# Laser Swarm

## Mid term review

Group 13, Aerospace Engineering

14-6-2010

# Contents

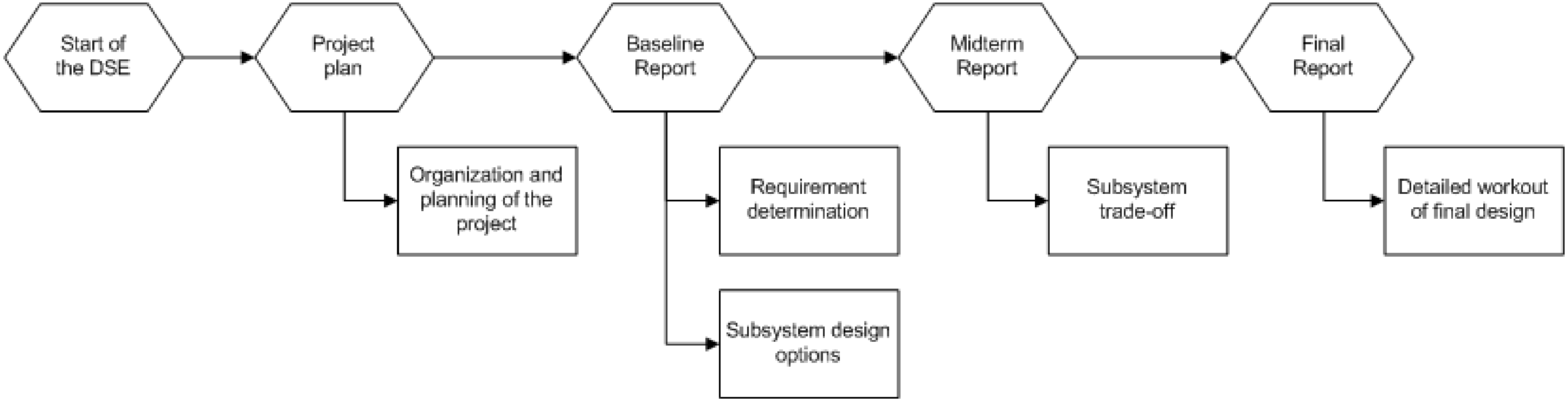
# 1.

