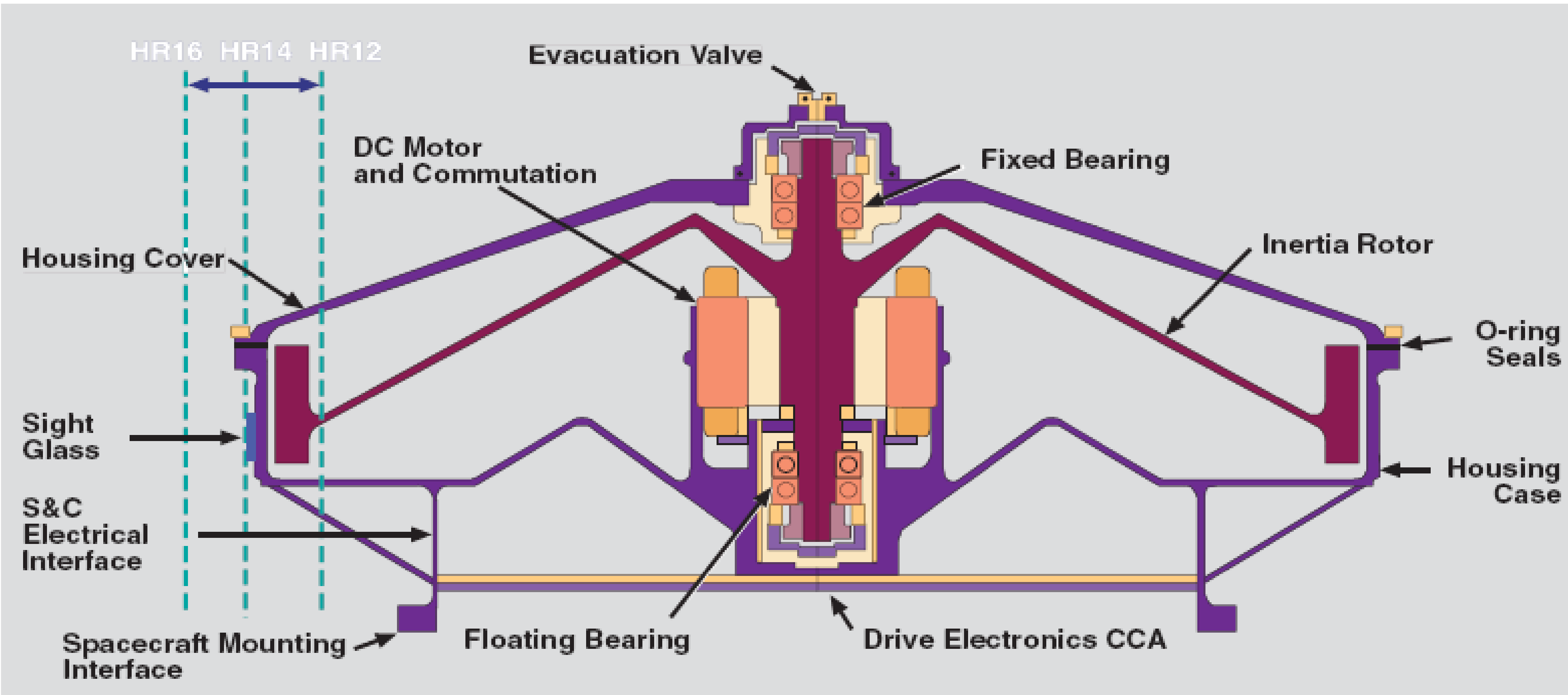
Magnetorquers do not allow for full 3-axis control: If the magnetic moment is aligned with the Earth's magnetic field, no torque can be created.



ACTIVE CONTROL

Reaction Wheels

Reaction wheels are spinning flywheels mounted on a central bearing whose rate of rotation can be adjusted by an electric motor.



ACTIVE CONTROL

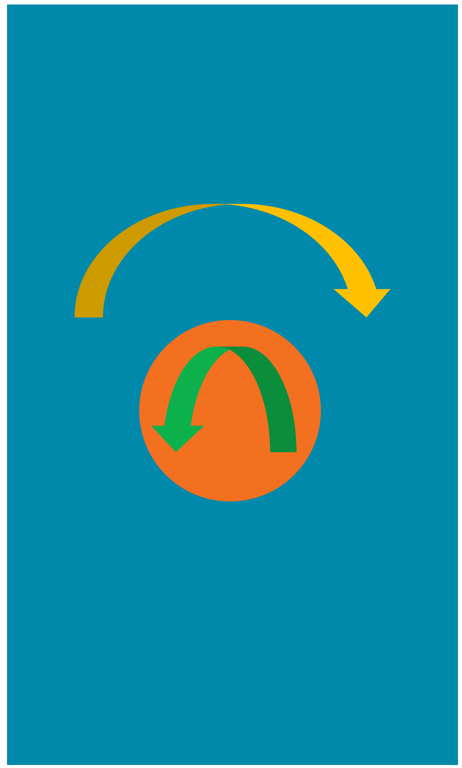
Reaction Wheels

They exchange momentum with the spacecraft by changing wheel speed but **no influence on the total angular momentum**.

