Laser Swarm

Mid term review

Group 13, Aerospace Engineering

19-5-2010

Contents

- Project plan

- Key requirements

- Trade-off method

- Subsystem Trade-offs

- Orbit design

- Software tool

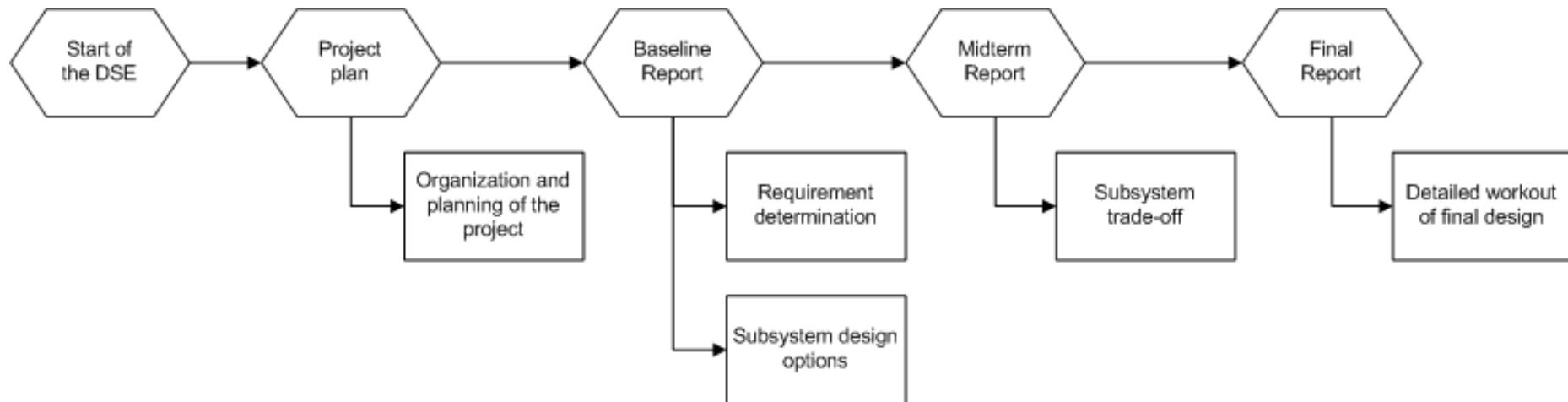TUDelft

1.

Project plan
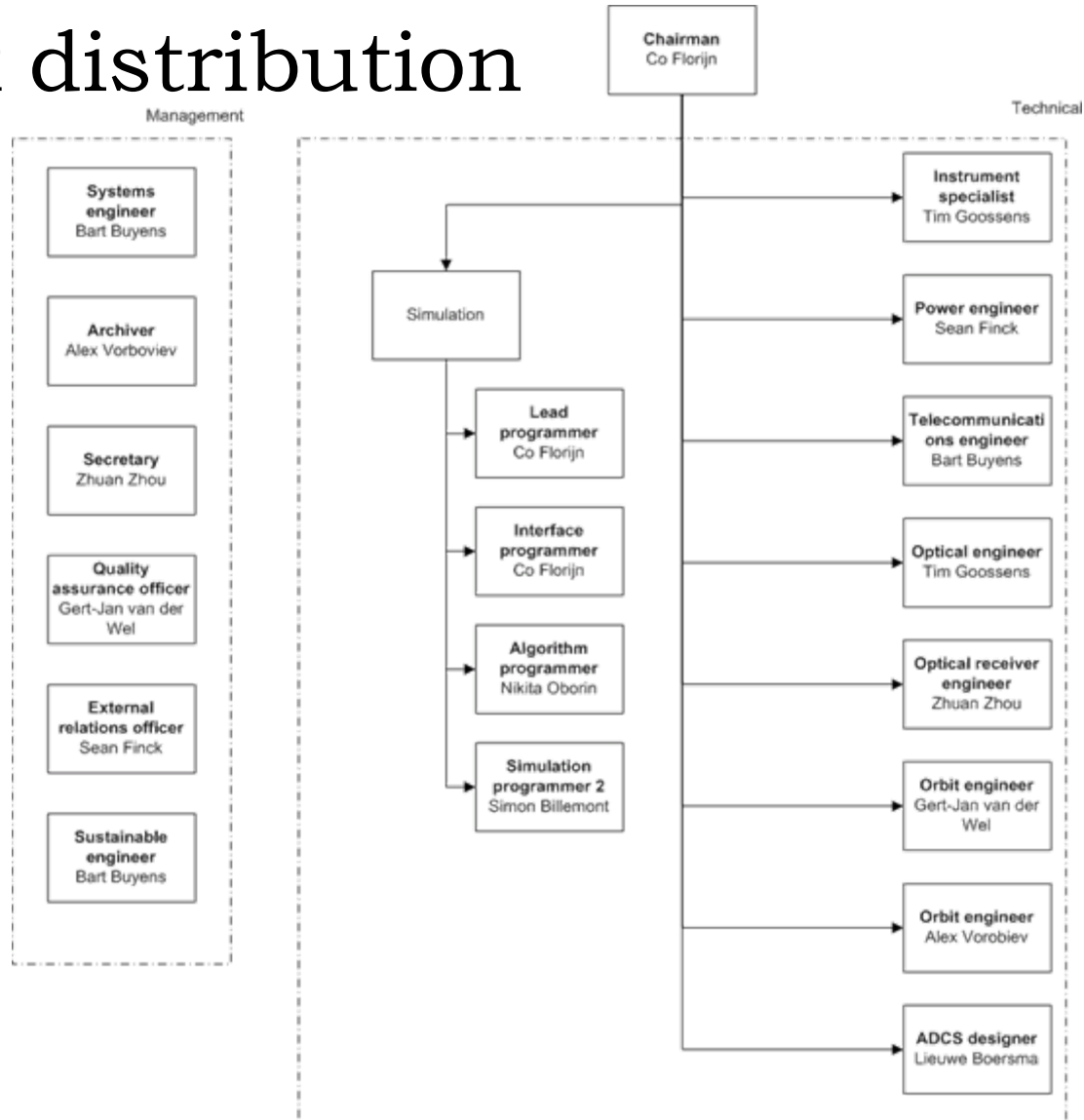
Mission need statement

Demonstrate that a satellite constellation, consisting of a single emitter and several receivers, will perform superior (in terms of cost, lifetime and performance) to existing spaceborne laser altimetry systems.

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Project Organization

Work distribution

2.

Key requirements

Key Requirements

- Low cost

- Lifetime of ~ 5 yrs

- Performance equivalent to IceSat

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Additional Requirements

- Mass ≤ existing spaceborne laser altimetry systems

- No scanner may be used

- Recreation of the DEM

- Extraction of the BRDF

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3.

Tradeoff method

Trade-off Method

- A set of criteria are defined

- Each criteria is assigned weight w.r.t. importance

- Varies for each subsystem
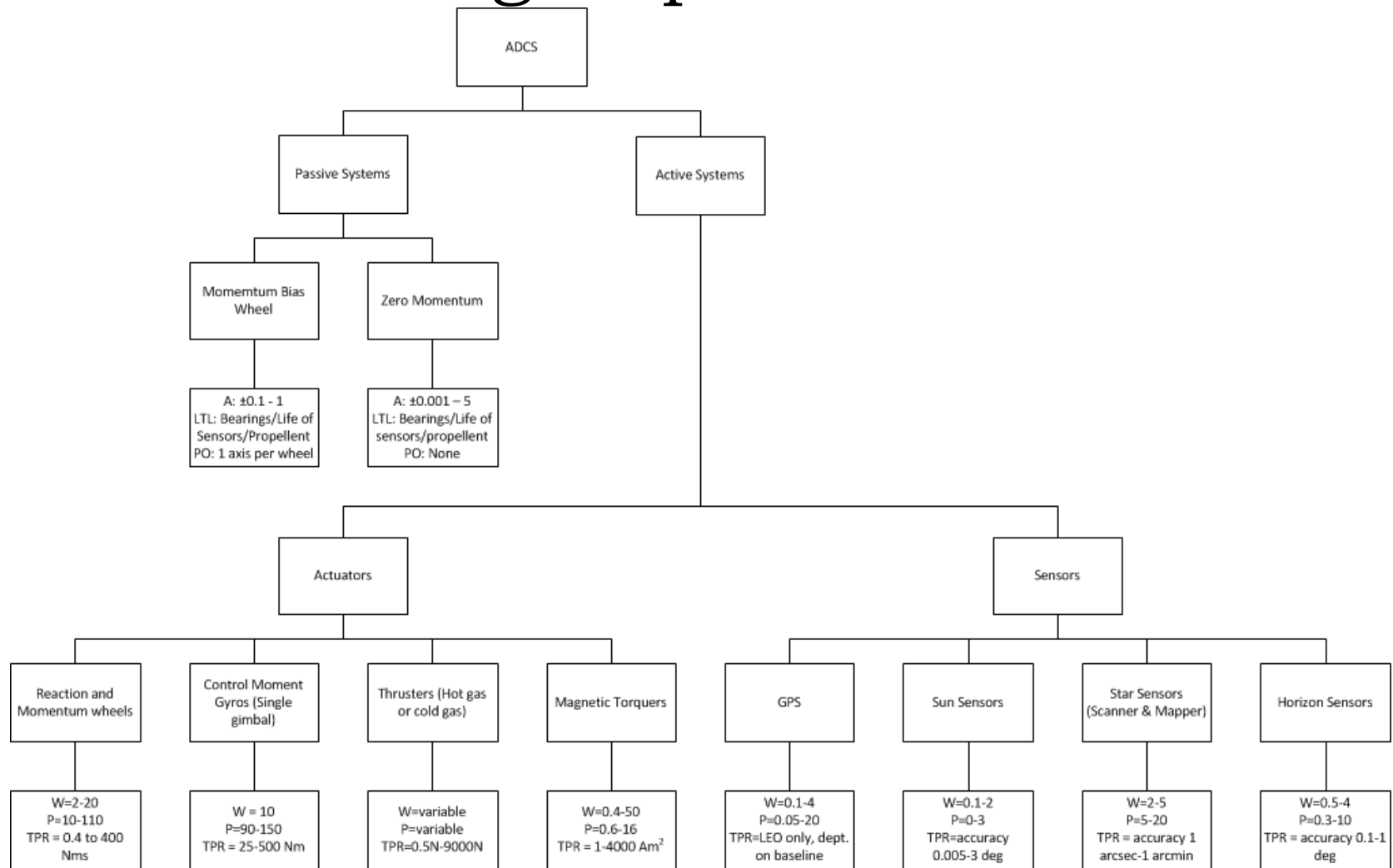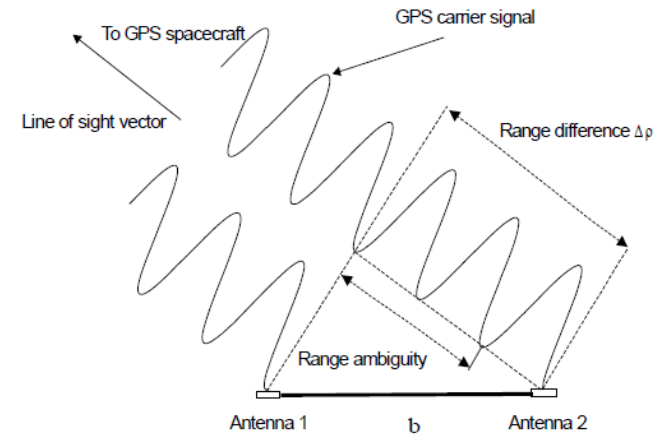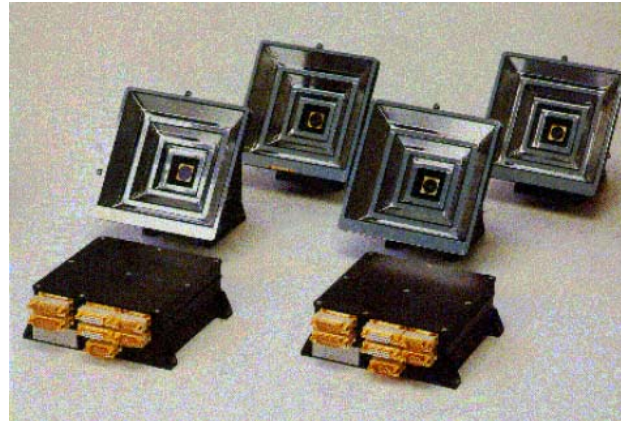
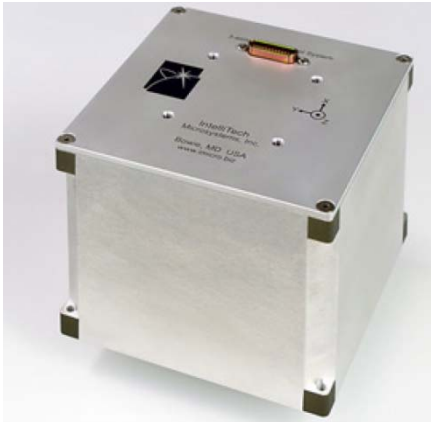- Each subsystem is graded

- Highest score wins

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4.

Subsystem trade off

# Pruned Design Option Tree ADCS

Selected ADS concepts

1. Maryland Aerospace Inc. IMI-100 ADACS

2. Sun Sensors and a Star Tracker

3. GPS based attitude control

Sources: http://www.cubesatkit.com/docs/datasheet/DS CSK ADACS 634-00412-A.pdf
Dr. Q.P. Chu. Spacecraft attitude dynamics and control, course notes

Trade-off ADS

Criteria	Weight Factor	Concept 1	Concept 2	Concept 3
Accuracy	9	4	**8**	4
Size	7	2	**6**	4
Power	7	6	5	**7**
Price	3	3	**5**	4
Development	5	**8**	4	5
Weighted total		141	**184**	150

Winner ADS
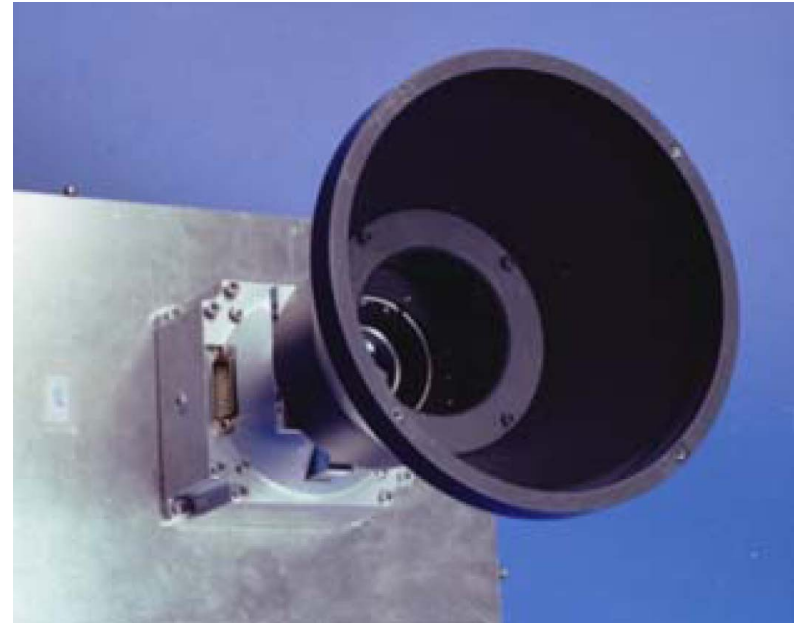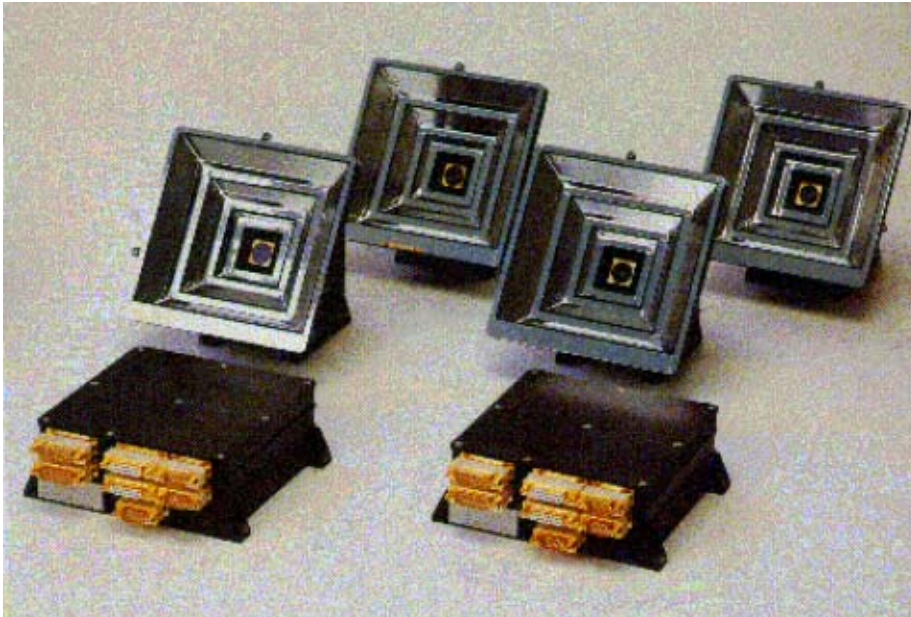
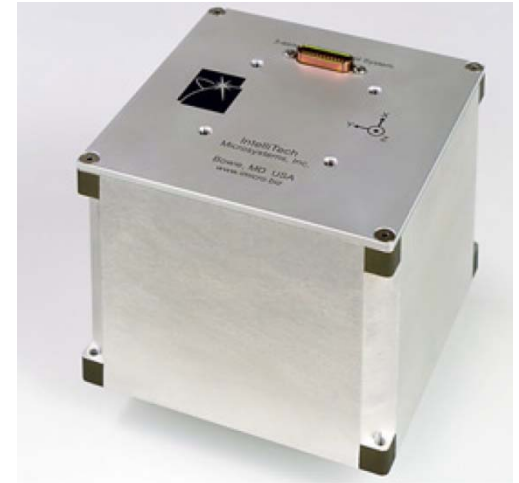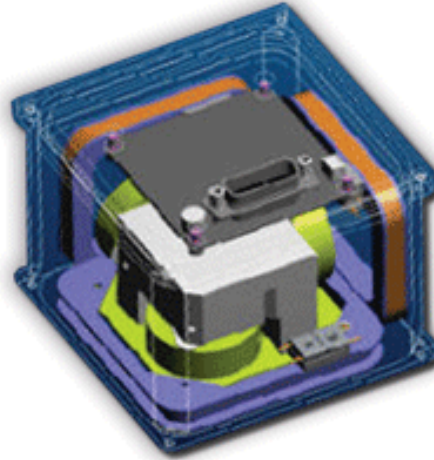Sources: Dr. Q.P. Chu. Spacecraft attitude dynamics and control, course notes