*Project plan*

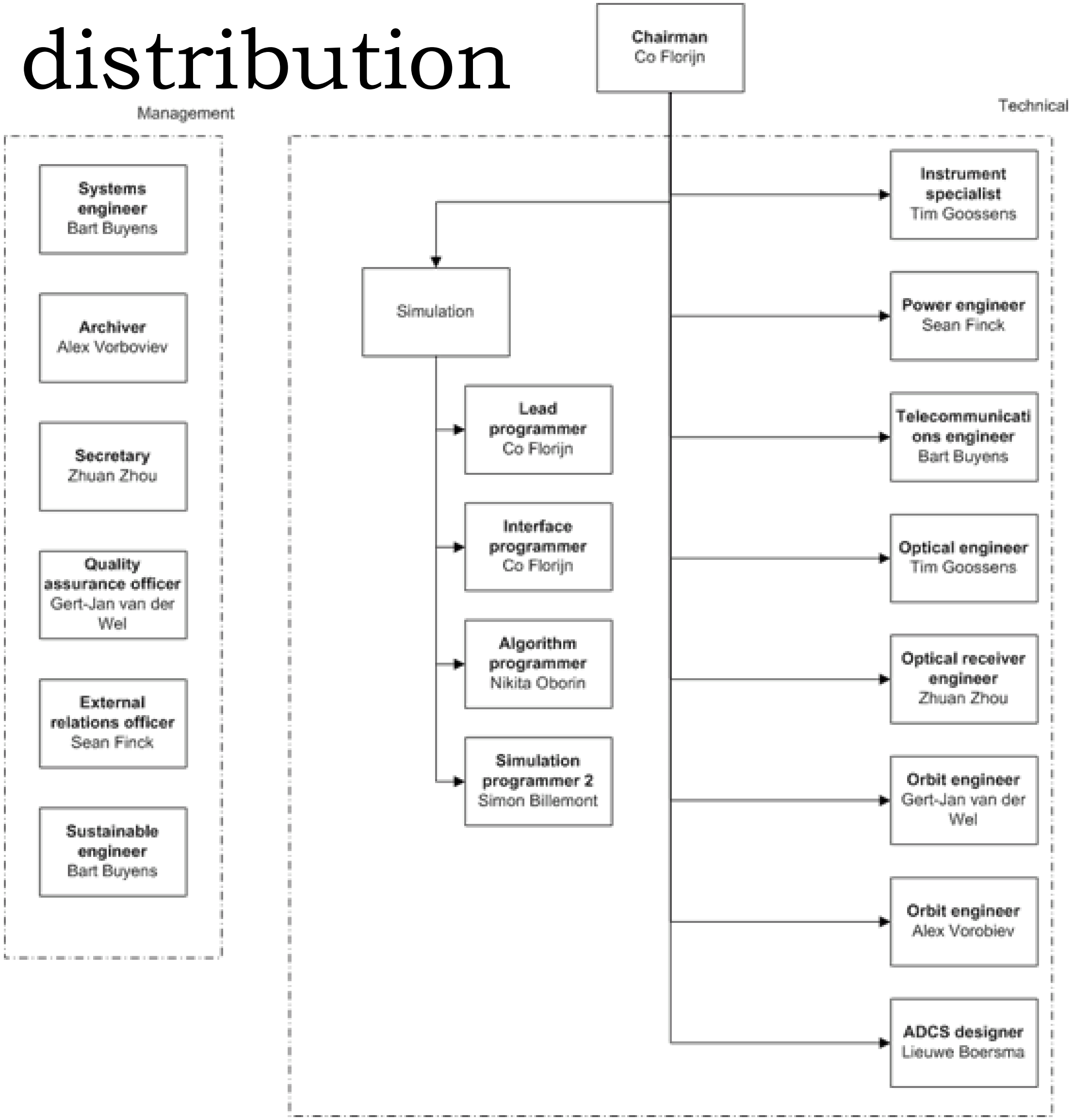
# Mission need statement

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.

# Project Organization



# Work distribution



# 2.

## *Key requirements*

# Key Requirements

- Low cost
- Lifetime  of ~ 5 yrs
- Performance equivalent to ICESat

# Additional Requirements

- Mass ≤ existing spaceborne laser altimetry systems
- No scanner may be used
- Recreation of the DEM
- Extraction of the BRDF