➔ If the reaction wheel spins up in one direction, the satellite spins up in the other direction.

$$\vec{H}_{sat} + \vec{H}_{wheel} = \vec{0}$$

$$\vec{I}_{sat}\vec{\omega}_{sat} + \vec{I}_{wheel}\vec{\omega}_{wheel} = \vec{0}$$



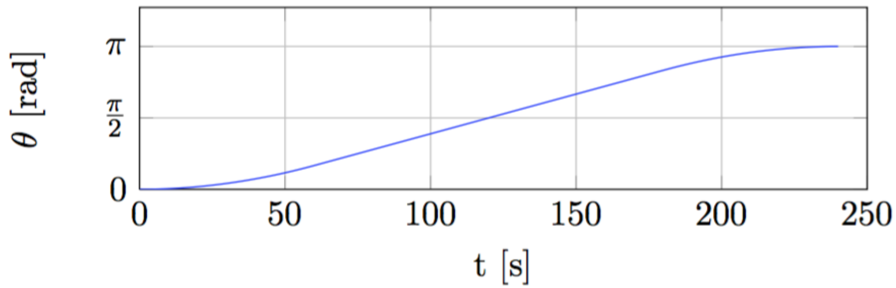
What do the torque, velocity and orientation profile of the satellite look like when performing a slew maneuver with a reaction wheel?

https://www.youtube.com/watch?v=-Cc-jGnIwCM

ACTIVE CONTROL

Reaction Wheels: Slew

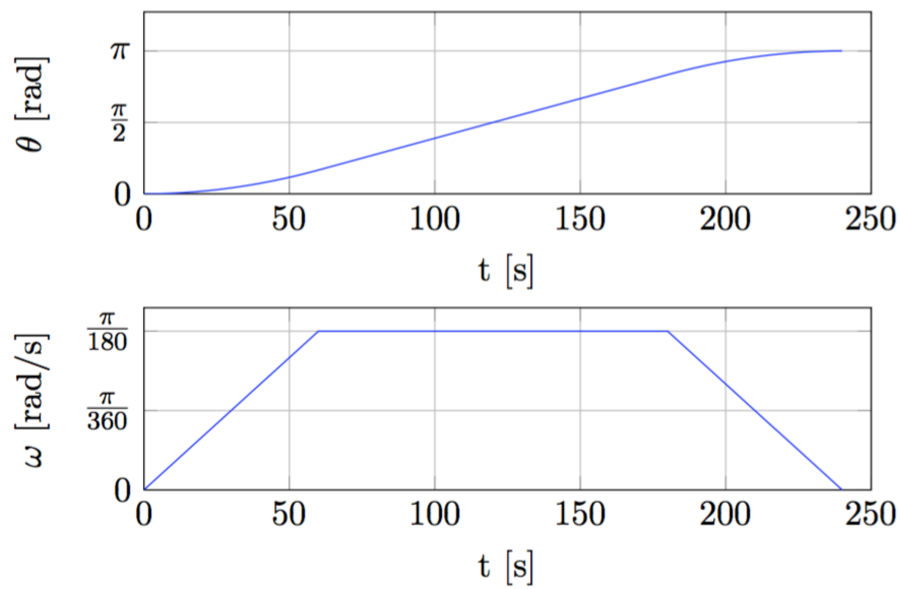
Let’s say we want to perform a slew maneuver of 90 degrees around one axis.