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Selected ACS concepts
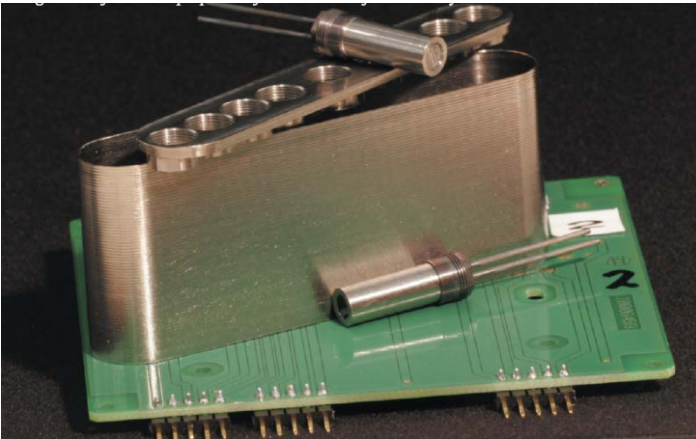
1. Thrusters

2. Reaction wheels and magnetic torquers

3. Maryland Aerospace Inc. IMI-100 ADACS

Sources: http://www.tno.nl
http://www.cubesatshop.com
http://www.cubesatkit.com/docs/datasheet/DS_CSK_ADACS_634-00412-A.pdf

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Trade-off ADS

Criteria	Weight Factor	Concept 1	Concept 2	Concept 3
Rate	5	**8**	6	6
Accuracy	8	4	**8**	7
Size	7	2	**6**	5
Power	7	3	**6**	**6**
Price	3	2	**8**	7
Development	5	4	6	**8**
Weighted total		133	**232**	224

Winner ADS
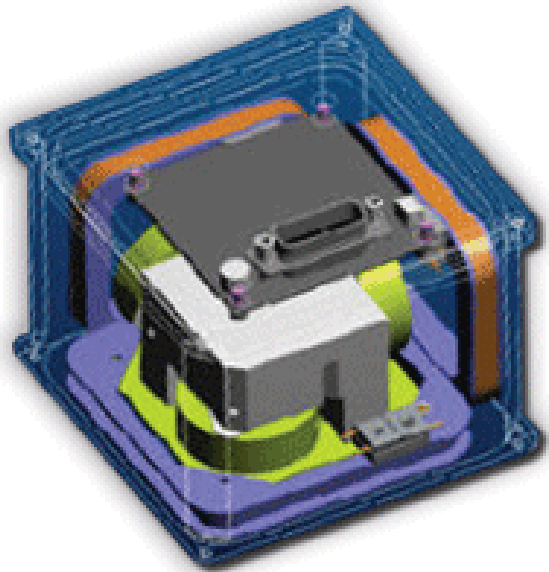
Sources: Dr. Q.P. Chu. Spacecraft attitude dynamics and control, course notes

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Selected Pointing Mechanism Concepts
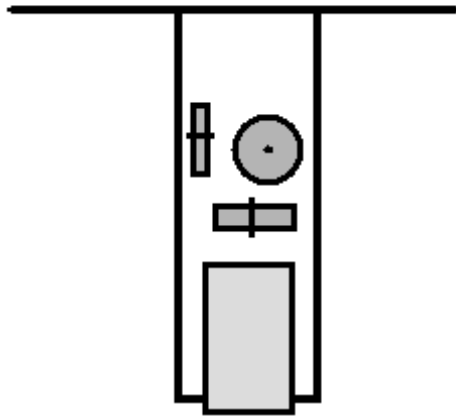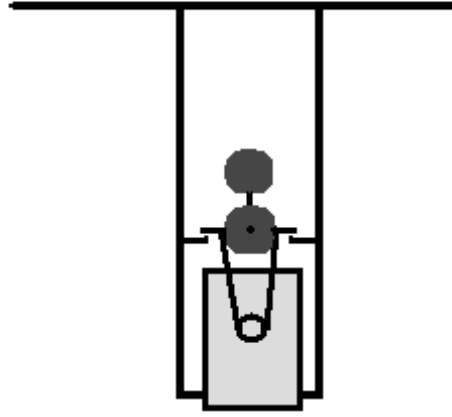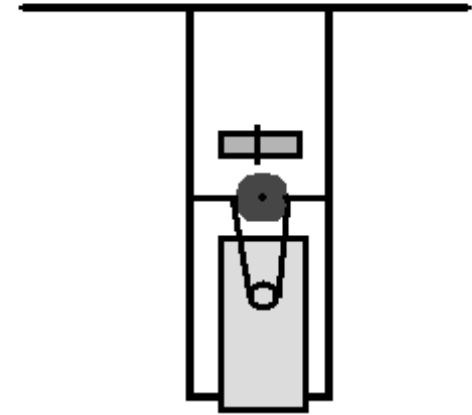
Concept 1   Concept 2   Concept 3

1. Using the ADCS

2. Using two stepper motors

3. Using one axis reaction wheel and one stepper motor

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Trade-off pointing mechanism

Criteria	Weight Factor	Concept 1	Concept 2	Concept 3
Pointing accuracy	10	2	**8**	6
Pointing rate	10	2	**8**	6
Added weight	4	**8**	2	5
Power	4	**7**	2	4
Influence	6	2	3	**7**
Complexity	6	**8**	2	6
Weighted total		208	221	**228**

Winner Pointing Mechanism
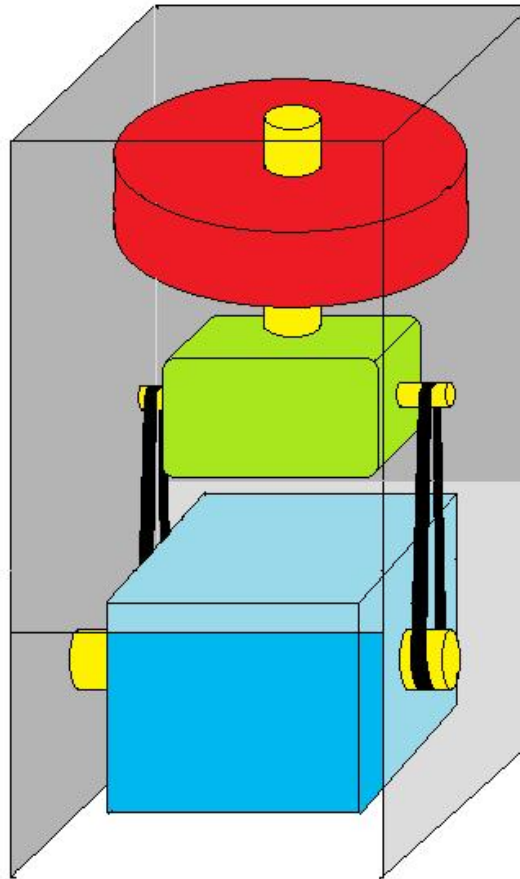
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Communications

Aspects considered

- Communications architecture
- Frequency bands
    - Ground-space link
    - Intersatellite link
- Antenna configuration
- Tracking

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Communications
Aspects considered

- **Communications architecture**
- Frequency bands
  - Ground-space link
  - Intersatellite link
- Antenna configuration
- Tracking

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Communications

Communications architecture

- **Swarm elements:**
  - Emitter satellite (1)
  - Receiver satellites (multiple)
  - Ground station

Swarm elements

- Centralized architecture
  - 1 ground-space link for emitter sat.
  - Intersatellite links between receiver sats & emitter sat
- Decentralized architecture
  - Ground-space link for emitter sat & each receiver sat
  - Intersatellite links between receiver sats & emitter sat
- Extremely decentralized architecture
  - Ground-space link for emitter sat & each receiver sat
  - No intersatellite links

Communications
Communications architecture

Centralized

- Swarm elements:
  - Emitter satellite (1)
  - Receiver satellites (multiple)
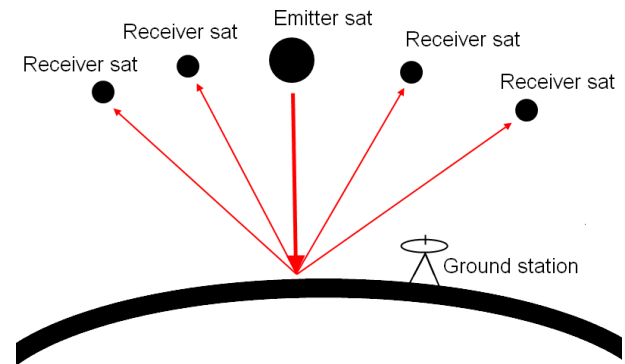 - Ground station

- **Centralized architecture**
  - 1 ground-space link for emitter sat.
  - Intersatellite links between receiver sats & emitter sat
- Decentralized architecture
  - Ground-space link for emitter sat & each receiver sat
  - Intersatellite links between receiver sats & emitter sat
- Extremely decentralized architecture
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Communications

Communications architecture

- Swarm elements:
  - Emitter satellite (1)
  - Receiver satellites (multiple)
  - Ground station

Decentralized

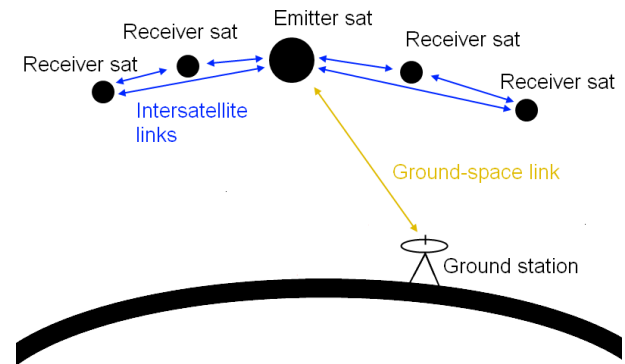- Centralized architecture
  - 1 ground-space link for emitter sat.
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- **Decentralized architecture**
  - Ground-space link for emitter sat & each receiver sat
  - Intersatellite links between receiver sats & emitter sat
- Extremely decentralized architecture
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Communications
Communications architecture

- Swarm elements:
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  - Receiver satellites (multiple)
  - Ground station
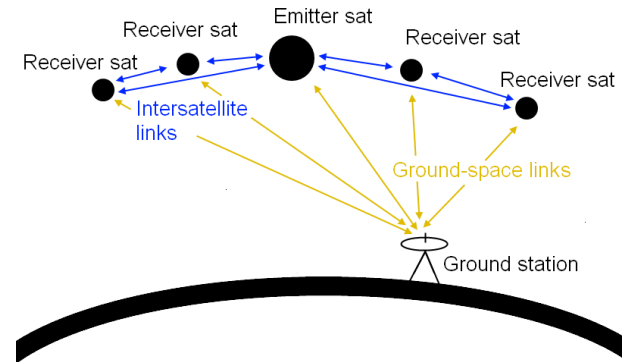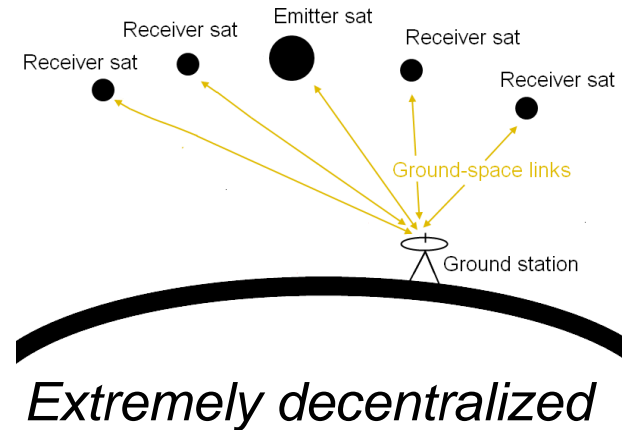
Extremely decentralized

- Centralized architecture
  - 1 ground-space link for emitter sat.
  - Intersatellite links between receiver sats & emitter sat
- Decentralized architecture
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  - Intersatellite links between receiver sats & emitter sat
- **Extremely decentralized architecture**
  - Ground-space link for emitter sat & each receiver sat
  - No intersatellite links

Communications
Communications architecture

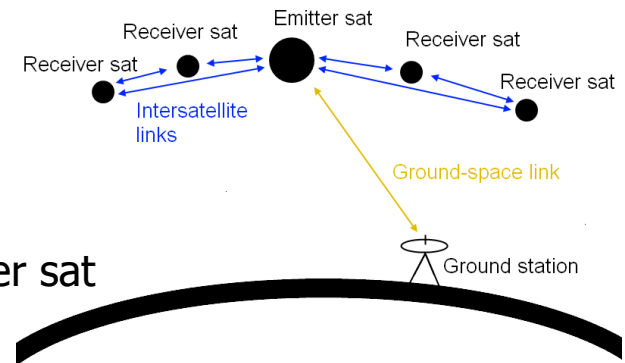**Centralized architecture:**

- Advantages
  - Low mass, power consumption & volume receiver sat
  - Scientific data compressed before transmitting to the ground station
- Disadvantages
  - Less robust
  - High mass, power consumption & volume emitter sat
  - High data rate ground-space link

Centralized
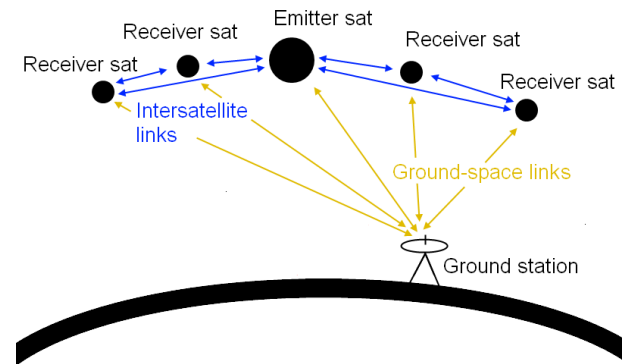
Communications
Communications architecture

Decentralized architecture:

- Advantages
  - Low data rate ground space link
  - More robust
- Disadvantages
  - Higher mass, power consumption & volume receiver sat

Receiver sat   Emitter sat   Receiver sat
Receiver sat   Receiver sat
Intersatellite links
Ground-space links
Ground station

Decentralized
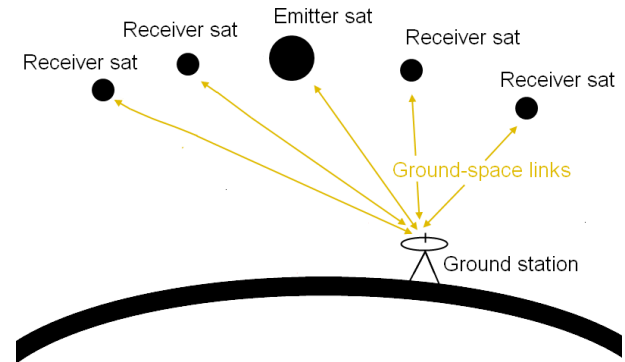
Communications
Communications architecture

Extremely decentralized architecture:

- Advantages
  - Low data rate ground space link
  - No frequency allocation required for intersatellite links
- Disadvantages
  - Higher mass, power consumption & volume receiver sat
  - Desynchronization

Extremely decentralized

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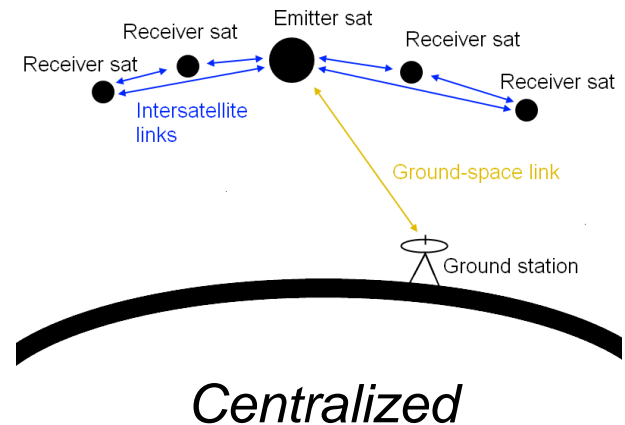# Communications
Communications architecture

Winning architecture:

- Centralized architecture
  - No danger for synchronization
  - Lower total mass
  - Maximum use of allocated frequency

Centralized

Communications
Aspects considered

- Communications architecture
- **Frequency bands**
    - Ground-space link
    - Intersatellite link
- Antenna configuration
- Tracking

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Communications
Frequency allocation

Ground space link:

- Possible frequency bands
    - C-band
    - S-band
    - X-band
    - Ku-band
    - Ka-band
    - SHF/EHF-band

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Communications
Frequency allocation

Ground space link:

- Possible frequency bands
  - C-band
  - S-band
  - **X-band**
    - High data rate possible
    - Most common for large Earth observation sats
  - Ku-band
  - Ka-band
  - SHF/EHF-band

Receiver sat

Ground-space links

Ground station

Communications
Frequency allocation

Ground space link:

- Possible frequency bands
  - C-band
  - **S-band**
    - Low data rate
    - Good for house keeping data
  - X-band
  - Ku-band
  - Ka-band
  - SHF/EHF-band

Receiver sat

Ground-space links

Ground station

Communications
Frequency allocation
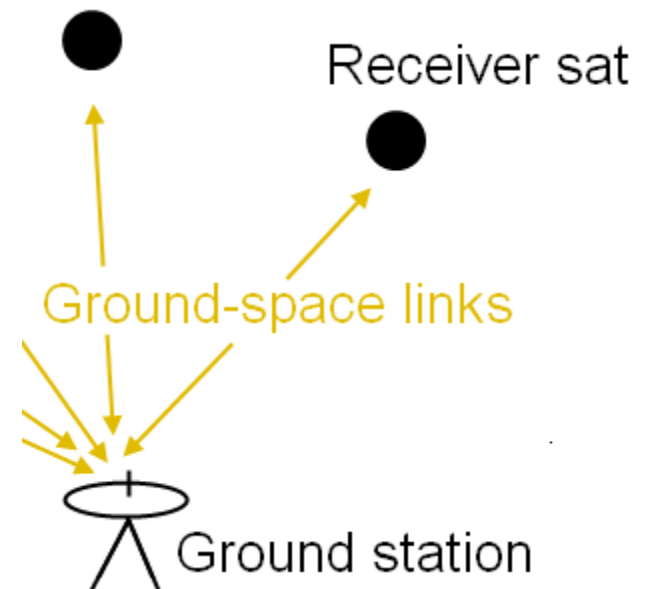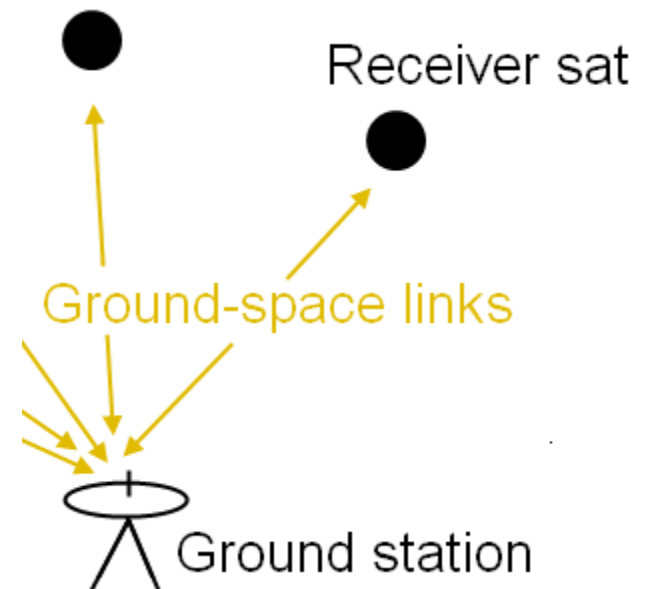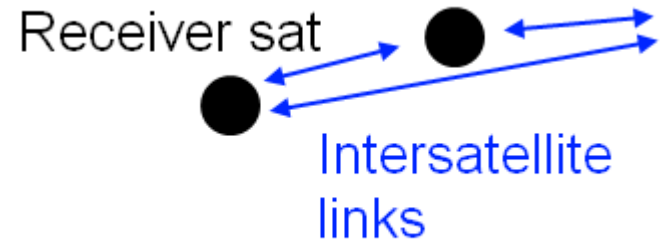
Intersatellite link:

- Possible frequency bands
    - C-band
    - S-band
    - X-band
    - Ku-band
    - Ka-band
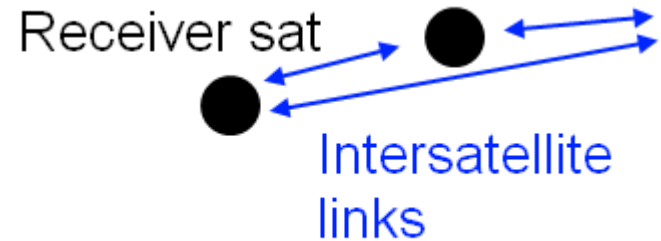   - SHF/EHF-band

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Communications
Frequency allocation

Intersatellite link:

- Possible frequency bands
  - C-band
  - S-band
  - X-band
  - **Ku-band**
    - Lots of existing systems for reference during design
  - Ka-band
  - SHF/EHF-band
  - V-band

Receiver sat

Intersatellite links

Communications
Aspects considered

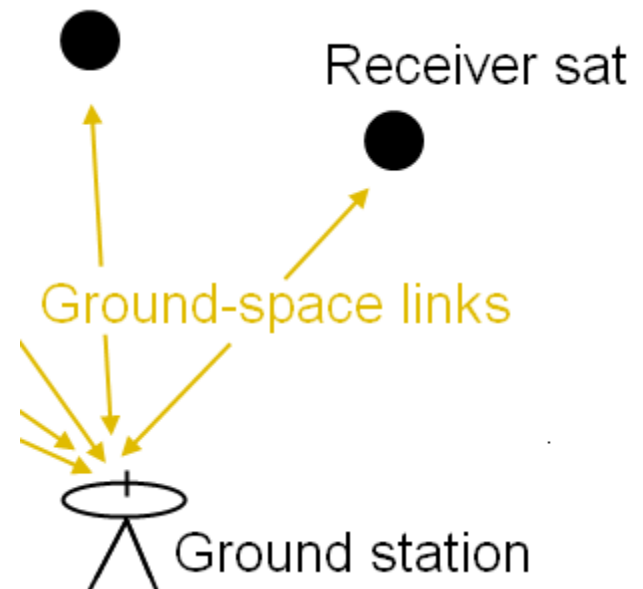- Communications architecture
- Frequency bands
  - Ground-space link
  - Intersatellite link
- **Antenna configuration**
- Tracking

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Communications
Antenna configuration

Ground space link:

- Possible high gain antennas
  - Parabolic reflector
    - High volume
    - Low mass
  - Phased array
    - Low volume
    - High mass

Receiver sat

Ground-space links
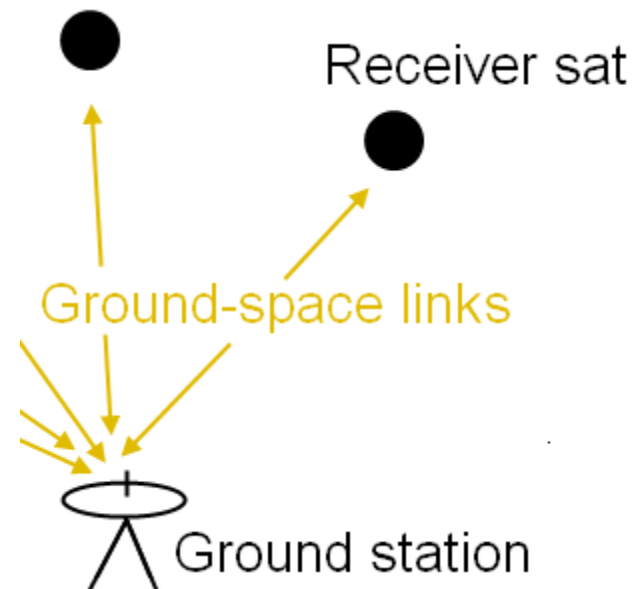
Ground station

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Communications
Antenna configuration

Ground space link:

- Possible high gain antennas
  - Parabolic reflector
    - High volume
    - Low mass
  - **Phased array**
    - **Low volume**
    - **High mass**

Receiver sat

Ground-space links

Ground station

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Communications
Antenna configuration

- Intersatellite links
  - Horn antenna
    - Low gain
    - >4 Ghz
  - Helix antenna
    - Low gain
    - <2 Ghz

Receiver sat
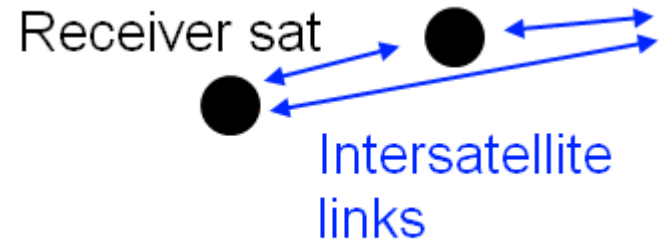
Intersatellite links

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Communications
Antenna configuration

- Intersatellite links
  - **Horn antenna**
    - **Low gain**
    - **>4 Ghz**
  - Helix antenna
    - Low gain
    - <2 Ghz

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Communications
Aspects considered

- Communications architecture
- Frequency bands
  - Ground-space link
  - Intersatellite link
- Antenna configuration
- **Tracking**

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Communications
Tracking method

- GPS
  - High precision
  - Provides time signal
- TDRS
  - High accuracy
  - Requires TDRS tracking antenna
- Satellite crosslinks
  - Reuses communication hardware
  - Only gives relative position
- Ground tracking
  - Well established
  - Operations intensive

Communications
Tracking method

- **GPS**
  - •**High precision**
  - •**Provides time signal**
- TDRS
  - •High accuracy
  - •Requires TDRS tracking antenna
- **Satellite crosslinks**
  - •**Reuses communication hardware**
  - •**Only gives relative position**
- Ground tracking
 - •Well established
  - •Operations intensive

Communications
Summary

- Communications architecture
  - Centralized
- Frequency bands
  - X-band and S-band for ground-space link
  - Ku-band for intersatellite link
- Antenna
  - Phased array for ground-space link
  - Horn antenna for intersatellite link
- Tracking
  - Combination GPS and crosslink method

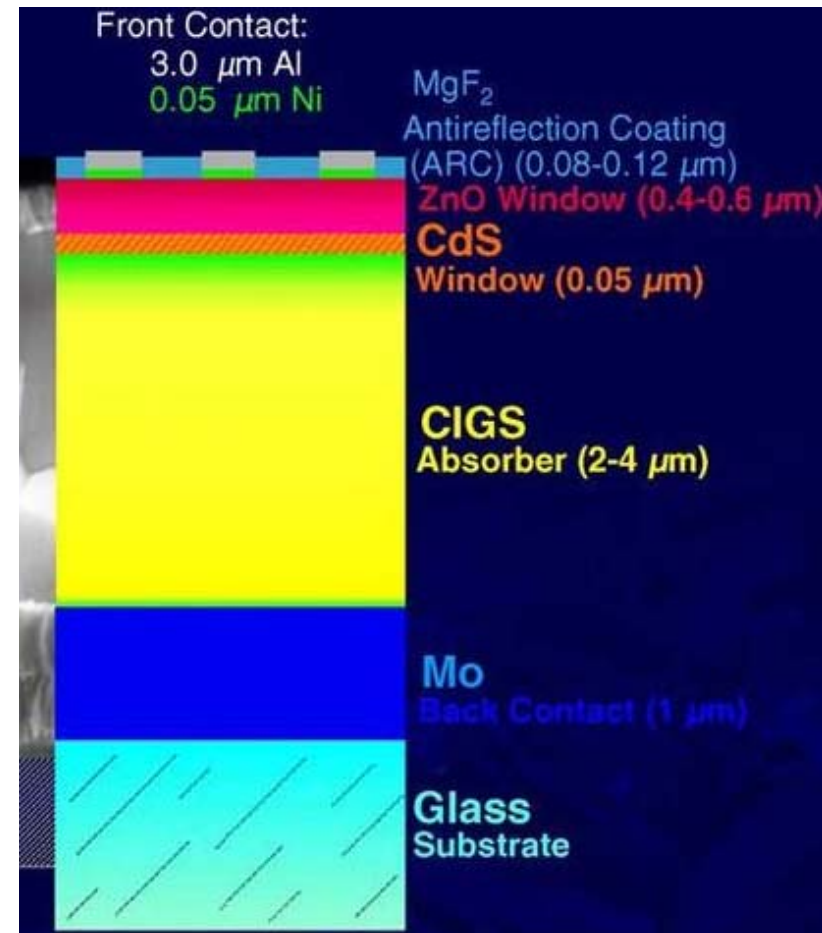# Electrical Power System

Pruned design option tree
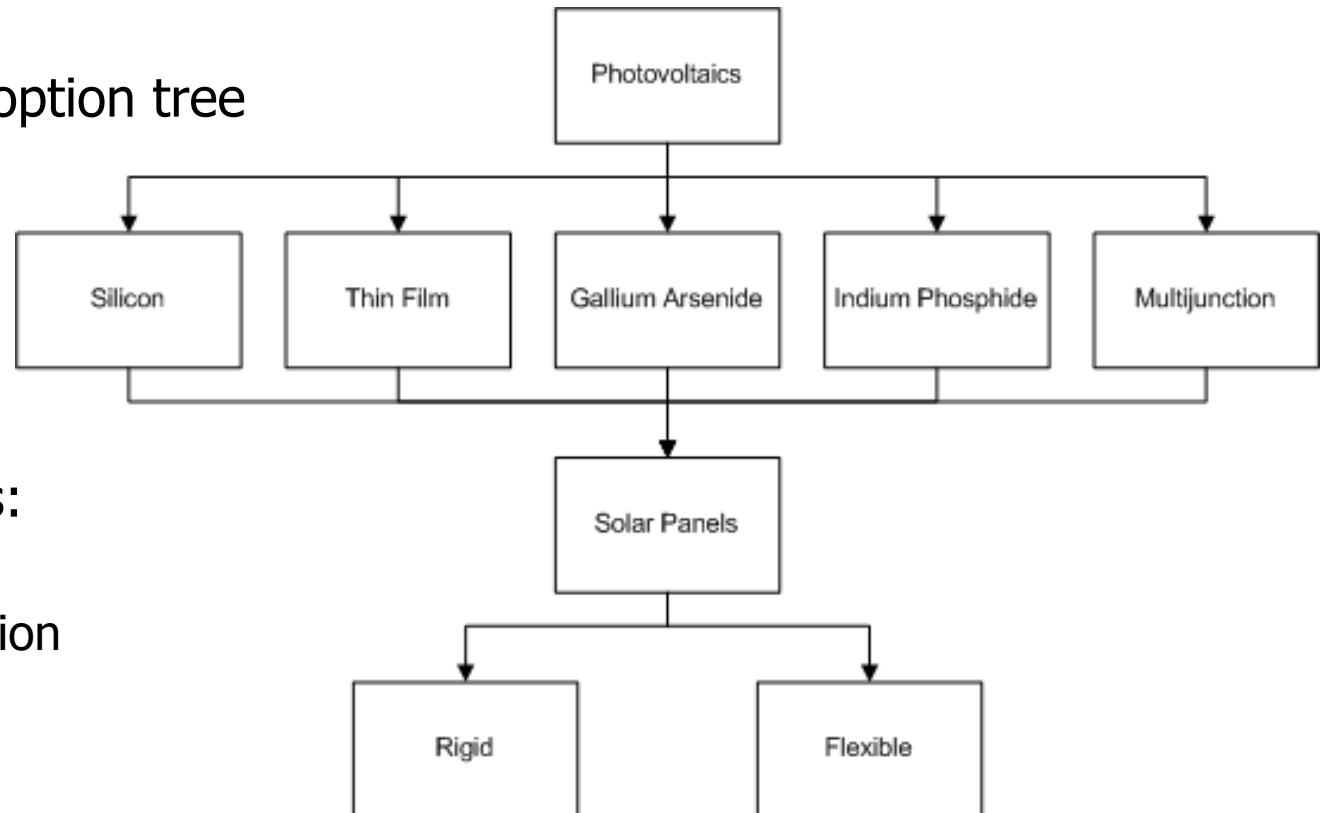
Two candidates:
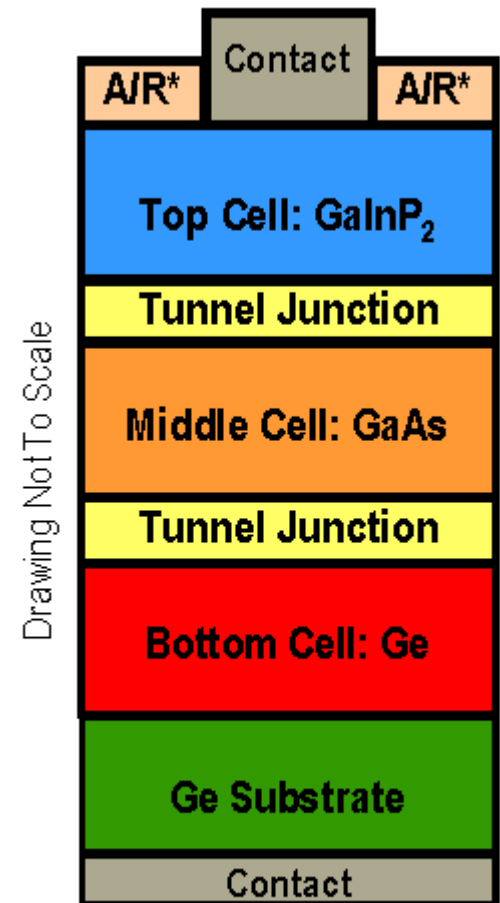- Thin film
- Triple junction

EPS – Thin Film CIGS

- Multiple layers of thin photovoltaic material

- Copper-Indium-Gallium-Selenium absorber

- Low efficiency

- Low production cost

- High absorptance coefficient
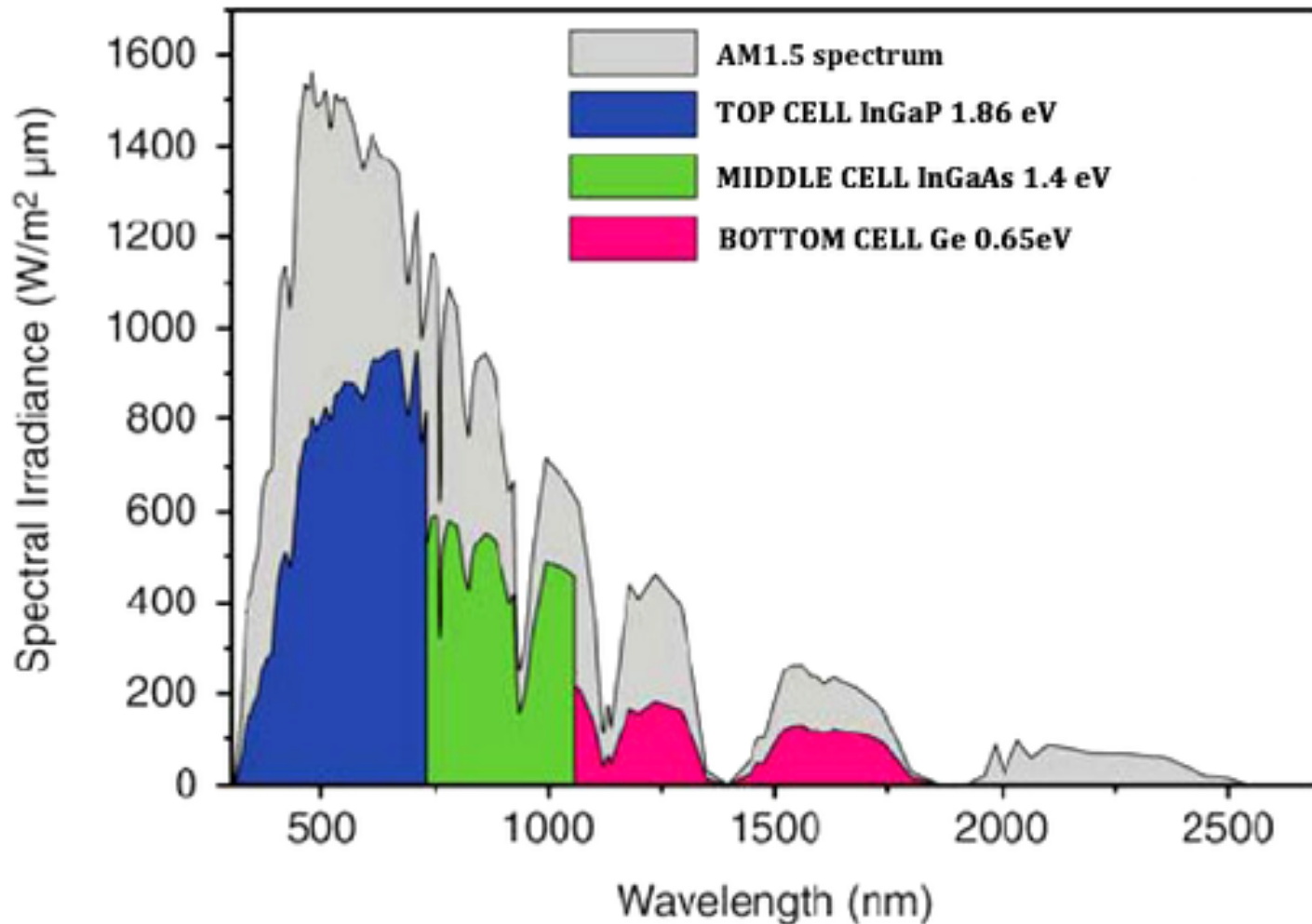

Front Contact:
3.0 μm Al
0.05 μm Ni

MgF$_2$ Antireflection Coating (ARC) (0.08-0.12 μm)