# 3.

## *Tradeoff method*

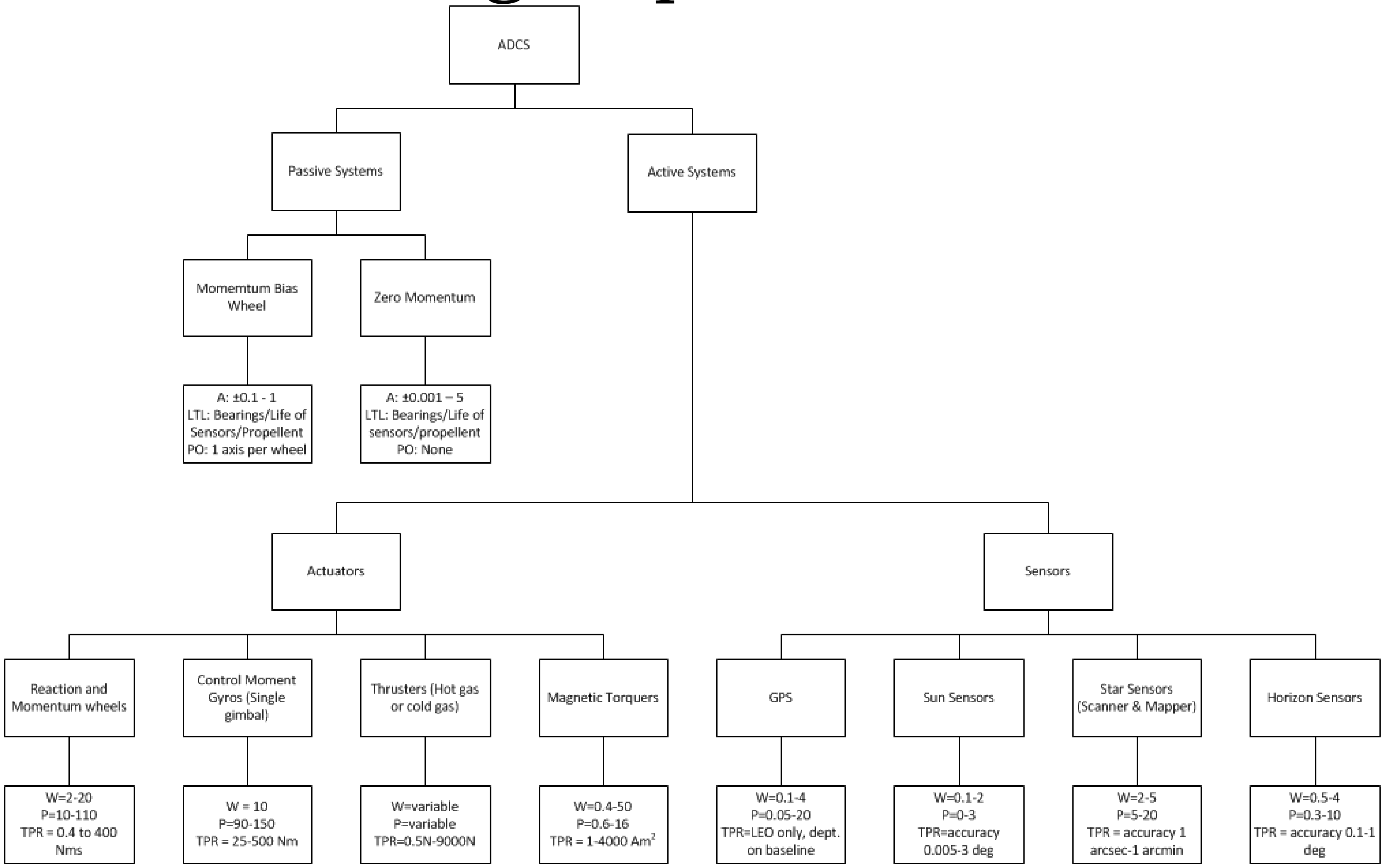
# Trade-off Method

- A set of criteria are defined
- Each criterium is assigned weight w.r.t. importance
- Varies for each subsystem
- Each subsystem is graded
- Highest score wins

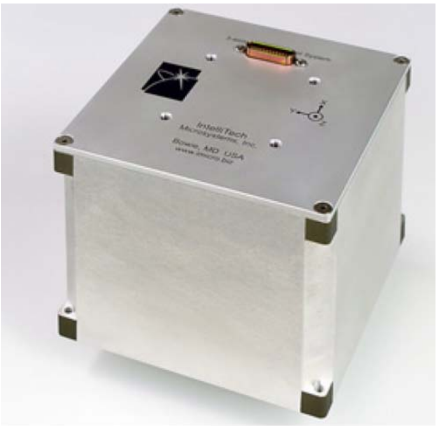
# 4.