ACTIVE CONTROL

Reaction Wheels: Slew

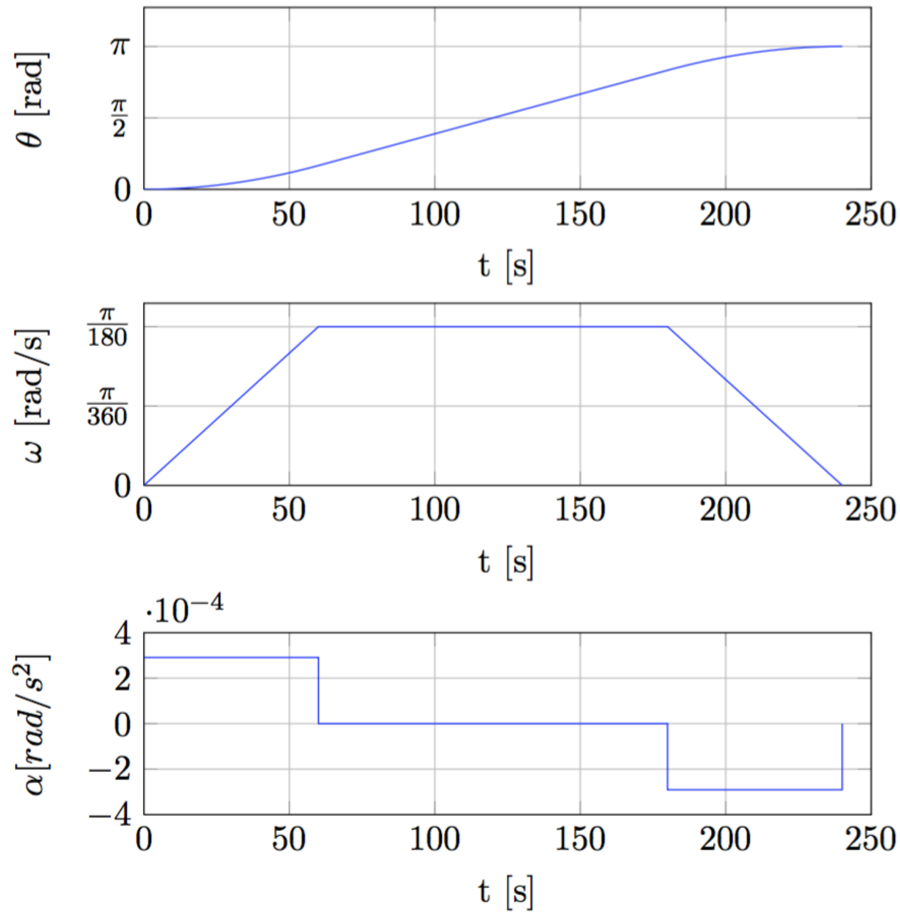
Let's say we want to perform a slew maneuver of 90 degrees around one axis.



ACTIVE CONTROL

Reaction Wheels: Slew

Let's say we want to perform a slew maneuver of 90 degrees around one axis.