ZnO Window (0.4-0.6 μm)

CdS Window (0.05 μm)

CIGS Absorber (2-4 μm)

Mo Back Contact (1 μm)

Glass Substrate

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EPS – Triple Junction

- Multiple pn-junctions

- High efficiency

- High production cost

- Larger covering of the solar spectrum

Contact

AR* | Contact | AR*

Top Cell: GaInP$_2$

Tunnel Junction

Middle Cell: GaAs

Tunnel Junction

Bottom Cell: Ge

Ge Substrate

Contact

Drawing Not To Scale

*A/R: Anti-Reflective Coating

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EPS – Triple Junction

EPS – Trade-off

|	Weight factors	Candidates	
		Thin sheet (CIGS)	Triple-junction
Efficiency	10	4	10
Mass	10	10	3
Cost	10	10	4
Degradation	8	10	9
Packing factor	7	8	8,5
Resistance to vibrations	5	8	6
Height	7	10	2
Total	570	486	345,5

Optical Receiving Payload

- Single-Photon Detection
  - Photonmultiplier tube
  - Single Photon Avalanche Diode (SPAD)

- Wavelength Estimation
  - Atmospheric transmittance
  - Wavelength ratio

Optical Receiving Payload

Single-Photon Detection

• Convert light(photons) to measurable quanlity(electronical V or I)

• Multiple ways
  • Photonmultiplier tube
  • SPAD
  • Quantum dot(under developed)
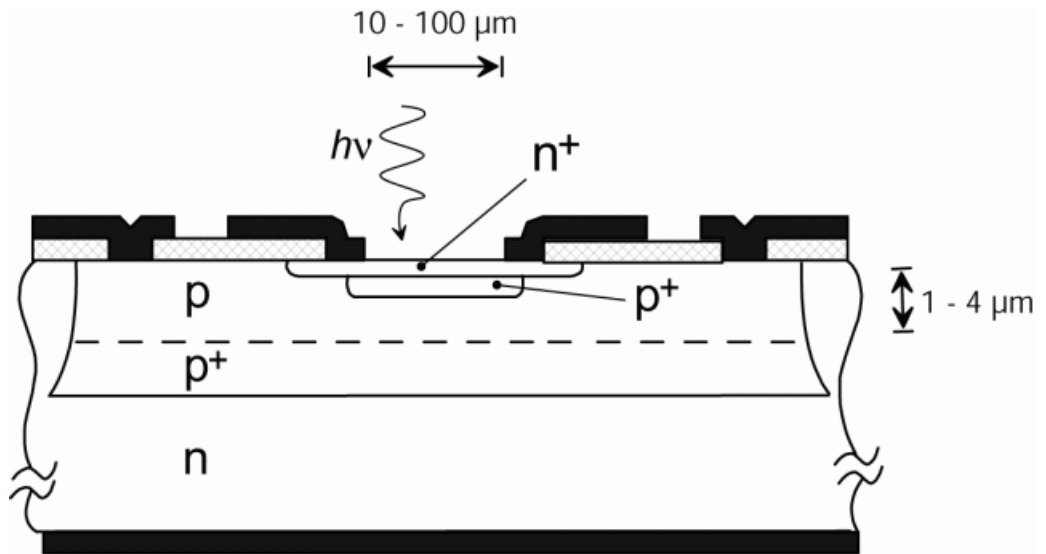
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Photonmultuplier tube
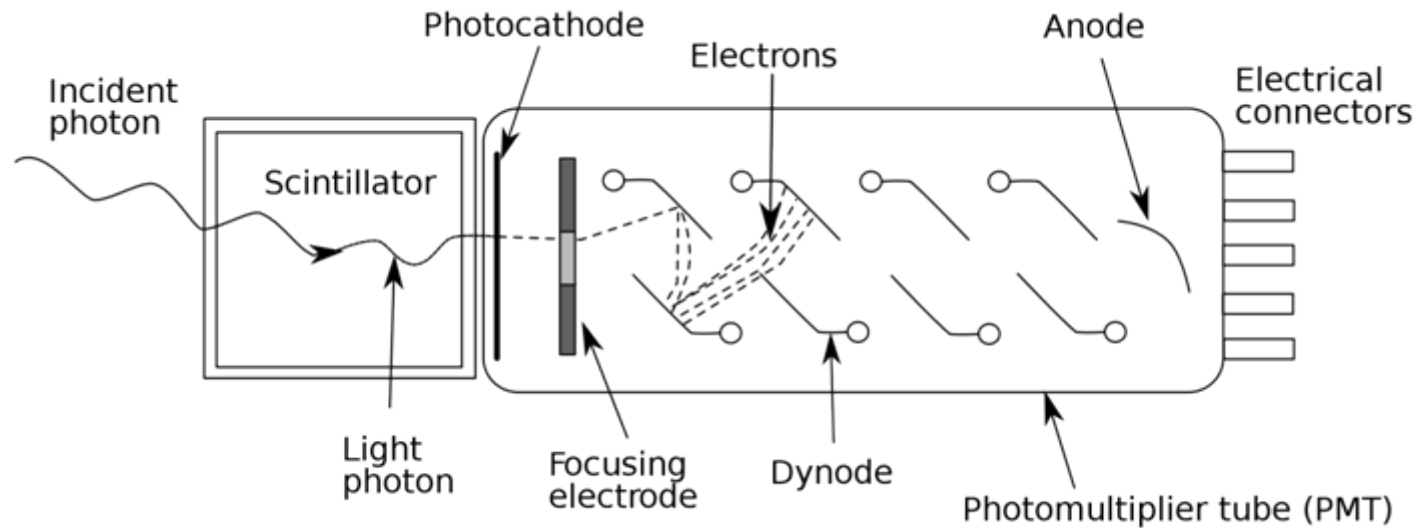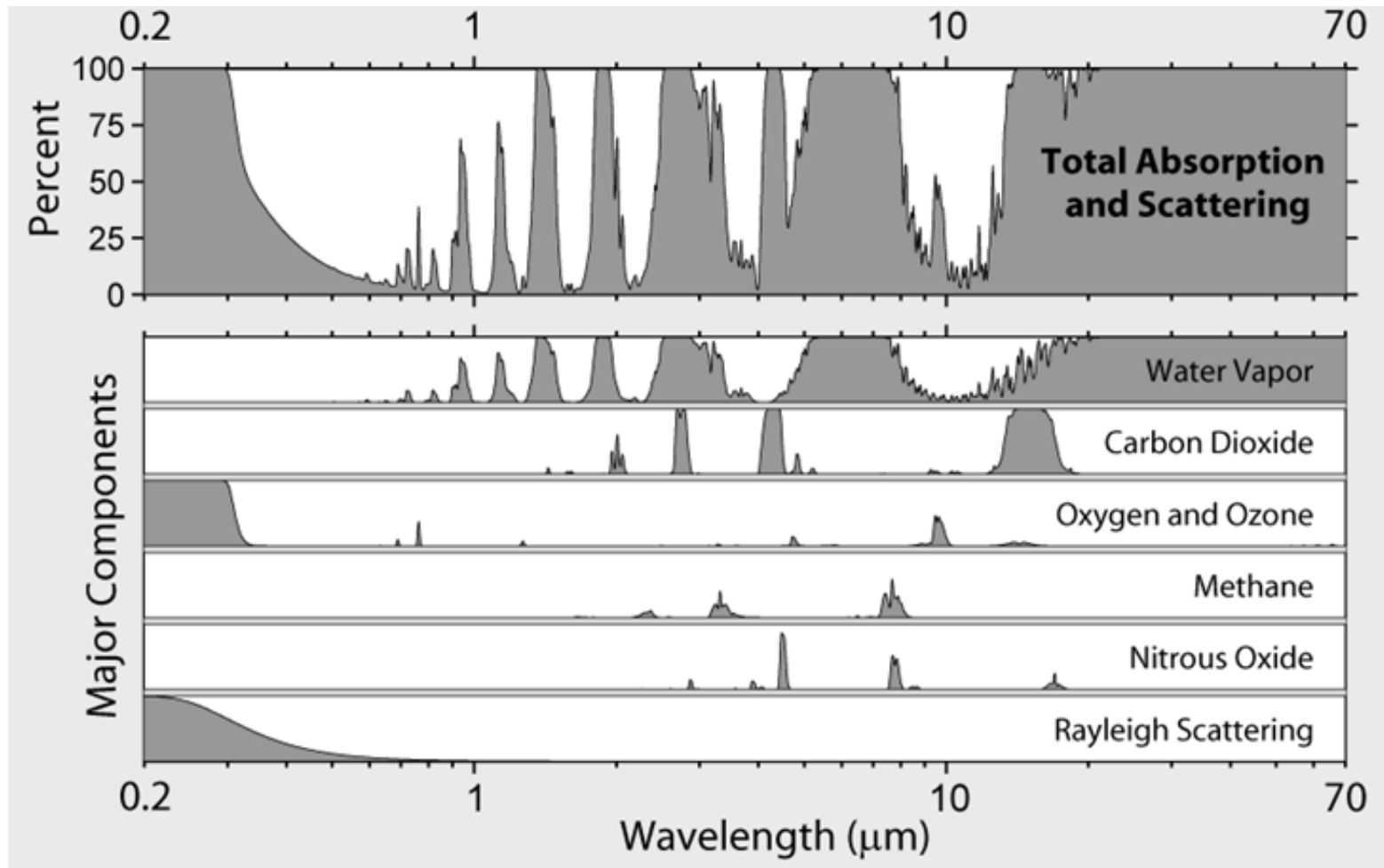

Typically 1000 to 2000v used

SPAD
Single Photon Avalanche Diode

- Based on p-n junction

- Reversed biased voltage

- Sensing avalanche current
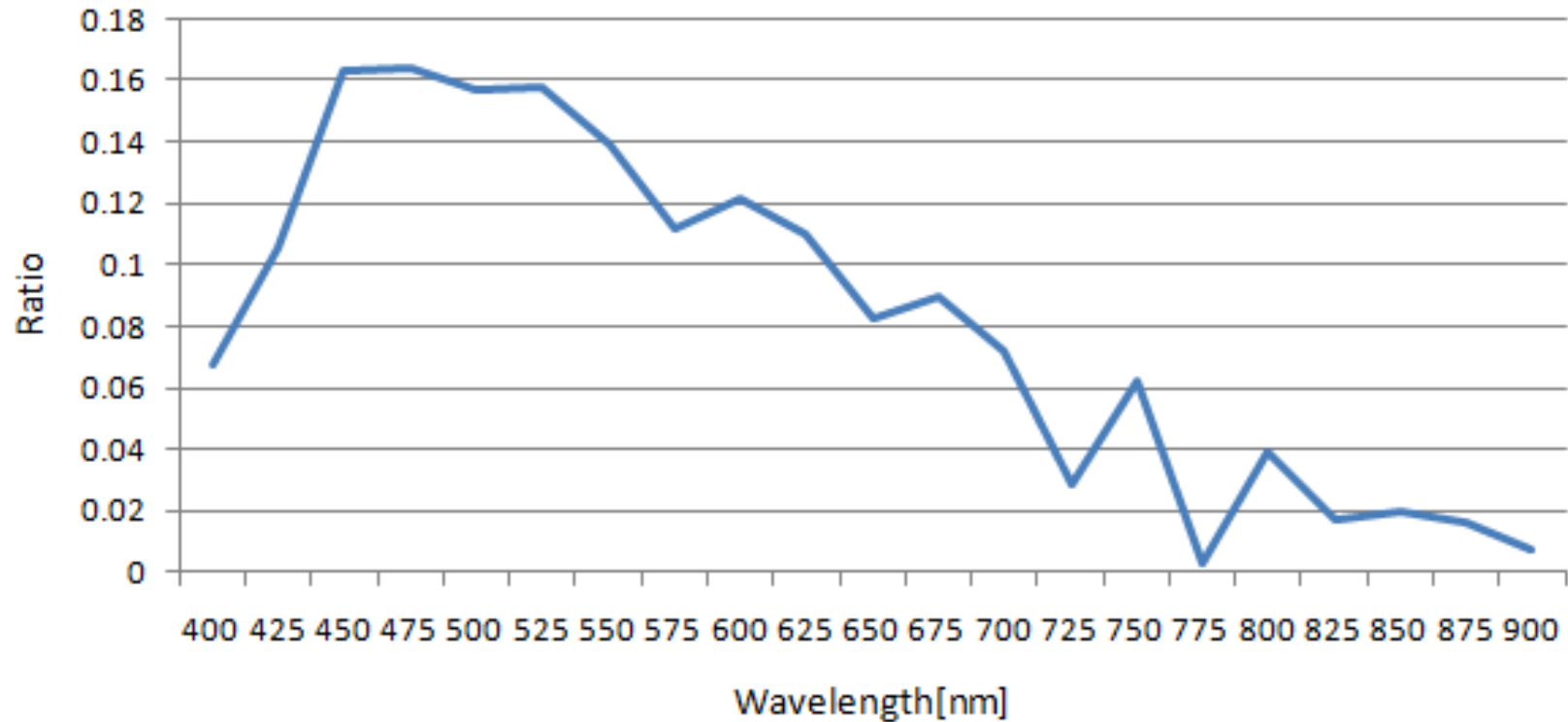
- Small size, less power

Atmospheric Absorption Bands

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Wavelength estimation

- General sufficient wavelength range 400nm to 900nm

- Atmospheric transmittance Vs. Photon detection efficiency

- Wavelength ratio
        R = transmittance^2*efficiency

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Wavelength estimation

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Laser Optics

- To get the desired footprint.

- Three options:
  - No optics
  - Two lenses
  - Mirrors

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Laser Optics – No Optics

Advantages:
- Really simple
- No optics to get out of focus
- Dirt-cheap

Disadvantages:
- Footprint directly depends on:
    - Laser beam divergence
    - Satellite height
- These two dependencies severely limit design options
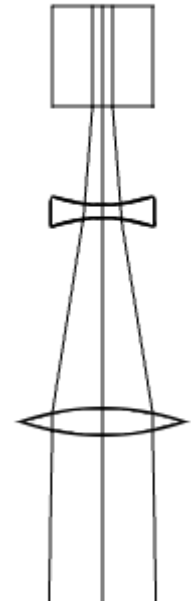- Characteristics might not be optimal

Laser Optics – Two lenses

Advantages:
- Technology is well-understood

Disadvantages:
- Very heavy (even with Fresnel lenses)
- Focal length of > 4 m, so:
- Need mirrors to add light path length
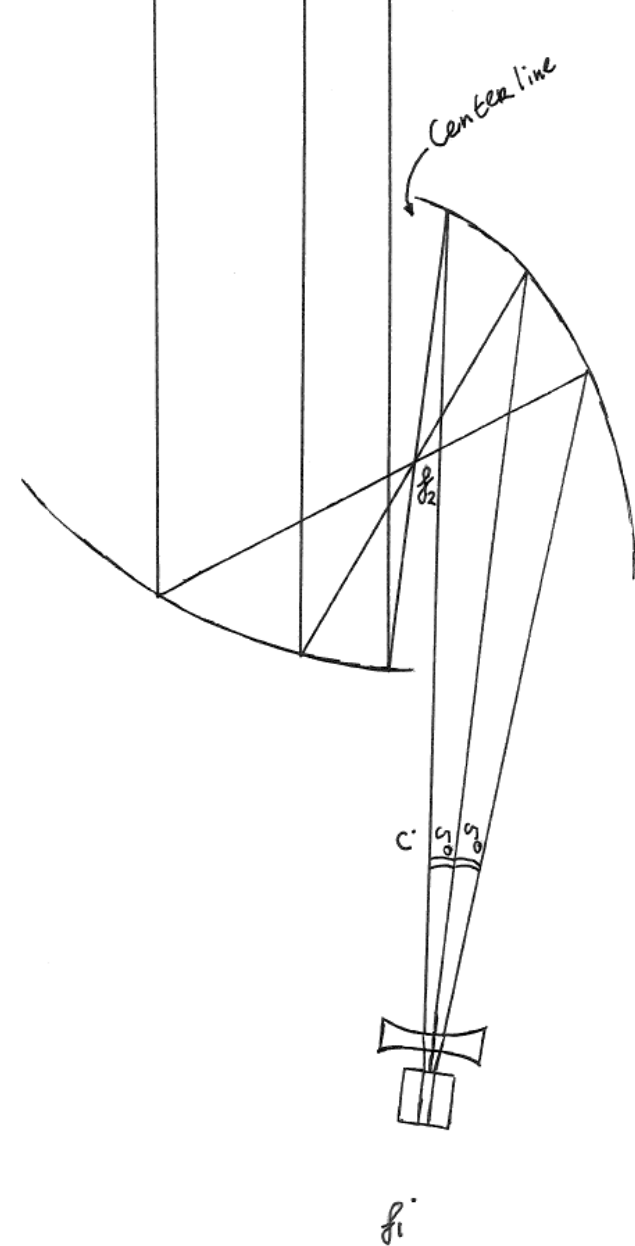- Still limits the footprint a lot
- Limits the satellite height a little

Laser Optics – Mirrors

Advantages:
- Much lighter than lenses
  - Herschel: <4 mm thick mirror
- Any footprint, any satellite height
- Potentially tunable in flight
- Small (~20 cm)
- Lense optional for some lasers

Disadvantages:
- Most complicated system
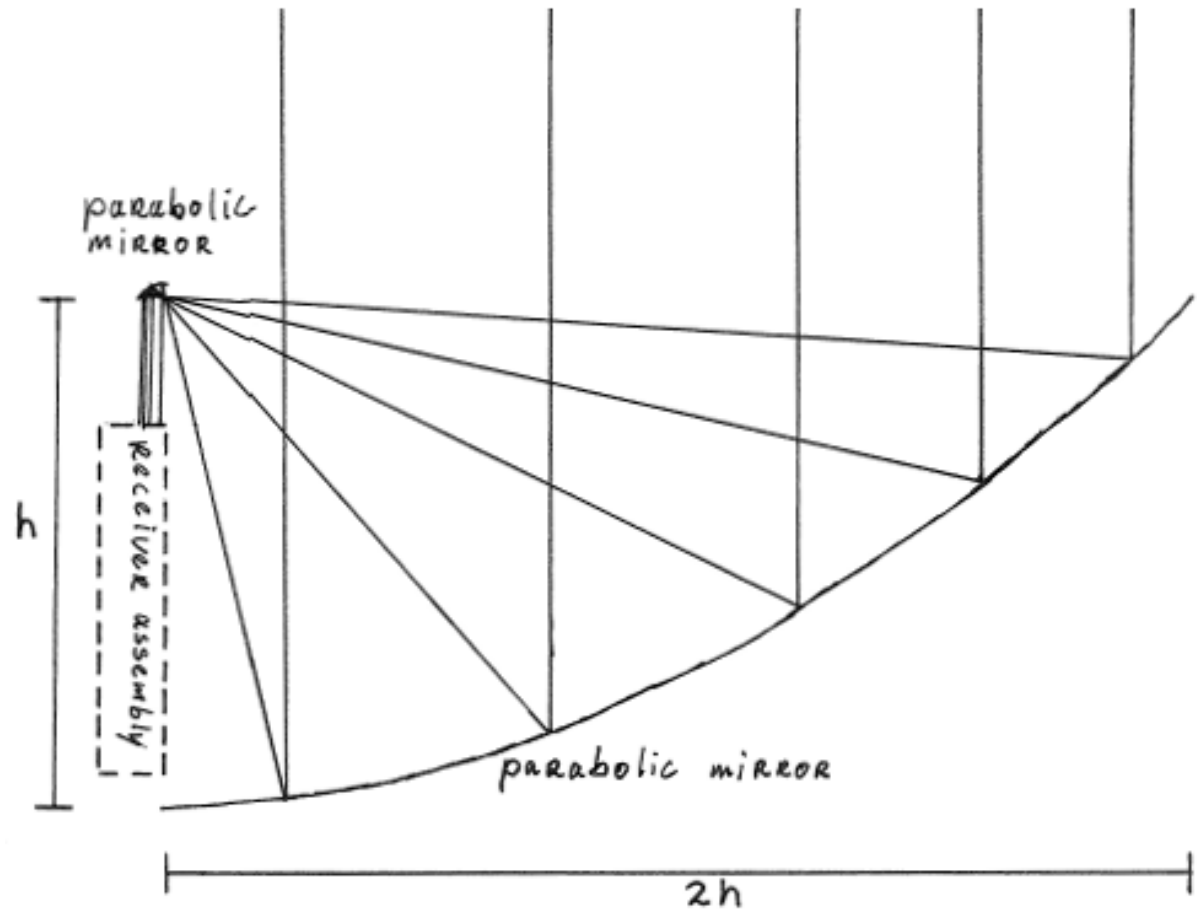- Assembly must remain rigidly fixed

Receiver Optics – Common Part

Basically the reverse of the laser optics.