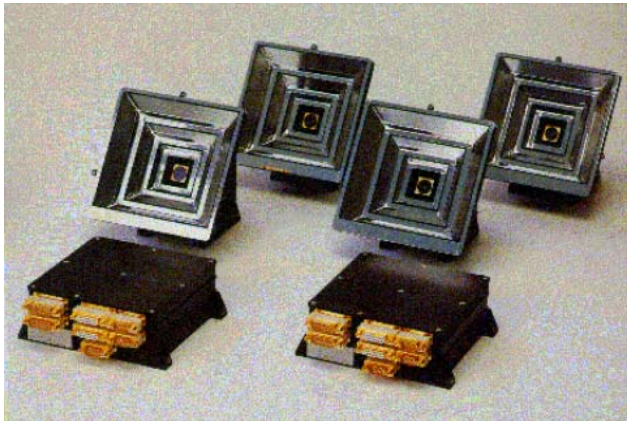
## *Subsystem trade off*

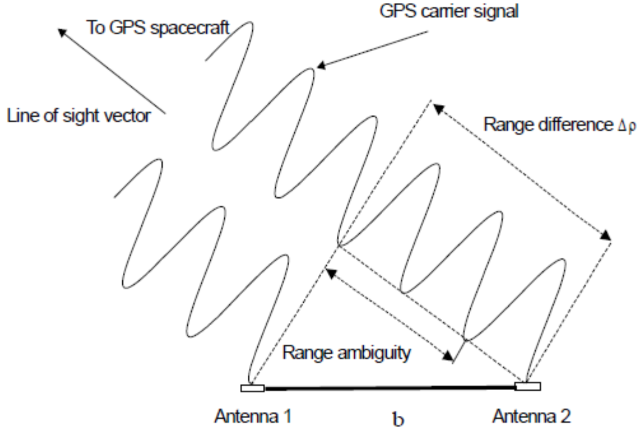
# Pruned Design Option Tree ADCS



# Selected ADS concepts







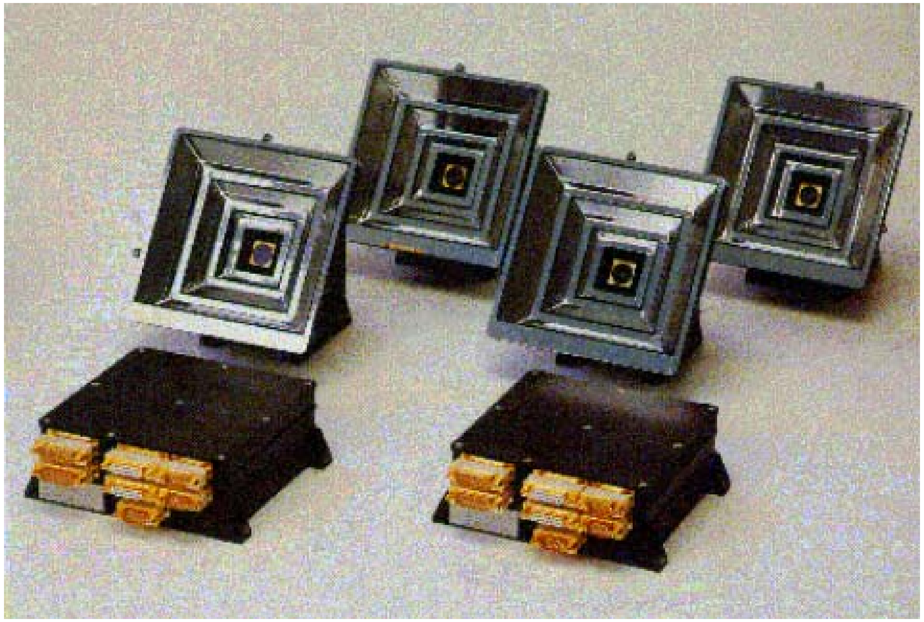

1. Maryland Aerospace Inc. IMI-100 ADACS
2. Sun Sensors and a Star Tracker
3. GPS based attitude control

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

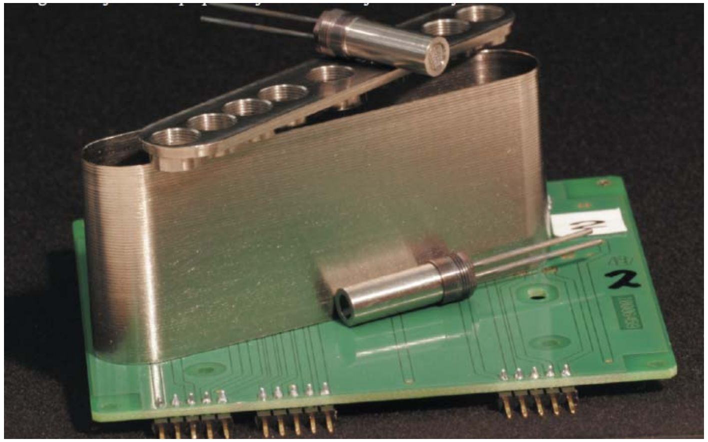
| Criteria | Weight Factor | Concept 1 | Concept 2 | Concept 3 |
|---|---|---|---|---|
| **Accuracy** | 9 | 4 | **8** | 4 |
| **Size** | 7 | 2 | **6** | 4 |
| **Power** | 7 | 6 | 5 | **7** |
| **Price** | 3 | 3 | **5** | 4 |
| **Development** | 5 | **8** | 4 | 5 |
| **Weighed total** | | 141 | **184**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