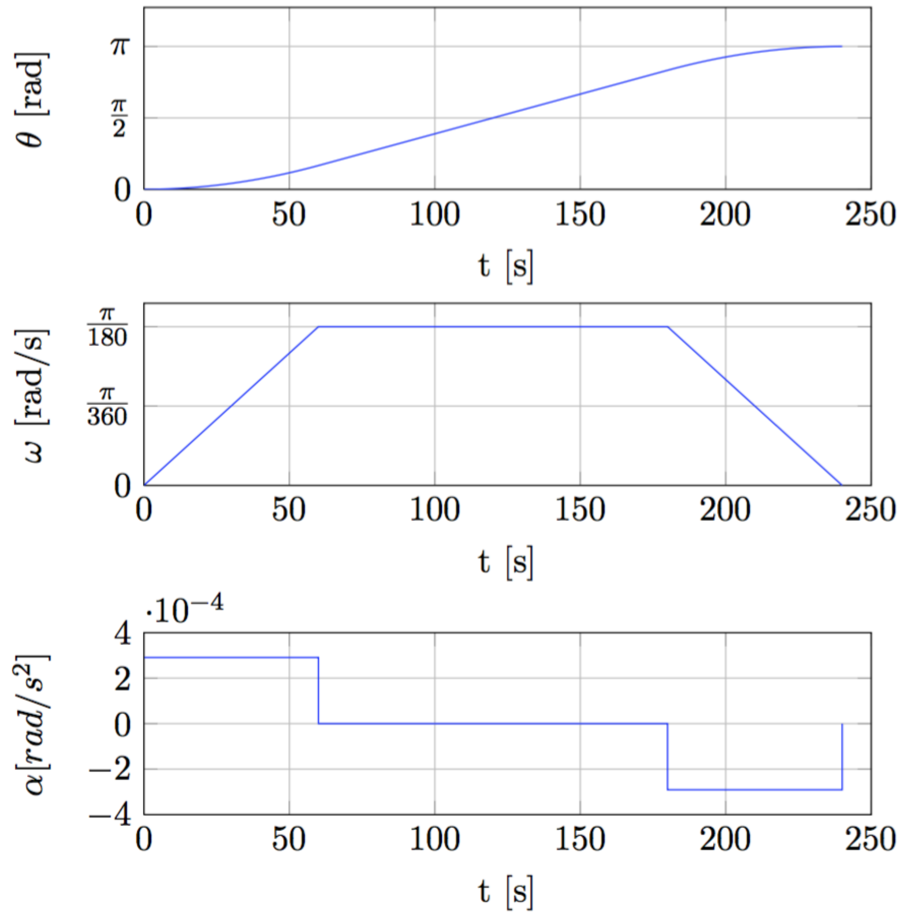


ACTIVE CONTROL

Reaction Wheels: Slew

Let's say we want to perform a slew maneuver of 90 degrees around one axis.

Momentum is borrowed from the wheels and then returned to the wheel. There is no net change of momentum of the wheel in this case.



ACTIVE CONTROL

Reaction Wheels: Resist disturbance torques

External torques give rise to unwanted angular momentum. The control system applies control torques to the reaction wheels to leave the spacecraft angular momentum unchanged.

Example: when a clockwise disturbance torque is imposed on the spacecraft, the attitude control system holds attitude constant by rotating a reaction wheel counterclockwise.

ACTIVE CONTROL

Reaction Wheels: Momentum Dumping

When disturbing torques do not average out over one orbit, constant wheel speed increase is necessary to hold the spacecraft.

There is a risk to “saturate” the wheel; the wheel is spinning at its maximum rate and cannot counterbalance further disturbing torques.

The stored momentum needs to be cancelled; this process is called momentum dumping.

Thrusters or magnetorquers are used to hold the spacecraft stationary while reducing wheel speed.

ACTIVE CONTROL

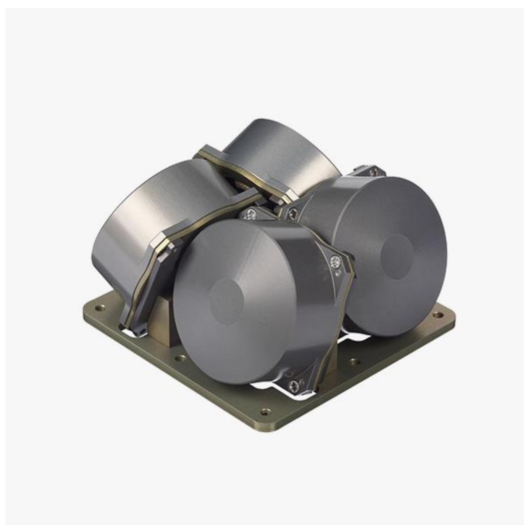
Reaction Wheels: Some Remarks

Wheels are not operated near 0 rpm, because:

- Nonlinear wheel friction.
- Zero-crossing is a large factor in bearing wear
- Hard to control electronically

The rotational axis of a wheel is usually aligned with a vehicle control axis; the vehicle must carry one wheel per axis for full attitude control.

Redundancy is usually desired, requiring four or more wheels, in a position oblique to all axes.



https://n-avionics.com/subsystems/cubesat-reaction-wheels-control-system-satbus-4rw/

ACTIVE CONTROL

Reaction Wheels: Some Remarks

PERFORMANCE ITEM	UNIT	CAPABILITY HR12	HR14	HR16
Momentum	N-m-s	12, 25, 50[2]	25, 50, 75	50, 75, 100[1]
Reaction torque				
Nominal	N-m		0.1 to 0.2[3]	
Extended	N-m		up to 0.4 (@3000 rpm)[4]	
Rotor Balance[6]				
Static	g-cm	0.15, 0.24, 0.44	0.22, 0.35, 0.48	0.28, 0.38, 0.48
Dynamic	g-cm^2	2.2, 4.6, 9.1	4.6, 9.1, 13.7	7.7, 11.5, 15.4
Peak Power	Watts		105, 195[5]	
Steady State (@ 6000 rpm)	Watts		< 22 typical	
Bus Voltage Range	Volts		14 up to 80	
Wheel Speed	rpm		± 6000	
Mass	kg	6.0, 7.0, 9.5	7.5, 8.5, 10.6	9, 10.4, 12
Integrated Wheel Outline (Height x Width)	mm	159 x 316	159 x 366	178 x 418
Separate Electronics Outline	mm	WU H148X316D WDE H60XW169XL230	WU H148X366D WDE H60XW169XL230	WU H152X418D WDEH60XW169XL230
Life				
Storage	Years		> 5	
On-orbit Operation	Years		> 15	
Radiation Hardness Capability	Krads (Si)		> 300	
Parts Screening			S	
Operational Temperature Range (Qual)	°C		-30 to 70	
Vibration	Grms		13.8	
Interface	NA		Analog/Digital	