The secondary mirror is really small (mm range).

The difference is in the receiver assembly.

parabolic mirror

h

Receiver assembly

parabolic mirror

2h

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Receiver Optics – Fill Factor

Fill factor = ~2%.
Then fraction of light detected is:
QDE x FF = 37% x 2% = 0.74%

This is clearly inacceptable. Therefore, we need focusing optics after the main collector.

Receiver Optics – Noise

As the Sun bombards the Earth with photons, we need to filter the light, to prevent an unacceptable SNR.

Optical filters degrade fast and also filter put some of the wanted photons.

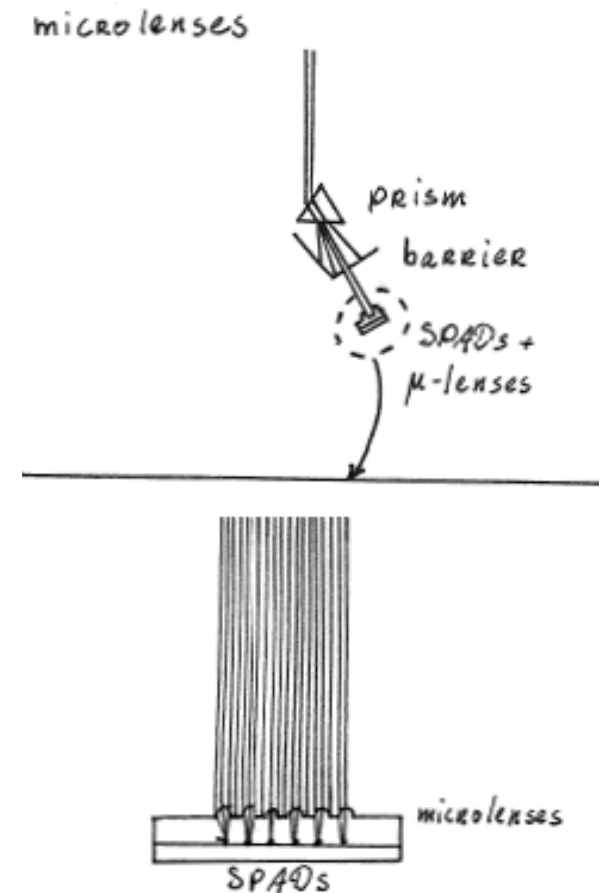Therefore, we will use a prism to filter out unwanted noise.

Receiver Optics – Microlenses

Advantages:
- Lightweight
- Conventional

Disadvantages:
- Only improves the fill factor to 10%
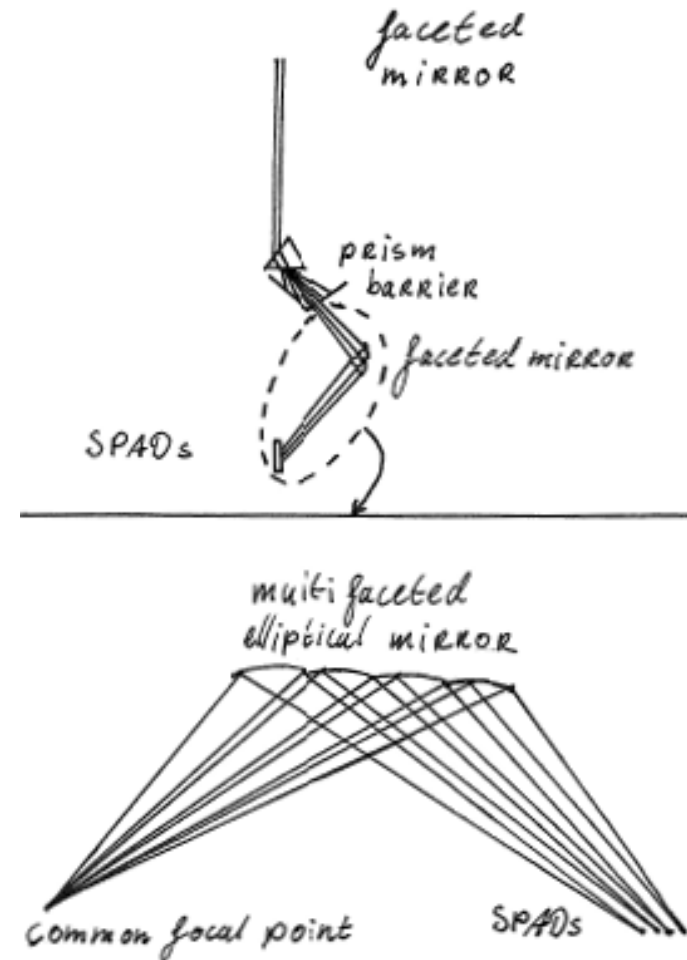- This means: QDE x FF = 37% x 10% = 3.7%
- Needs to be rigidly fixed
- Still inacceptible

Receiver Optics – Faceted Mirror

Advantages:
- Improves the fill factor to over 80-95%
- This means: QDE x FF = 37% x 80-95% = 30-35%
- Is acceptable

Disadvantages:
- Manufacturing is complicated
- Needs to be rigidly fixed

Receiver Trade-off
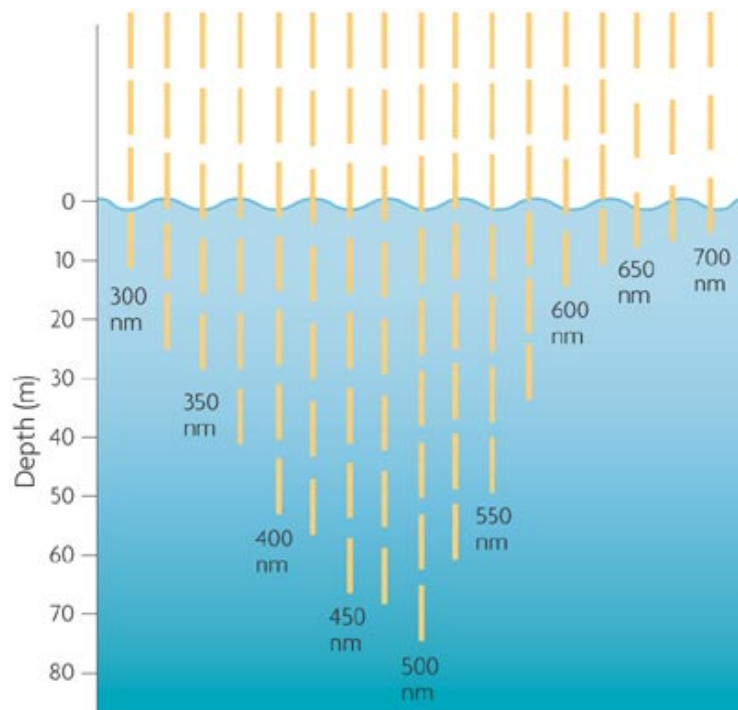
Criteria	Weight Factor	MPD	SILAT	SPAD + microlenses	SPAD + mirrors
Power	7	6	6	9	9
Mass	8	5	5	9	8
Volume	8	4	3	8	8
Reliability	7	8	8	6	5
Efficiency	10	7	6	1	5
Cost	5	4	3	7	5
Availability	3	10	8	5	3
Lifetime	10	8	8	6	6
Resolution	8	7	7	10	10
FOV	6	6	6	9	9
Weighed total		462	433	495	504

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Ocean Reflectance
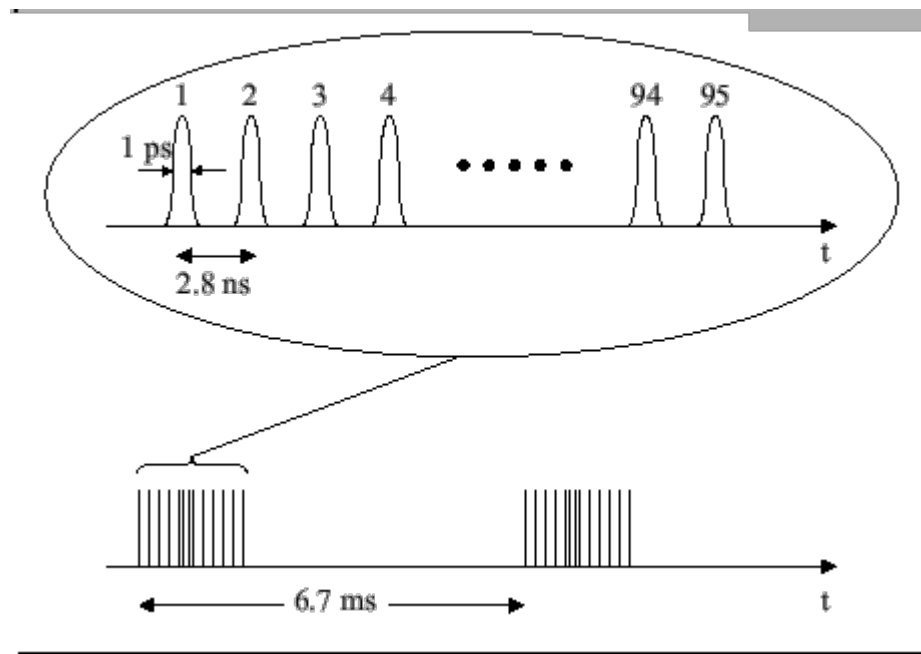
- Large part of the Earth is covered by water

Nature Reviews | Microbiology

'blue' has the highest absorption depth

However, the fractional reflectance is highest

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Continuous Versus Pulsed Waves

- By default: continuous
- By altering the laser: pulsed ~ nano- or picoseconds

Analysis of individual pulses

Increased spatial resolution

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Blue types of laser

- Optimum wavelength according to analysis ~ 425 – 500 [nm]

- Possible 'blue' lasers
  - Gas lasers
    - Wavelength: 441.6 [nm] (Helium-Cadmium)
    - Wavelength: 488 [nm] (Argon)

  - Solid-State laser (Nd-YAG: neodymium-doped yttrium aluminium garnet)
    - Wavelength: 946 [nm]

  - Diode laser
    - Difficult to produce for lifetimes > 1 year

Nd-YAG wavelength correction

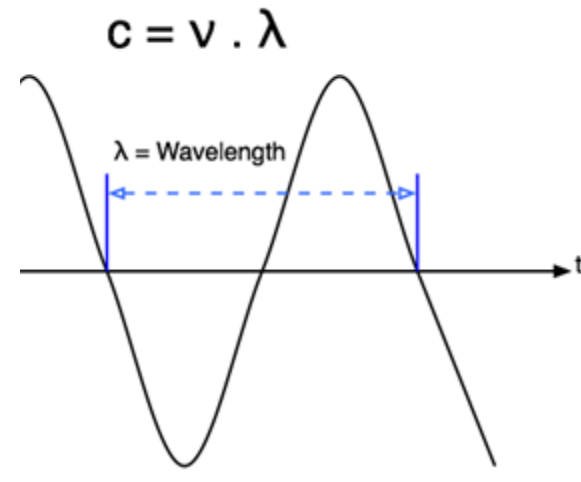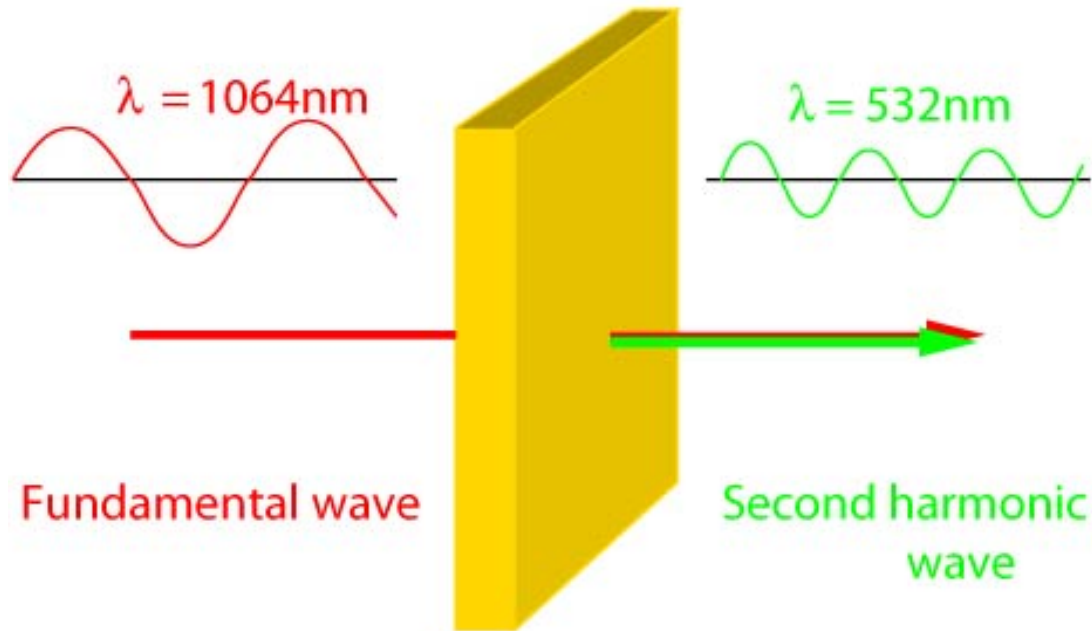- Second Harmonic Generation (non-linear optics)
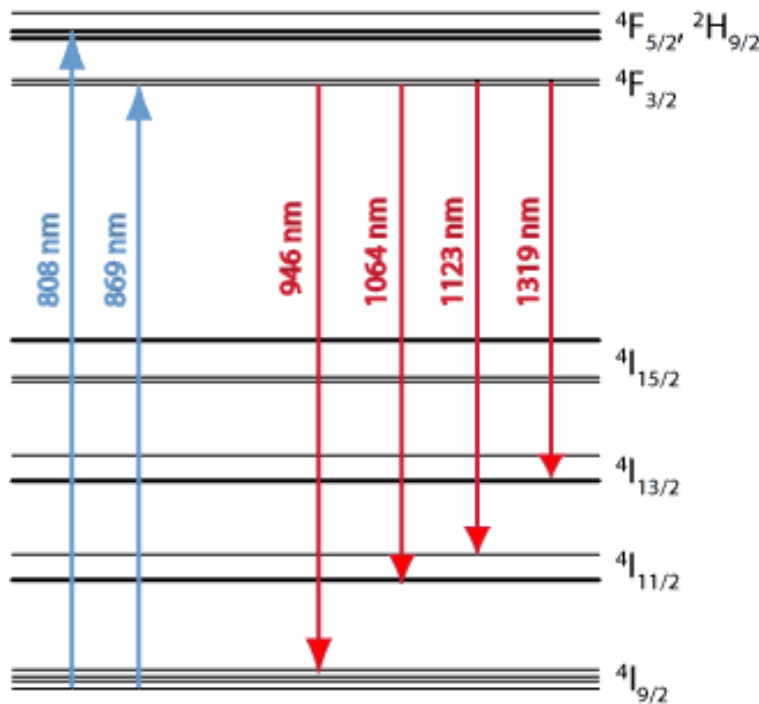
Nd-YAG energy levels

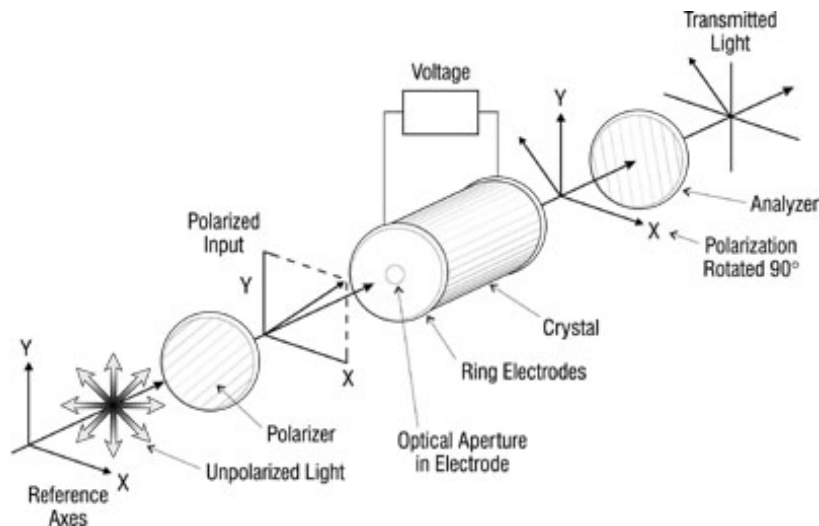Non-linear (Lithium-Boron) frequency doubling crystal

From 946 [nm] to 473 [nm]

$\lambda = 1064nm$

$\lambda = 532nm$

Fundamental wave

Second harmonic wave

$c = v \cdot \lambda$
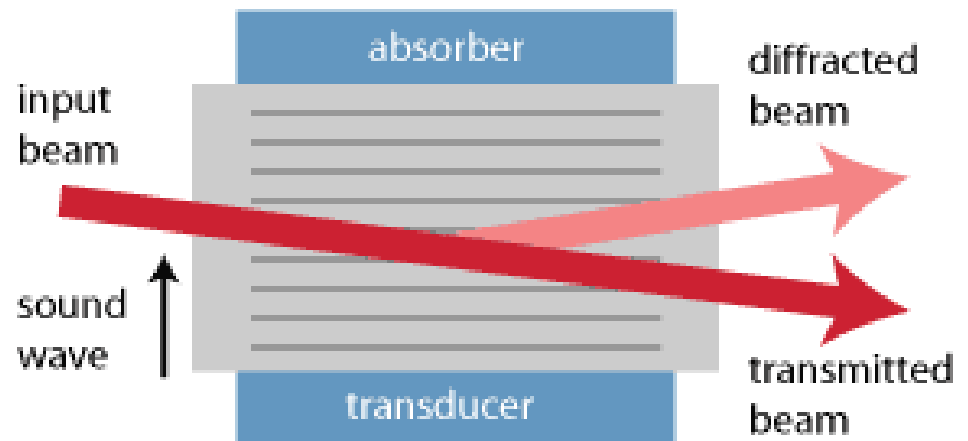
λ = Wavelength

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Pulse Duration Deviation

- Change pulse length (and pulse energy) over specific time intervals

Pockel Cells (**E**-field)   **Acoustic-Optic Switches** (RF 25 – 50 MHz)

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5.