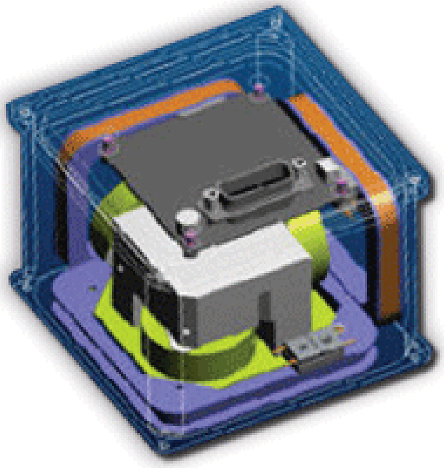
# Winner ADS

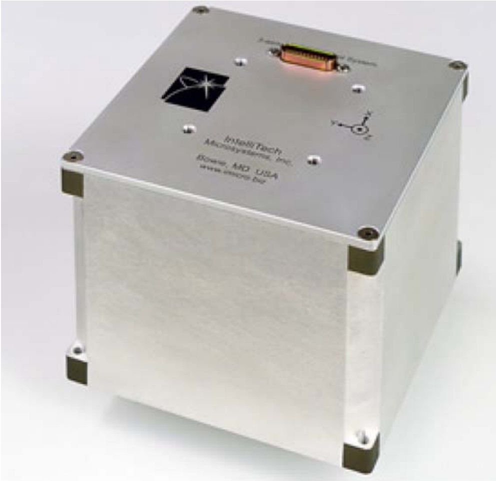


Sources: Dr. Q.P. Chu. Spacecraft attitude dynamics and control, course notes

# Selected ACS concepts







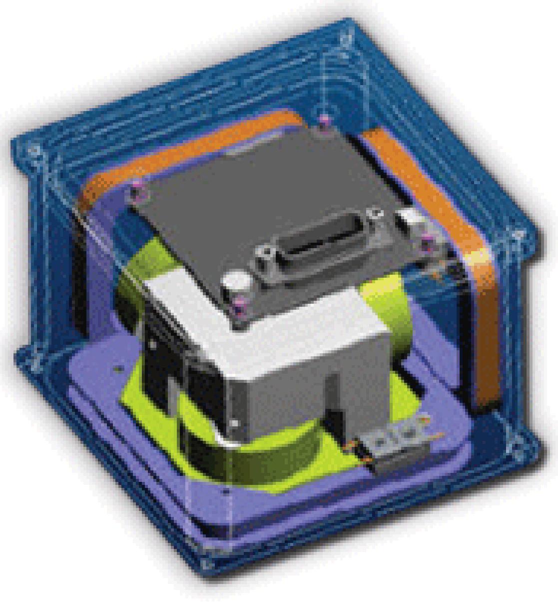

1. Thrusters
2. Reaction wheels and magnetic torquers
3. Maryland Aerospace Inc. IMI-100 ADACS

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

# Trade-off ADS

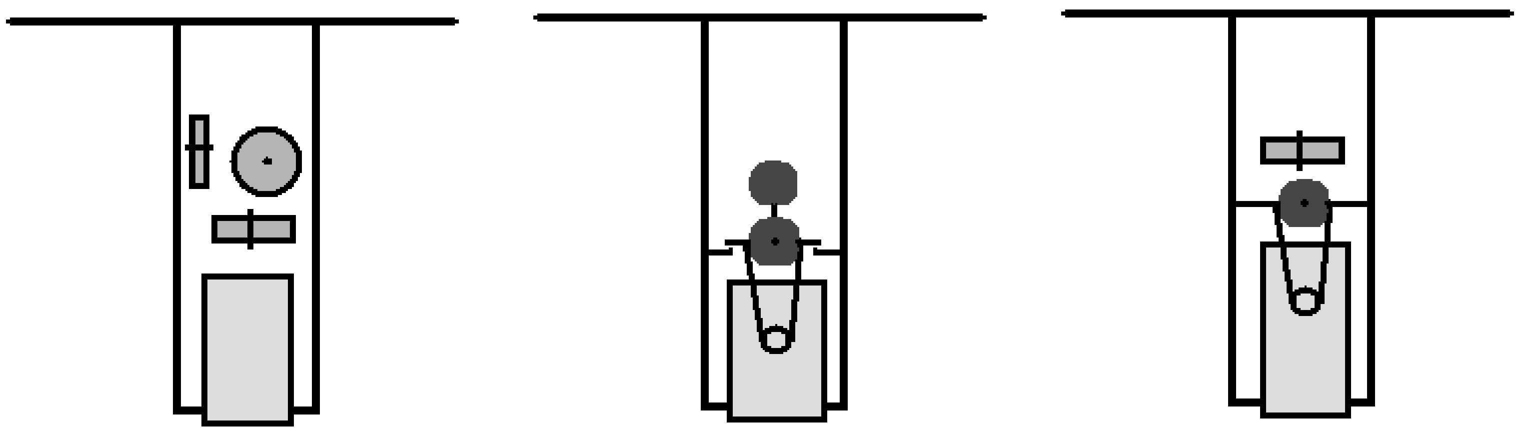
| Criteria | Weight Factor | Concept 1 | Concept 2 | Concept 3 |
|---|---|---|---|---|
| **Rate** | 5 | **8** | 6 | 6 |
| **Accuracy** | 8 | 4 | **8** | 7 |
| **Size** | 7 | 2 | **6** | 5 |
| **Power** | 7 | 3 | **6** | **6** |
| **Price** | 3 | 2 | **8** | 7 |
| **Development** | 5 | 4 | 6 | **8** |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