ACTIVE CONTROL

Actuators Overview

Actuator	Performance (deg)	Availability
Thrusters	0.05	Used in any environment, but needs propellant (limits lifetime)
Magnetorquers	1-5	Need a strong magnetic field (near Earth usage)
Reaction Wheels	0.005	Used in any environment, but need external torque device for momentum dumping.
Control Moment Gyros	0.005	Used in any environment

ACTIVE CONTROL
Examples of ADCS Configurations

Depending on the mission requirements, different ADCS configurations can be used.

The simplest configuration that delivers the required performance should be selected.

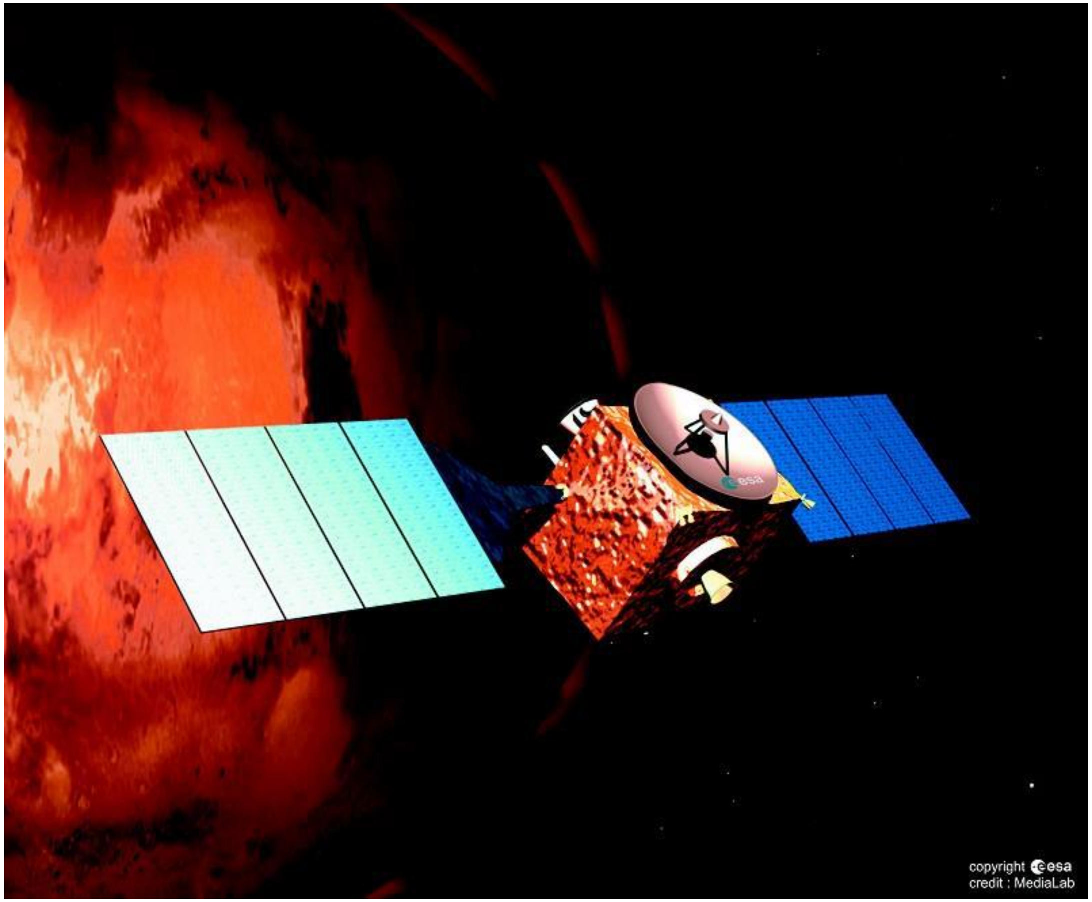
> 5 deg	If no control is needed and we just need to keep the spacraft stable → Passive stabilization Otherwise: sun sensors + magnetometer and magnetorquers
1-5 deg	Sun sensors + horizon sensors + magnetometers + gyroscope Reaction wheels or magnetorquers (thrusters if spin stabilization is used)
0.1-1 deg	Star Tracker + (Sun sensors + horizon sensors + magnetometers + gyroscope) Reaction wheels with magnetorquers or thrusters Flexible effects not modeled in the controller
<0.1 deg	Star Tracker + (Sun sensors + horizon sensors + magnetometers + gyroscope) Reaction wheels with magnetorquers or thrusters Flexible effects modeled in the controller Possibly vibration-isolation payload platform