Software tool

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Special orbits types

- Polar orbit

- Repeat orbit

- Sun Synchronous orbit

- Frozen orbit

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Special orbits types

Polar orbit

- Provides maximum coverage

- Can not provide continuous view of an area

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Special orbits types

Repeat orbit

Allows an area to be viewed more than once.

Assuming a footprint size of 100 meters:

40.000.000/(2*100)=200.000 revolutions
200.000*90 (minutes) = 34 years

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Special orbits types

Sun synchronous orbit

• Orbital plane fixed w.r.t. the sun vector

• Most useful orbit is the dawn/dusk orbit

> ➢ Solar panels are in the sunlight continuously

> ➢ Allows pointing to the night side of the Earth

Special orbits types

Frozen orbit

- Reduces the need for orbit station keeping.

- A constellation in formation flight has strict constraints.

  ➢ A frozen orbit helps meet these constraints

Special orbits types

Frozen orbit design equations

$$\dot{e} = \frac{3}{2} \frac{J_3 r_{eq}^3}{p^3} \left(1 - e^2\right) n \sin i \cdot \cos \omega \left(\frac{5}{4} \sin^2 i - 1\right)$$

$$\frac{di}{dt} = \frac{3}{2} \frac{J_3 n}{\left(1 - e^2\right)^3} \left(\frac{R_e}{a}\right)^3 e \cos i \cdot \cos \omega \left(\frac{5}{4} \sin^2 i - 1\right)$$

$$\dot{\omega} = \frac{3 J_2 n}{\left(1 - e^2\right)^2} \left(\frac{R_e}{a}\right)^2 \left(1 - \frac{5}{4} \sin^2 i\right) F$$

$$F = 1 + \frac{J_3}{2 J_2 \left(1 - e^2\right)} \left(\frac{R_e}{a}\right) \left(\frac{\sin^2 i - e^2 \cos^2 i}{\sin i}\right) \frac{\sin \omega}{e}$$

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Special orbits types

Frozen orbit design equations

$$\frac{di}{dt} = \frac{3}{2} \frac{J_3 n}{\left(1-e^2\right)^3} \left(\frac{R_e}{a}\right)^3 e \cos i \cdot \cos \omega \left(\frac{5}{4} \sin^2 i - 1\right) = 0$$

Circular orbit, so e = 0

$$\frac{di}{dt} = 0 \qquad \text{for any a, i or } \omega$$

Special orbits types

Frozen orbit design equations

$$\dot{e} = \frac{3}{2}\frac{J_3 r_{eq}^3}{p^3}\left(1-e^2\right)n\sin i \cdot \cos \omega \left(\frac{5}{4}\sin^2 i - 1\right) = 0$$

With e = 0 this becomes

$$\dot{e} = \frac{3}{2}\frac{J_3 r_{eq}^3}{a^3}n\sin i \cdot \cos \omega \left(\frac{5}{4}\sin^2 i - 1\right) = 0$$

Equation is satisfied for any a and i if ω = 90 degrees

Special orbits types

Frozen orbit design equations

$$\dot{\omega} = \frac{3J_2 n}{\left(1 - e^2\right)^2} \left(\frac{R_e}{a}\right)^2 \left(1 - \frac{5}{4}\sin^2 i\right) F$$

$$F = 1 + \frac{J_3}{2J_2\left(1 - e^2\right)} \left(\frac{R_e}{a}\right) \left(\frac{\sin^2 i - e^2 \cos^2 i}{\sin i}\right) \frac{\sin \omega}{e}$$

With e = 0 these equations reduce to

$$\dot{\omega} = 3J_2 n \left(\frac{R_e}{a}\right)^2 \left(1 - \frac{5}{4}\sin^2 i\right) F$$

$$F = 1$$

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Special orbits types

Frozen orbit

$$\dot{\omega} = 3J_2 n \left(\frac{R_e}{a} \right)^2 \left(1 - \frac{5}{4} \sin^2 i \right)$$

- Is equal to zero if i = 63.4 OR i = 116.6 degrees

- However a polar orbit is an orbit of 90 degrees inclination

  ➤ Definition: An orbit is a polar orbit if $80 \leq i \leq 100$ degrees

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Special orbits types

Frozen orbit

$$\dot{\omega} = 3J_2 n \left(\frac{R_e}{a} \right)^2 \left(1 - \frac{5}{4} \sin^2 i \right)$$

- The orbit is circular

  ➢ It does not matter if ω rotates in the orbit plane

- Taking collision avoidance into collision avoidance

  ➢ i = 85 degrees

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Special orbits types

Summary

- Sun synchronous is not required

- Repeat orbit is unfeasible
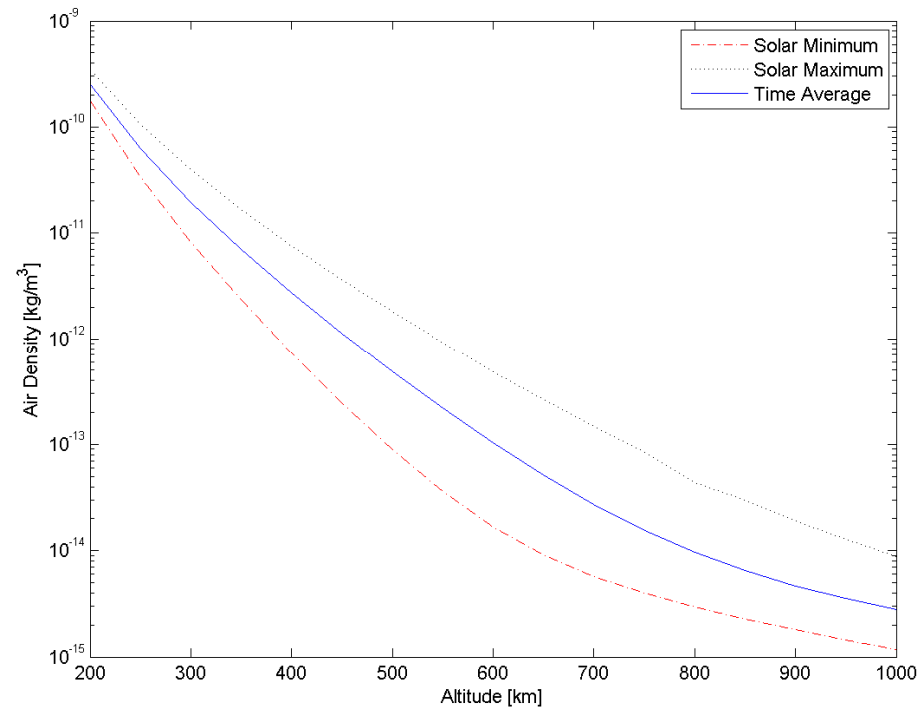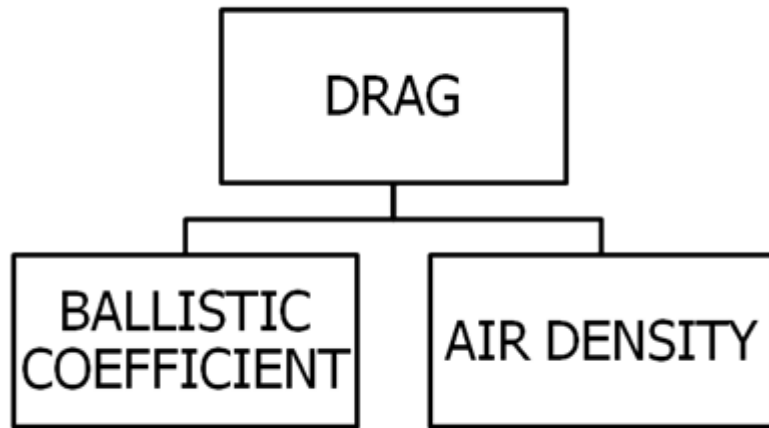
- The end result is a

    Frozen, polar orbit with

    - e = 0 degrees
    - i = 90 degrees
    - ω = 90 degrees

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Orbit Altitude Analysis
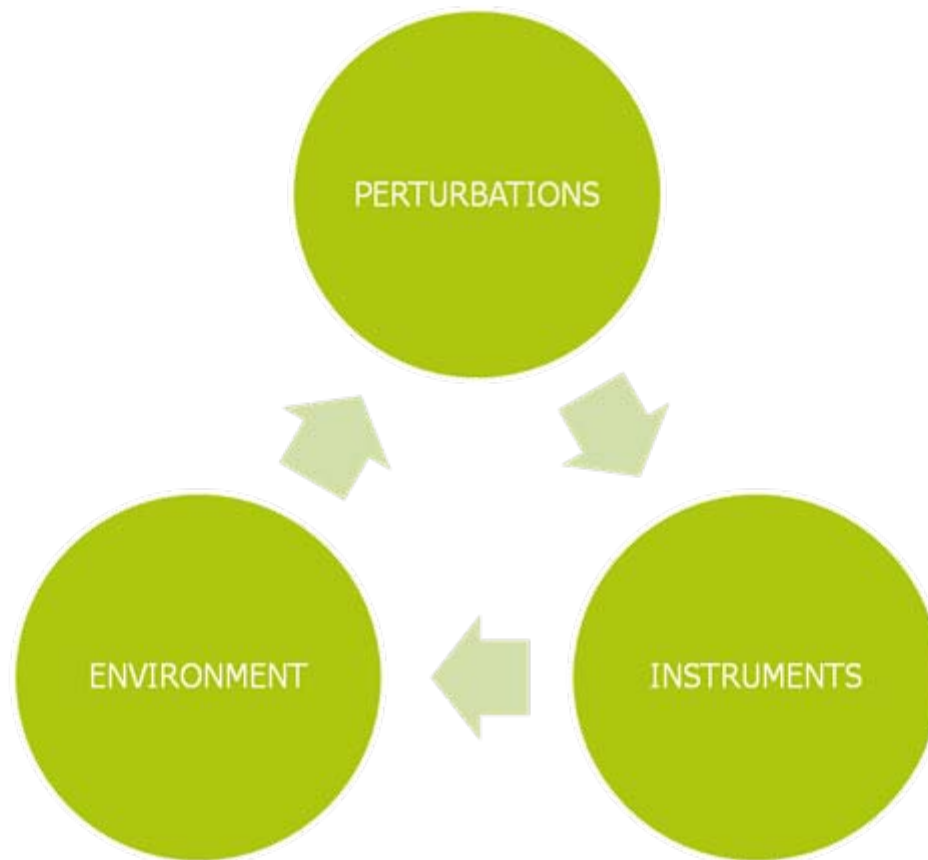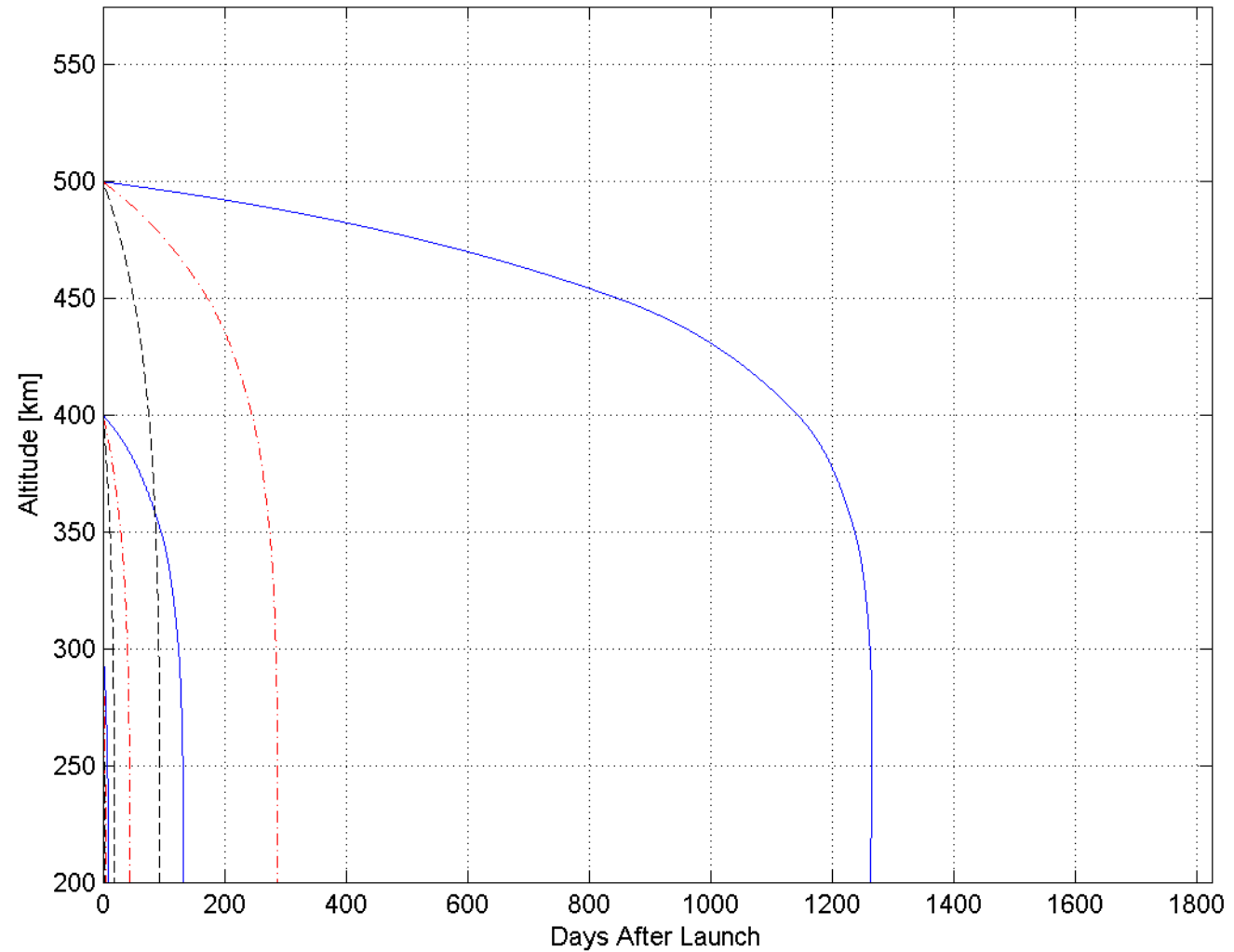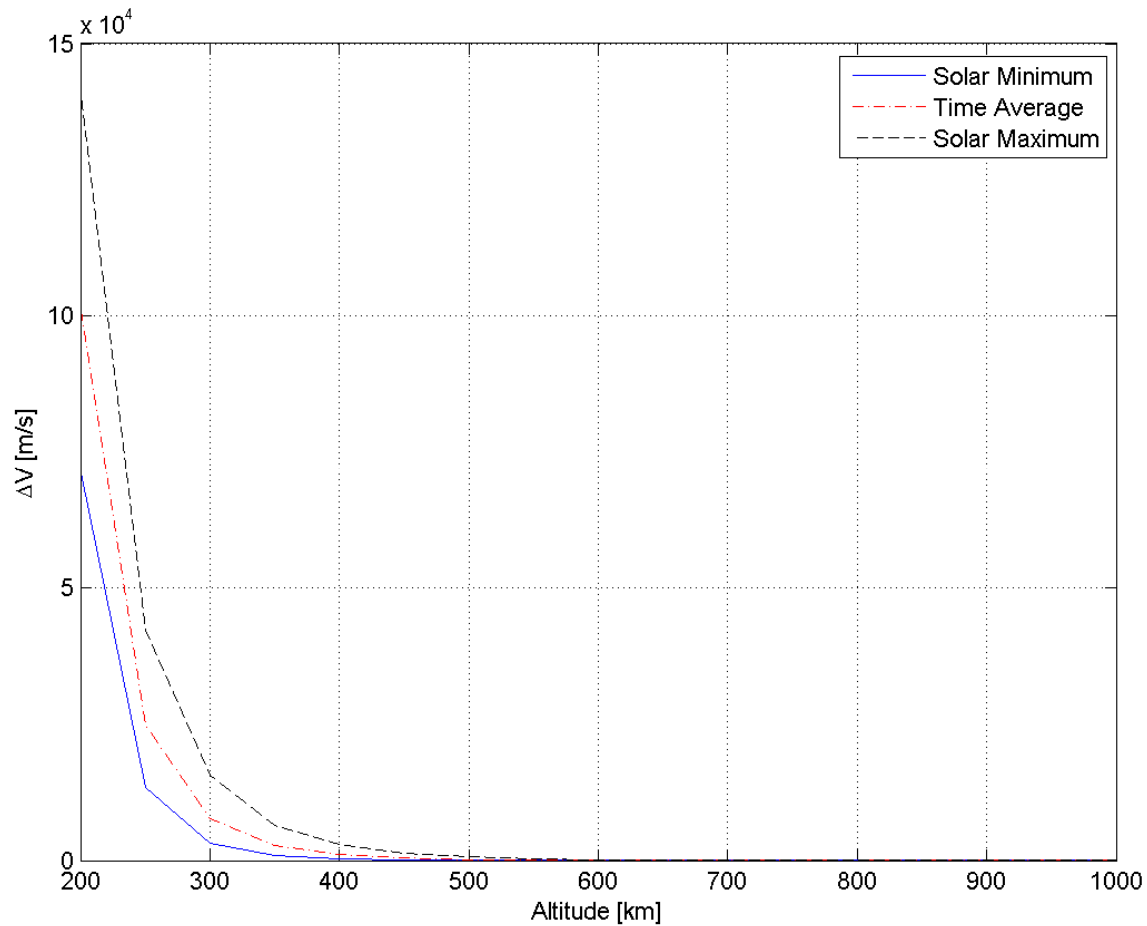
Orbit Altitude Analysis - Perturbations