# Winner ADS



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

# Selected Pointing Mechanism Concepts



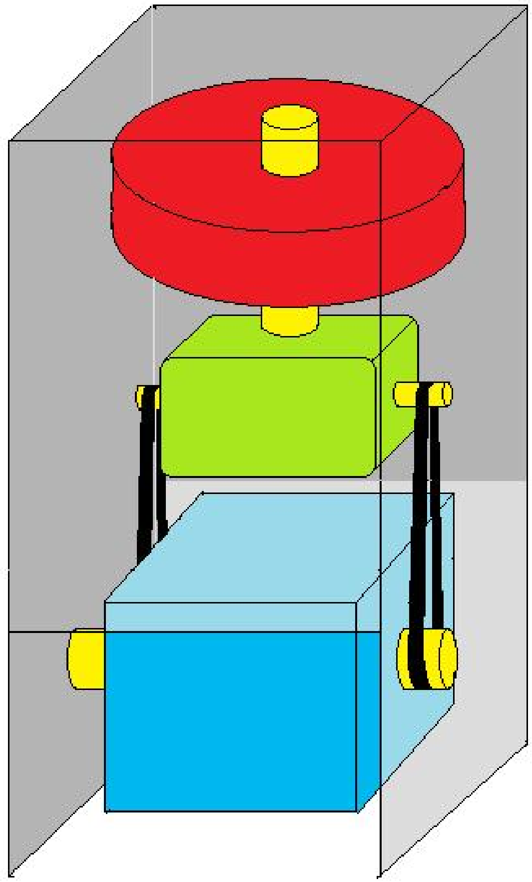
Concept 1 | Concept 2 | Concept 3

1. Using the ADCS
2. Using two stepper motors
3. Using one axis reaction wheel and one stepper motor

# 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



# Communications

## Aspects considered

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

# Communications

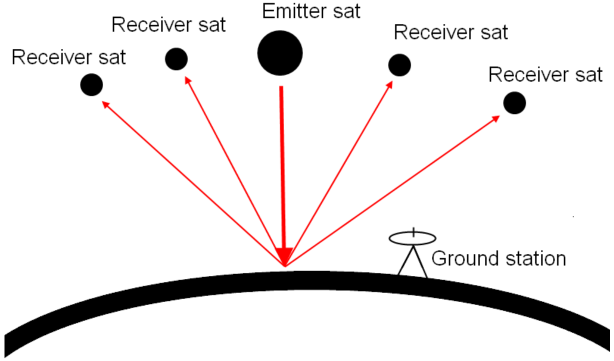
## Aspects considered

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

# Communications

## Communications architecture

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



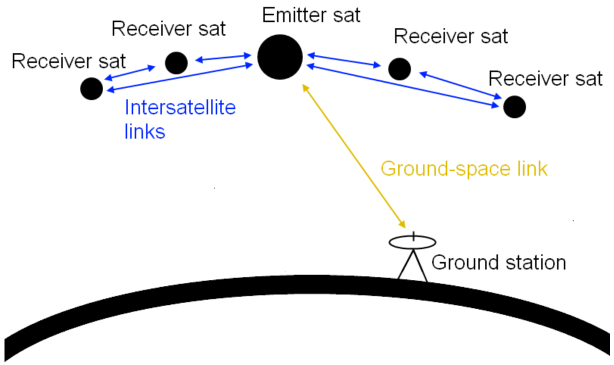