ACTIVE CONTROL

Examples of ADCS Configuration: Mars Express

8 attitude thrusters (10 N each)
4 reaction wheels (12 NMs)

Star trackers
Gyroscopes
Sun sensors



ACTIVE CONTROL

Designing the ADCS

INPUTS

Mission: orbit, cost, lifetime, payload, pointing requirements, spacecraft type, etc.

Thermal control

Communication

Power

Propulsion

Component selection

Configuration

Computational architecture

Hardware design

OUTPUTS

Propulsion
Thruster type + amount of propellant

Power
(ADCS power consumption

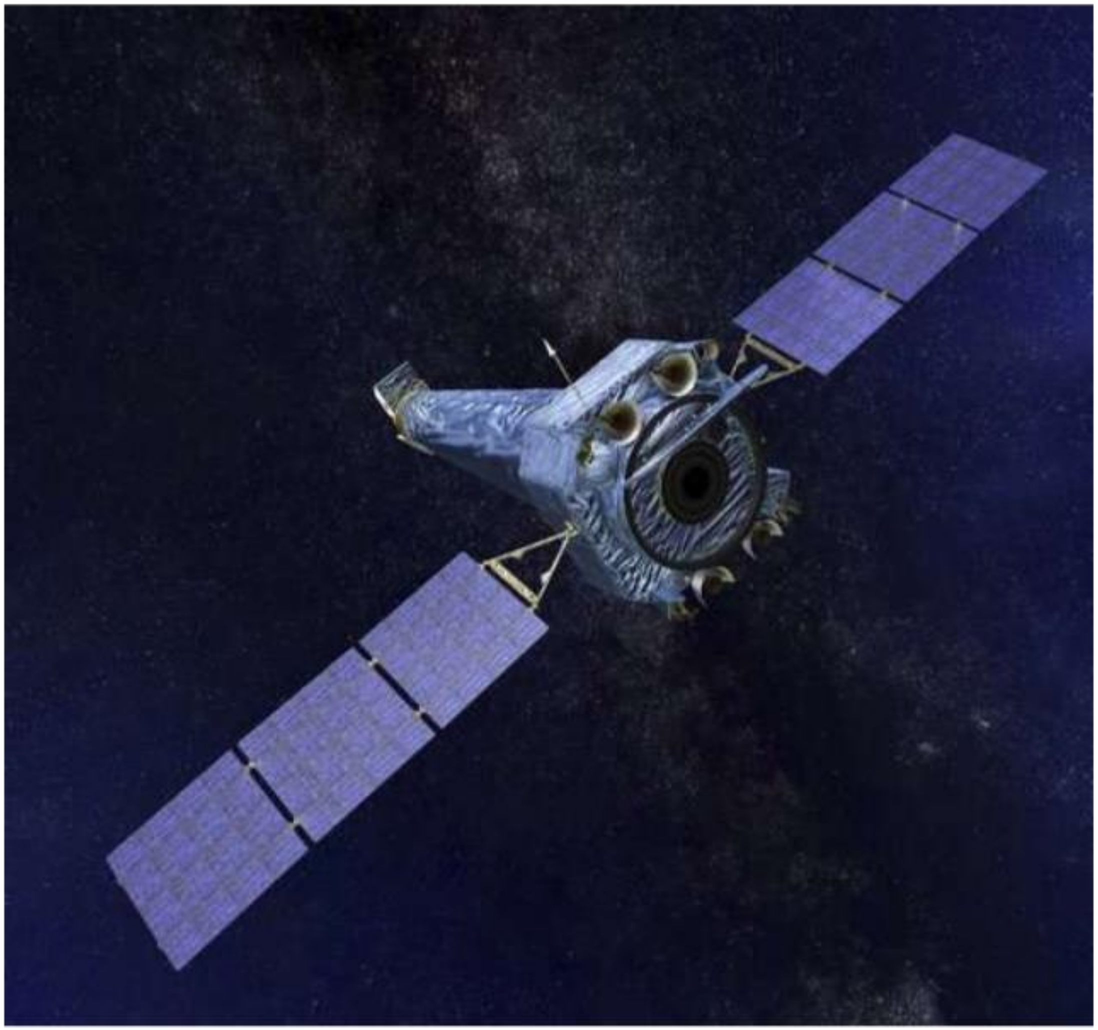
Structure
Center of mass + inertia constraints, flexibility, sensor and thruster locations

ACTIVE CONTROL

When things go wrong

Another NASA space telescope shuts down in orbit

October 12, 2018 by Marcia Dunn



Aging reaction wheels

ACTIVE CONTROL

When things go wrong

Software error doomed Japanese Hitomi spacecraft

Space agency declares the astronomy satellite a loss.