Drag

$$\Delta a = -2\pi \left(C_D \frac{A}{m} \right) \rho a^2$$

$$\Delta P = -6\pi \left(C_D \frac{A}{m} \right) \rho \frac{a^2}{V}$$

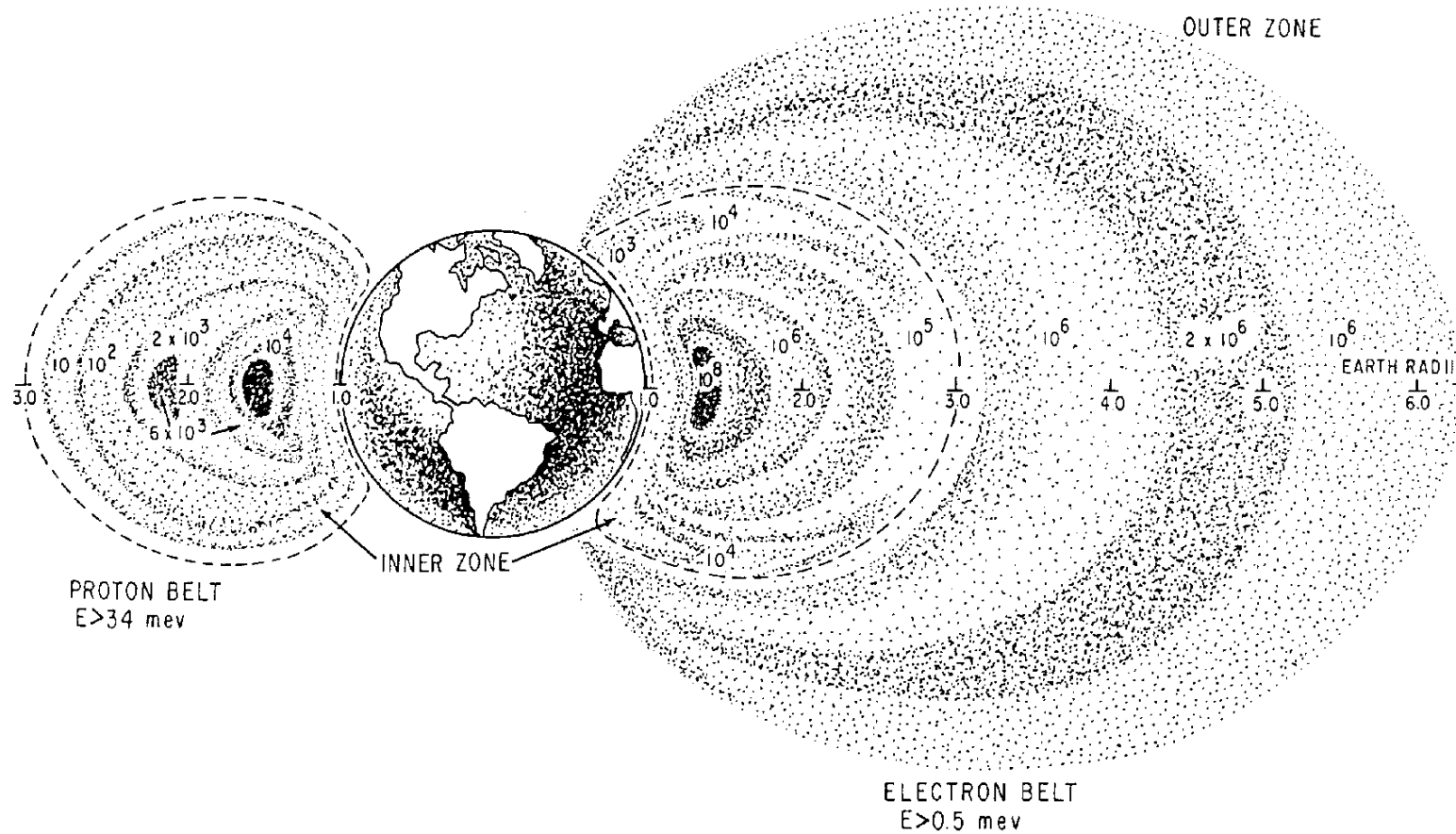$$\Delta V = \pi \left(C_D \frac{A}{m} \right) \rho a V$$

$\tilde{T}U$Delft

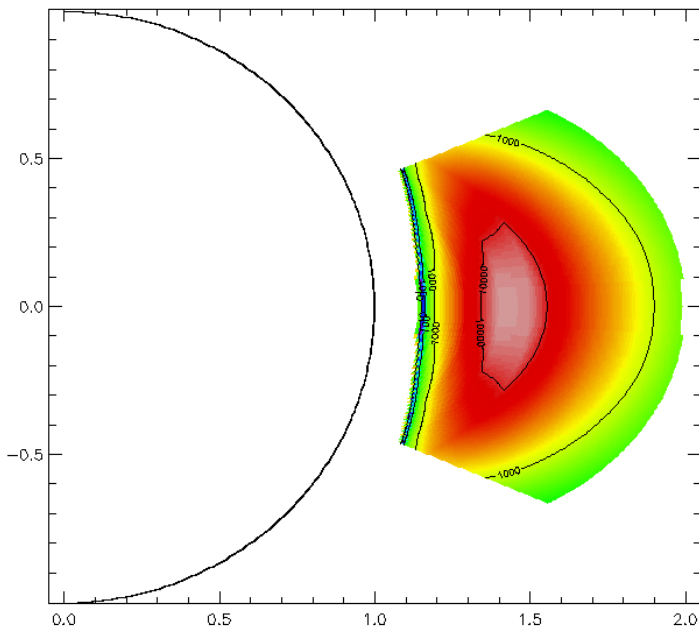# Drag - ΔV
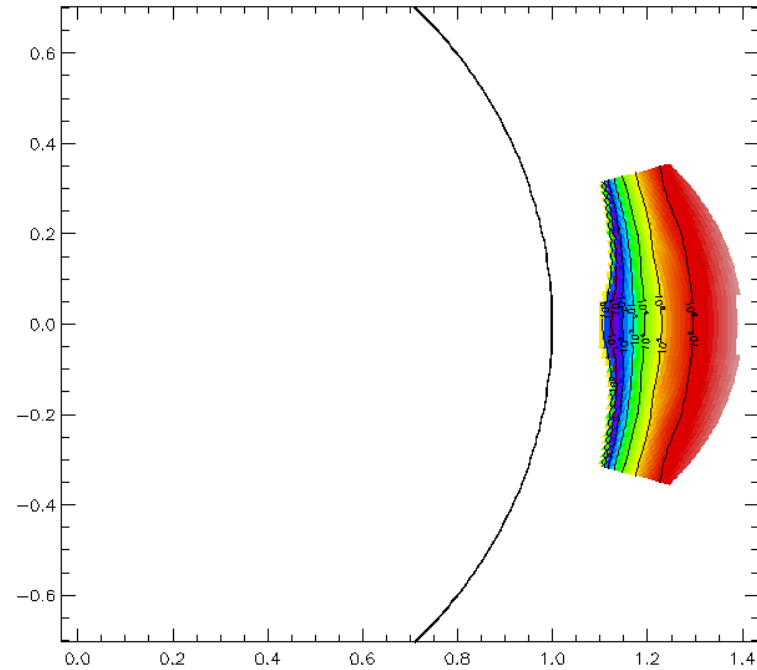
Environment
Trapped particle radiation

PROTON BELT
E>34 mev

INNER ZONE

OUTER ZONE

EARTH RADII

ELECTRON BELT
E>0.5 mev

TUDelft

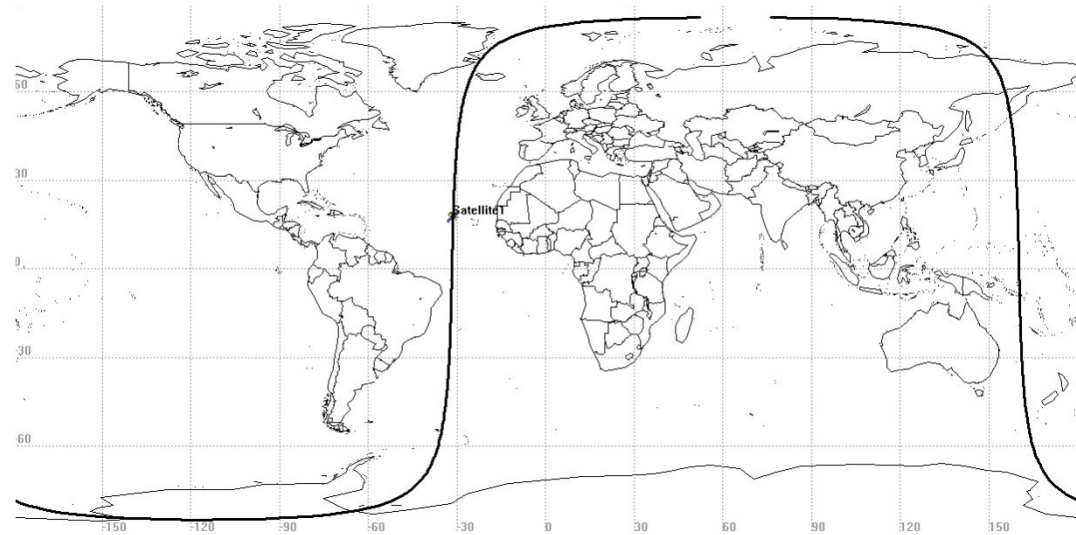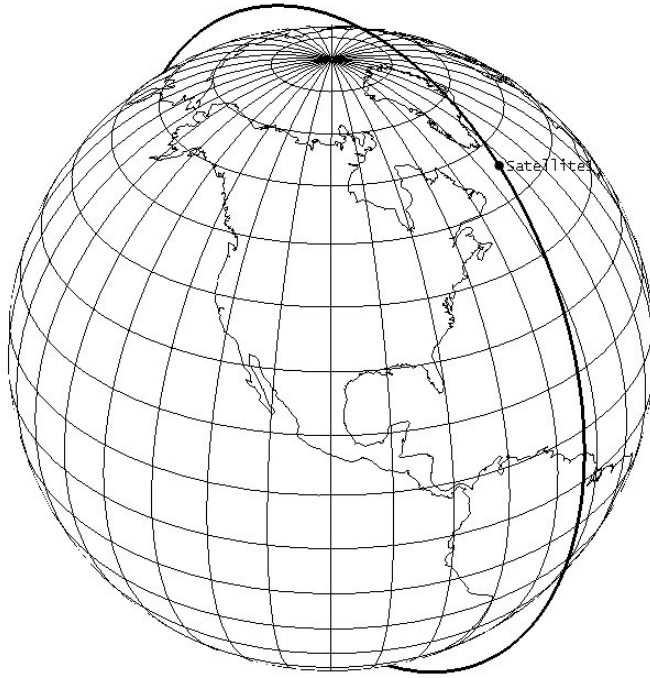# Environment
Trapped particle radiation

Orbit Altitude
Summary

- As high as possible to reduce propellant mass
- Mission timeframe is crucial – solar min/max
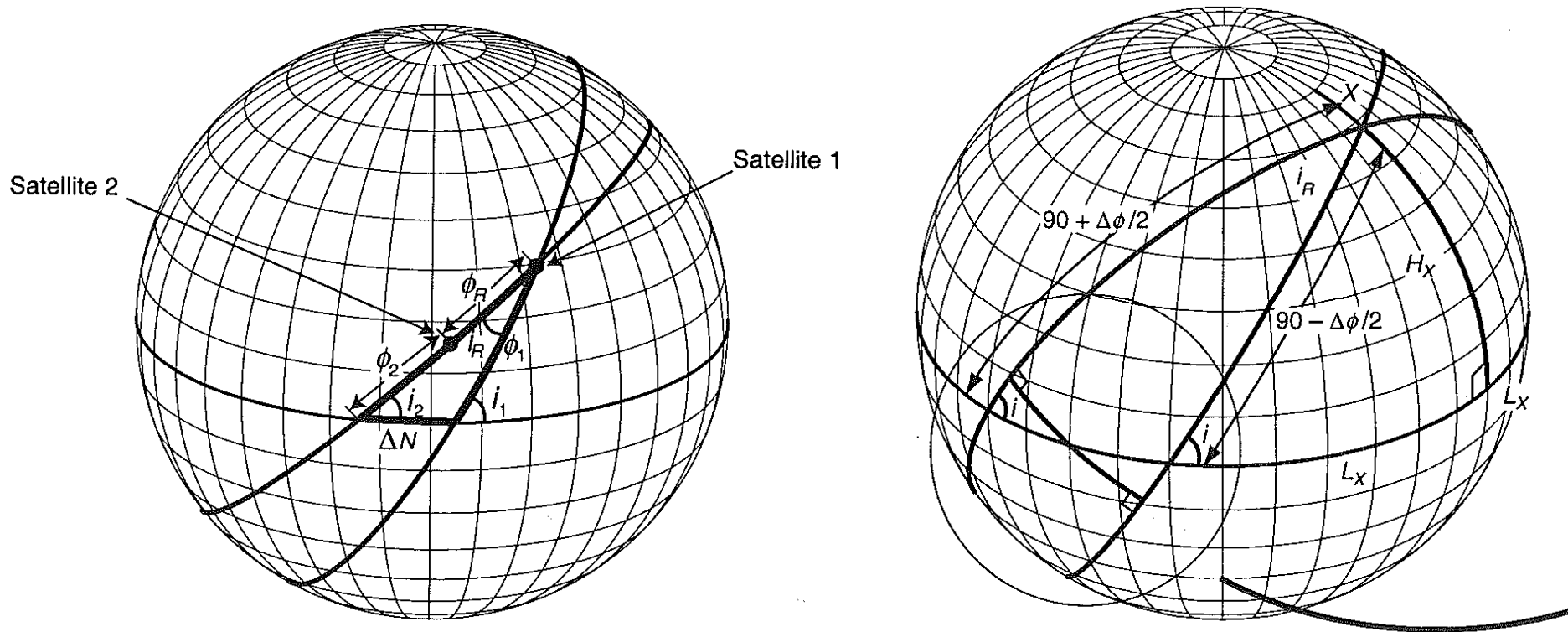- Keep ballistic coefficient close

TUDelft
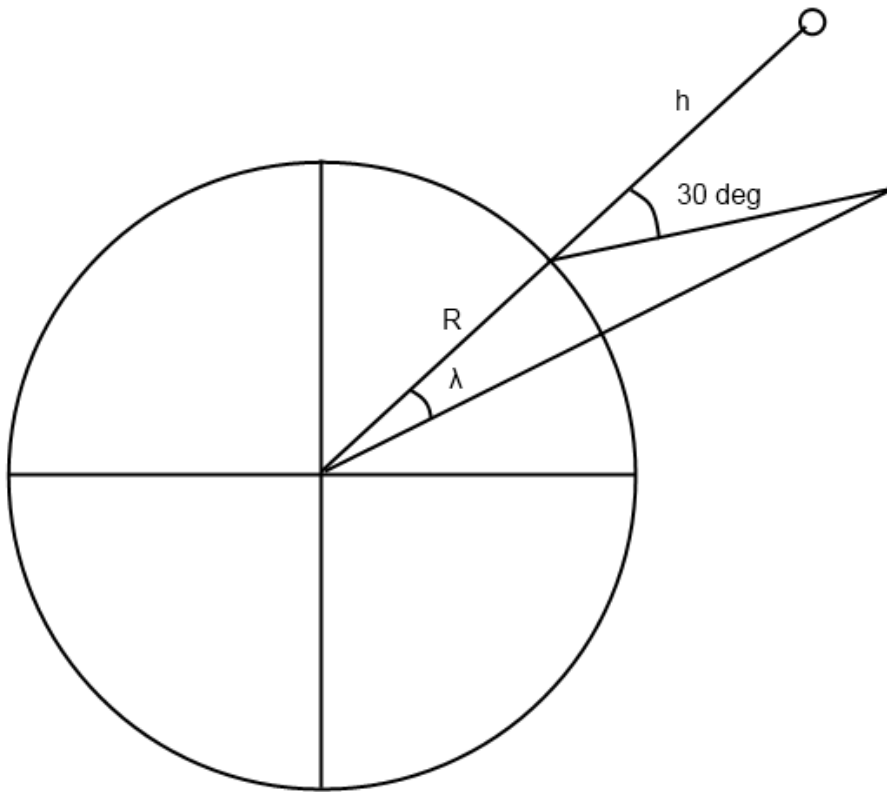
Orbit Altitude
Summary

Formation Design
SWARM

Formation Design

SWARM

$\lambda = 2.18°$

$i_R = 2.18°$

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Formation Design

Stationkeeping

Keeping the general constellation to insure better measurement data.

What affects it?

- Perturbations
- Differences in initial conditions

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Formation Design
Stationkeeping

What can be done?

- Nothing
- Relative Stationkeeping
- Absolute Stationkeeping
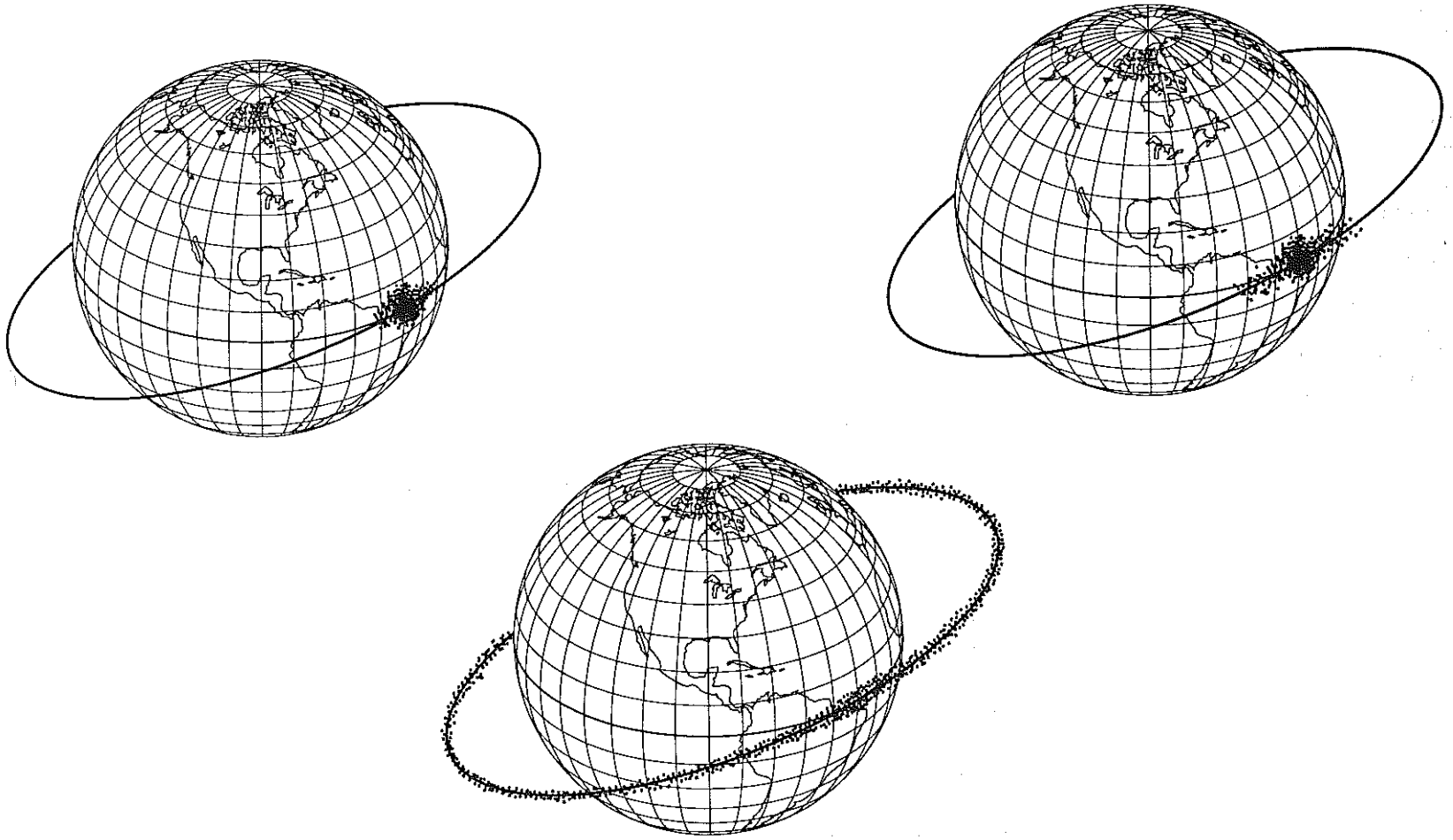
Formation Design
Collision Avoidance

Why is it important?

- Loss of 2 satellites, possibly vital
- Increased possibility of collision due to debris spread

Formation Design

Collision Avoidance

Formation Design
Collision Avoidance

Parameters	5 Satellite Formation in 3 Planes	9 Satellite Formation in 5 Planes
No. of satellites	5	9
No. of orbit planes	3	5
Vertical dispersion [km]	1	1
In-track dispersion [km]	276	276
Potential impact area [km^2]	276	276
Collision opp. per orbit	20	72
Orbit period [min]	94.62	94.62
Collision opp. per year	$1.1*10^5$	$4.0*10^5$
Collision opp. in 5 years	$5.6*10^5$	$2.0*10^6$
Collision prob. per opp.	$1.0*10^{-6}$	$1.0*10^{-6}$
Mean number of collisions per year	0.11	0.4

Information based on Wertz, 2001

6.

Software tool
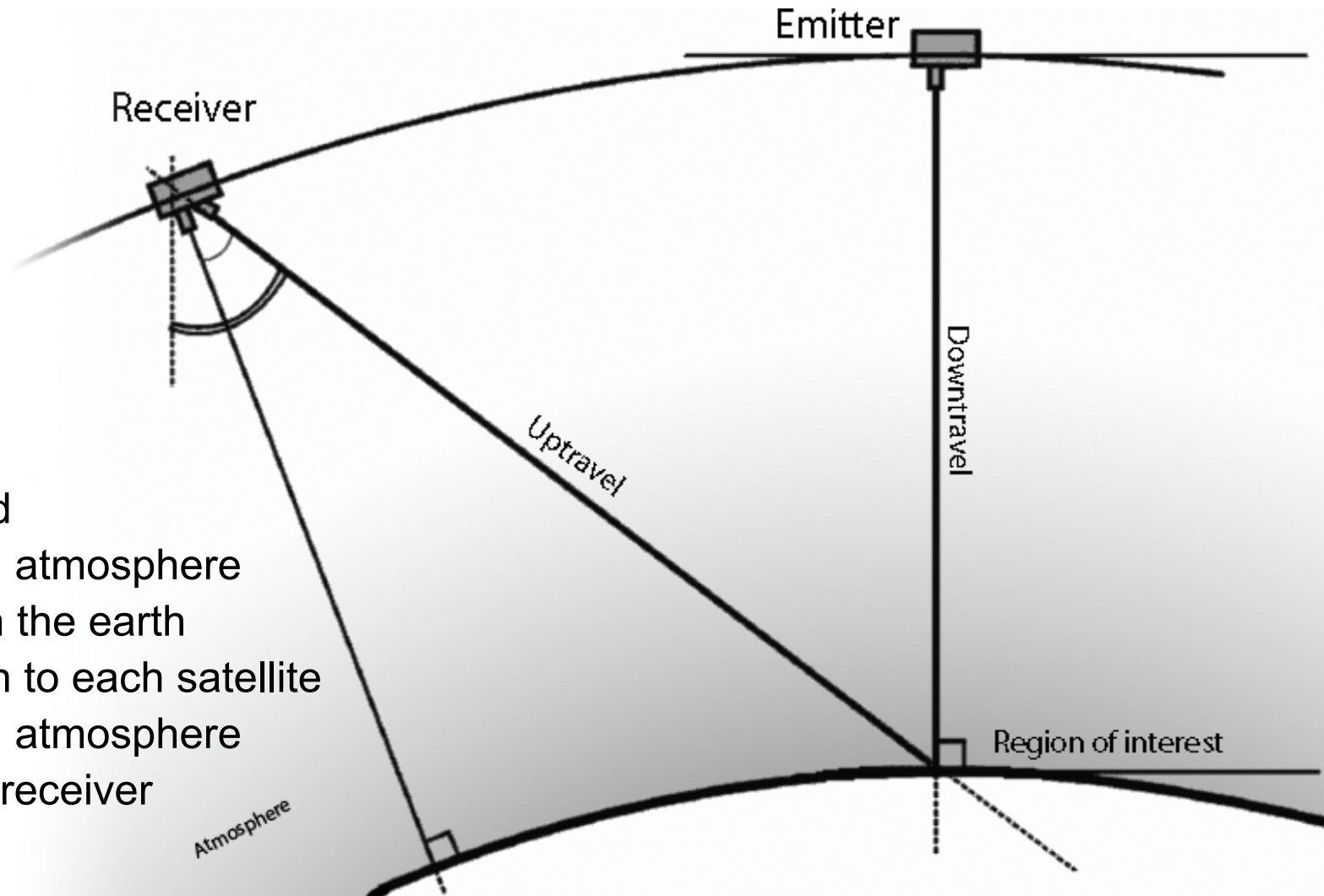
Software tool

Two parts

- Simulation

    Simulate the laser pulse photons and noise as received by the sensor.

- Data analysis

    Reconstructing the digital elevation model and BRDF from the received
        time series.

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Simulation

Pulse cycle

- Pulse emitted
- Absorption in atmosphere
- Scattering on the earth
- Small fraction to each satellite
- Absorption in atmosphere
- Received by receiver

Emitter

Receiver

Uptravel

Downtravel

Atmosphere

Region of interest

Noise

- Noise is introduced into the system

- Sources are the Earth and the Sun

- In a selective wavelength band

- Strong dependence on
  - Receiver footprint area
  - Receiver sensitivity band
  - Constellation altitude

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Photon count variation with altitude

- Exponential decrease in photon count with altitude

- Lower is better

- Higher altitudes:
  - larger receiver aperture
  - higher emitter power

$$photons = e^{-0.0052 \cdot alt + 0.6558}$$
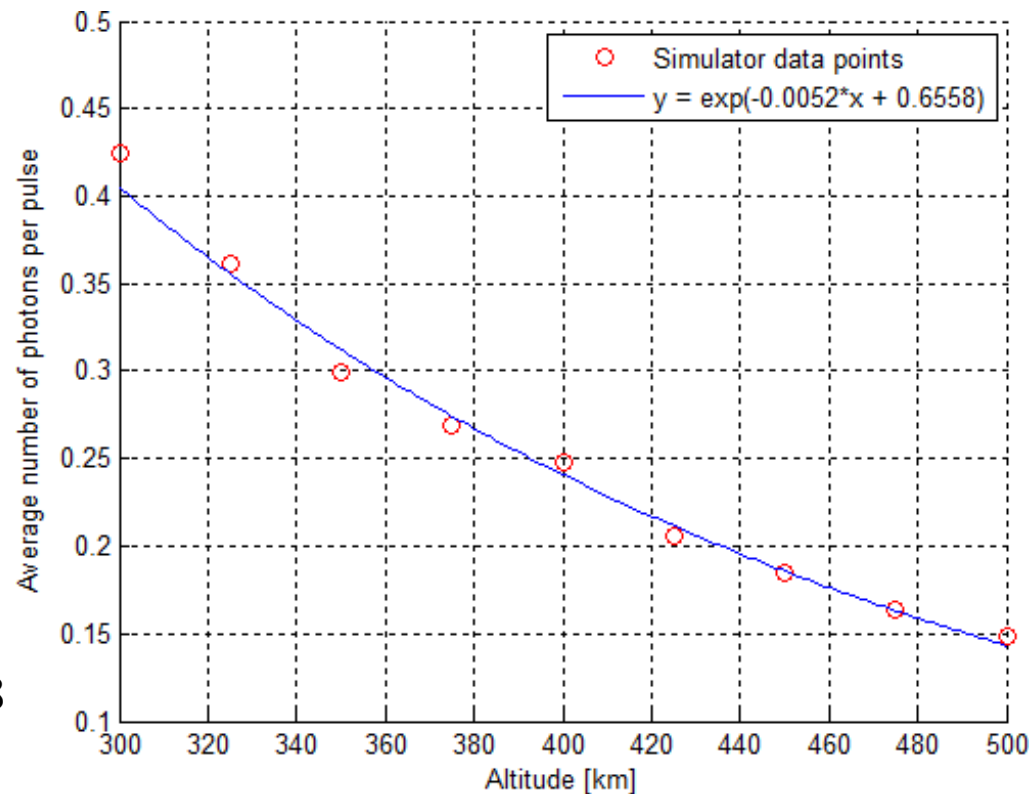
Solar noise photons fraction

Orbit at 450 km, 33W laser

Simulation results:

- Pulses sent: 24989 (about 5s)
- Photons from pulses received: 12289 (86.5%)
- Sun noise photons received: 1930 (13.5%)
- Total photons received: 14219

Majority of the photons from the emitter laser
Noise can be filtered out (constellation)

Terrain Reconstruction Algorithm

•Define time range

•Find the peaks

•Calculate altitudes

•Find the most common altitude

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Defining Range

- Known:
  - Time pulse sent
  - Time <u>SOME</u> pulse received

- Window : 1/5000 sec = 200 micro sec

- Offset: 500km/c = 1.666 milliseconds travel time

- Height range: 60 km

TUDelft

Find the Peaks
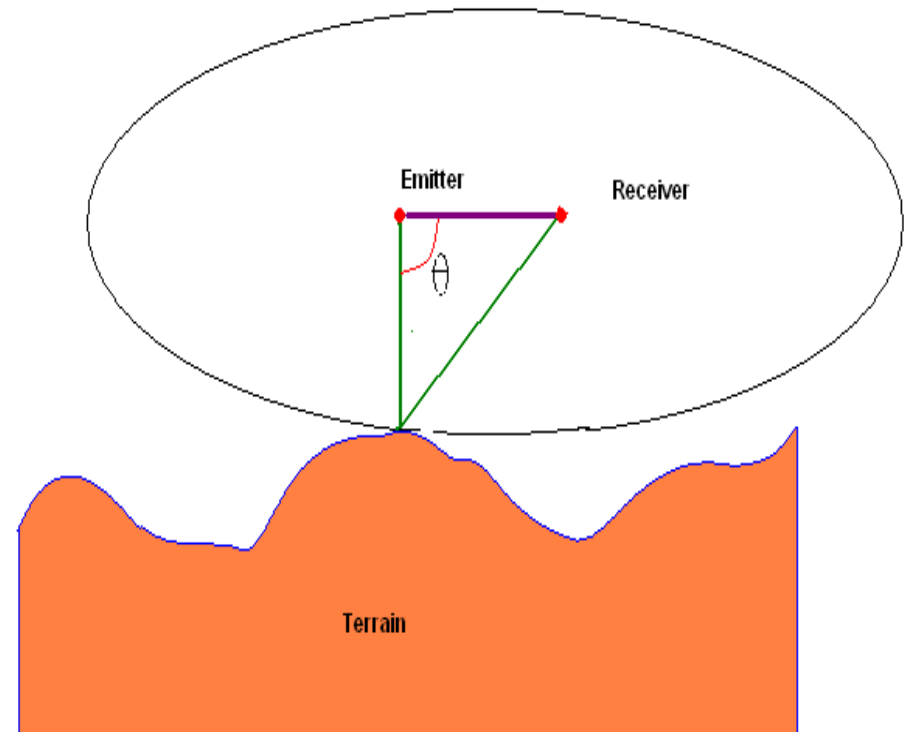
- The peaks correspond to received pulses

- Noise introduced creates "false" peaks

- N*mean threshold

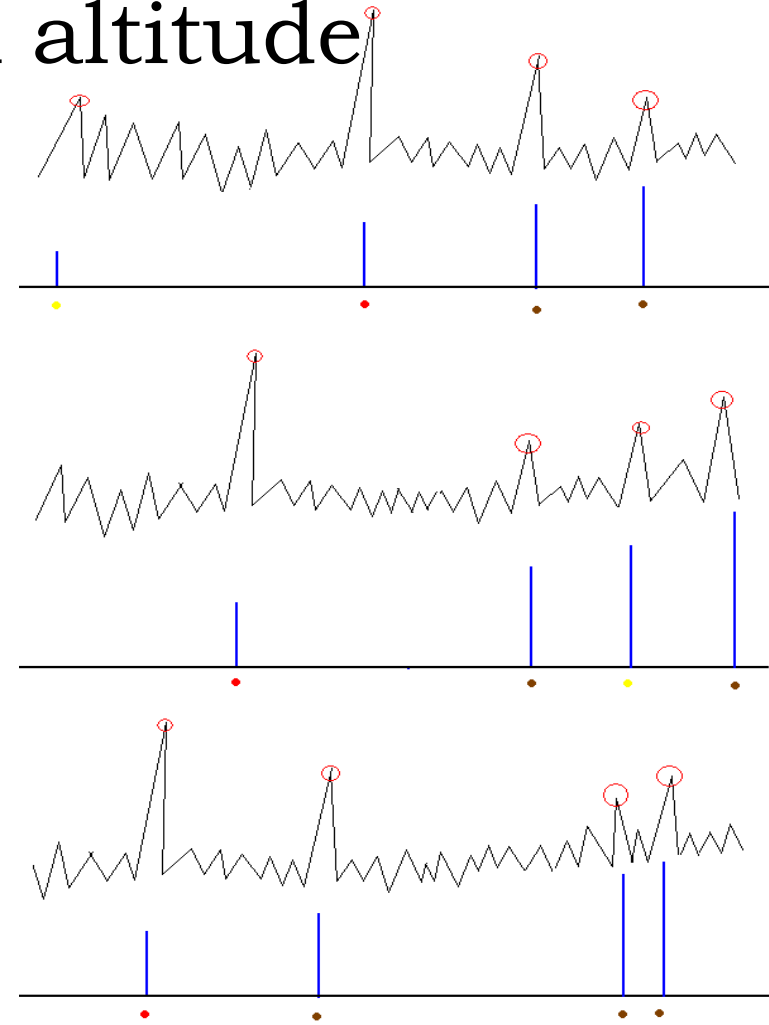- Intermediate step for BRDF determination
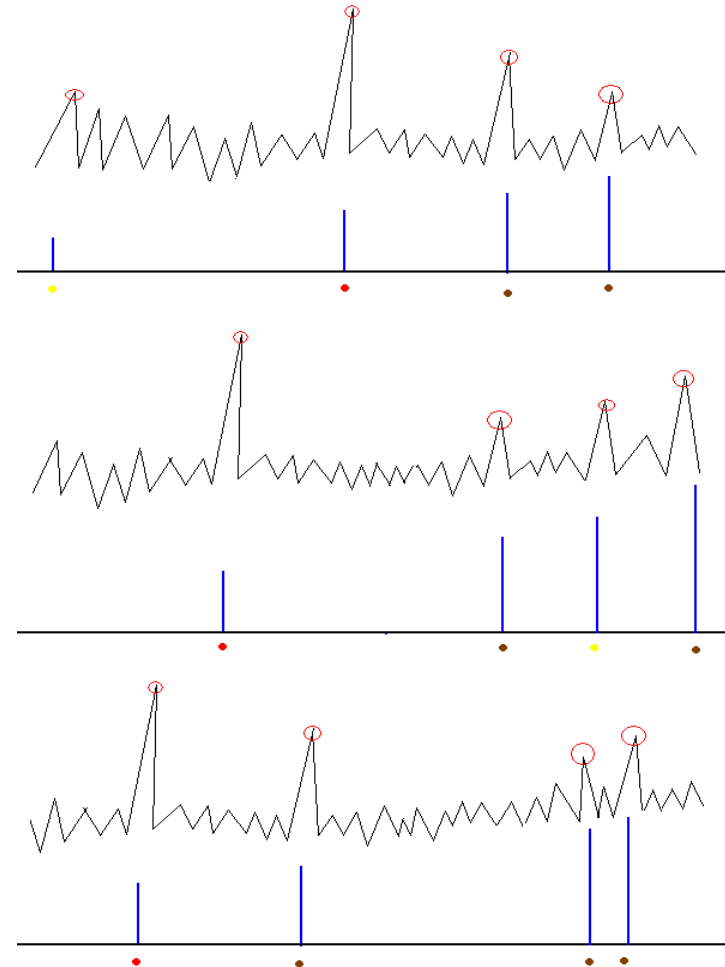
Calculate altitudes

- Required:
  - Position of emitter
  - Position of receiver
  - Travel time

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Finding most common altitude

- Filtering noise

- Peak = specific altitude

- Least standard deviation configuration

TUDelft

7.

Summary and conclusions

Summary

- ADCS   Sun sensor & star tracker
  Reaction wheels and magneto torquers

- COMS   Centralized architecture

- EPS   Thin film solar cells

- ORP   32x32 SPAD with faceted mirror

- OEP   Nd-YAG laser 473 nm

- ORBIT   Frozen polar orbit, 500 km, $I = 85°$, $\lambda_{max} = 2.18°$

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