Alexandra Witze

28 April 2016

PDF | Rights & Permissions

Star tracker errors (due to South Atlantic Anomaly)

Had to rely on gyroscopes which gave incorrect measurement. They saw a spin rate of 20 deg/s while this was not the case.

RW started counteracting this non-existing spin

MTQs were not aligned correctly to desaturate the reaction wheels.

Thrusters had to desaturate, but fired in the wrong direct, increasing the spin rate

The satellite actually started spinning at high rate

OVERVIEW

- Introduction
- Rationale
- Attitude Requirements and Errors
- Governing Equations
- Attitude Parameterization
- Disturbance Torques
- Passive Control
- Active Control
- Going Further
- I am interested, what now?

GOING FURTHER

What lies beyond?

Going Further
What lies beyond

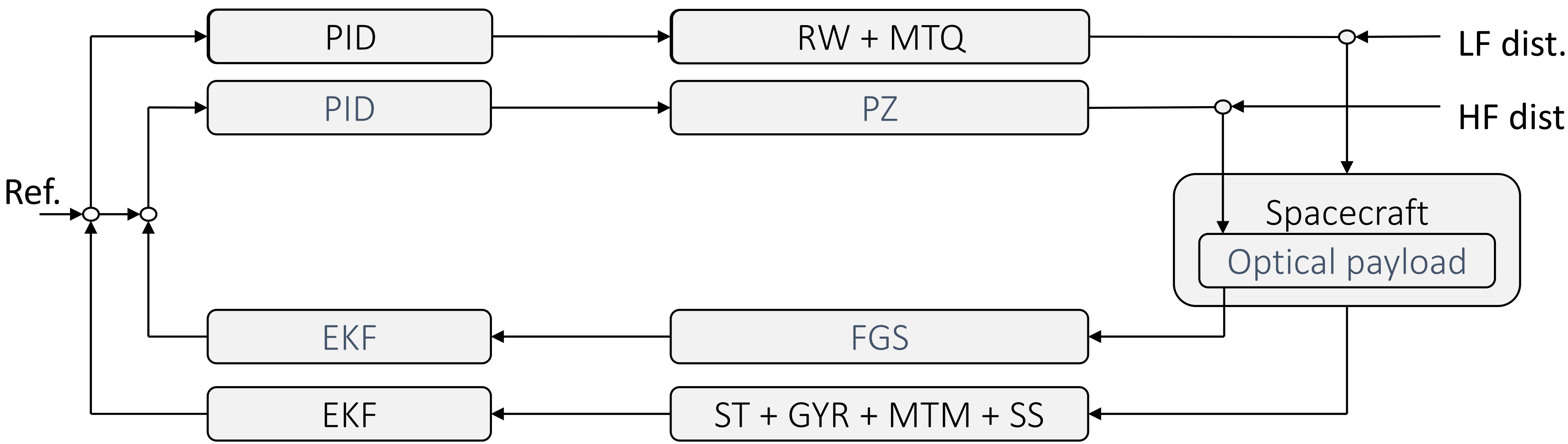
Main trends:

- Miniaturization: Small spacecraft are on the rise and the ADCS needs to scale with it.
- More accurate: There is no such thing as “good enough” for scientists. They always want higher accuracy

Going Further

Higher accuracy: Novel approach needed

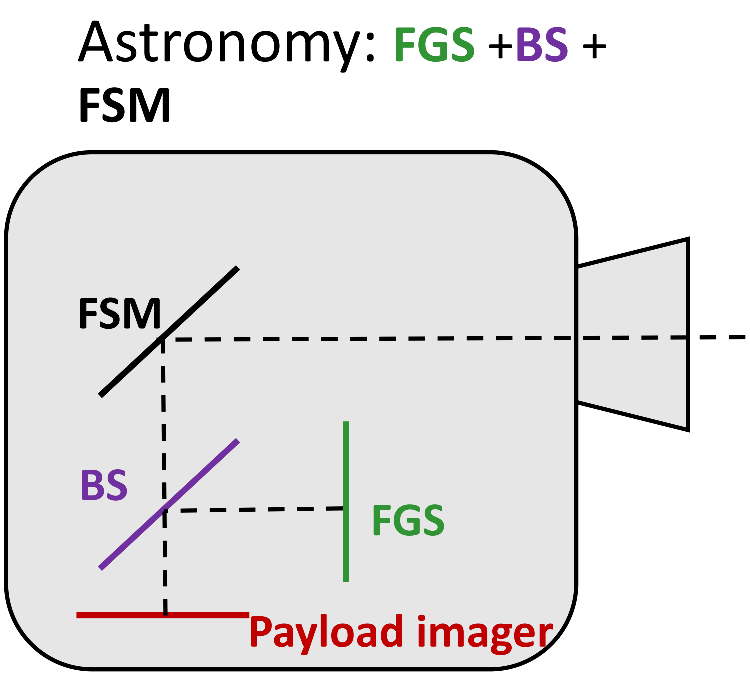
Once we want to point a satellite with arc second range accuracy, we can no longer rely on the ADCS alone.
(The sensors and actuators are too slow to compensate for high frequency errors)

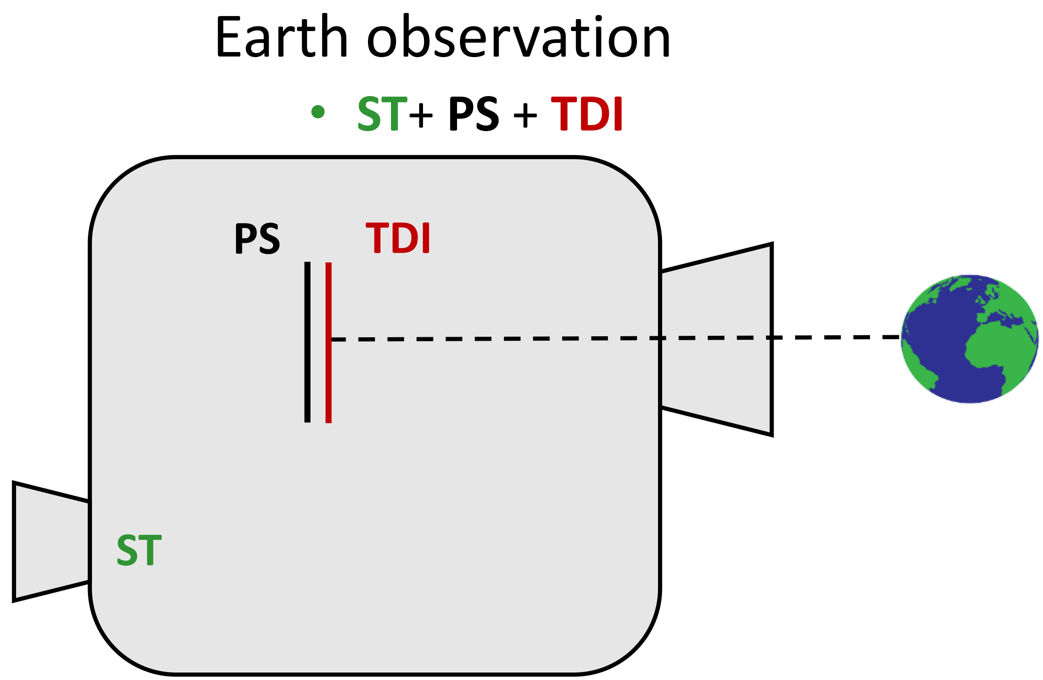


Going Further

Higher accuracy: Novel approach needed

Once we want to point a satellite with arc second range accuracy, we can no longer rely on the ADCS alone.
(The sensors and actuators are too slow to compensate for high frequency errors)





OVERVIEW

- Introduction
- Rationale
- Attitude Requirements and Errors
- Governing Equations
- Attitude Parameterization
- Disturbance Torques
- Passive Control
- Active Control
- Going Further
- I am interested, what now?

I AM INTERESTED, WHAT NOW?

How can I find eternal glory in the field of attitude determination and control?

REFERENCES

J. R. Wertz, Spacecraft Attitude Determination And Control. D Reidel Publishing Company, Dordrecht, Holland, 1978

J.R. Wertz, Space Mission Analysis and Design, 3rd ed. Hawthorne, CA and New York NY: Microcosm Press and Springer, 1999

J. Vandersteen, "Observation and Estimation for Space Applications," KU Leuven, 2012

T. Delabie, "Star Tracker Algorithms and a Low-Cost Attitude Determination and Control System for Space Missions," KU Leuven, 2012