*Swarm elements*

- 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

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



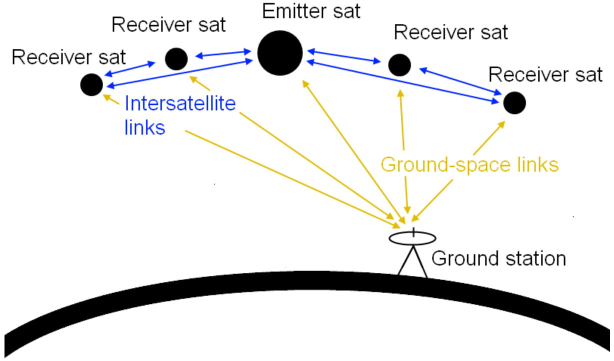

*Centralized*

- **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

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

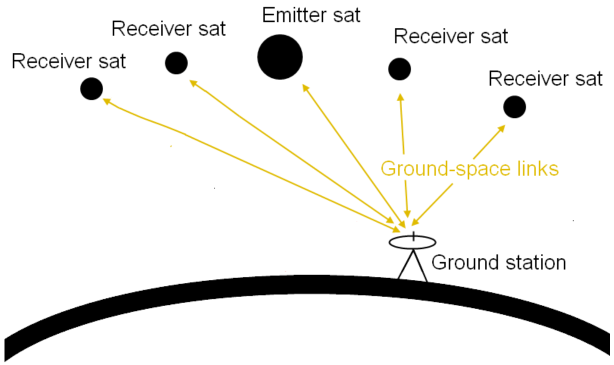



*Decentralized*

- 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



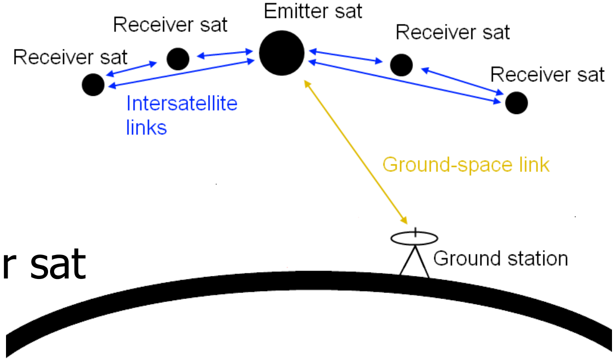

*Extremely decentralized*

- 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**
  - Ground-space link for emitter sat & each receiver sat
  - No intersatellite links

# Communications

## Communications architecture

**Centralized architecture:**




*Centralized*

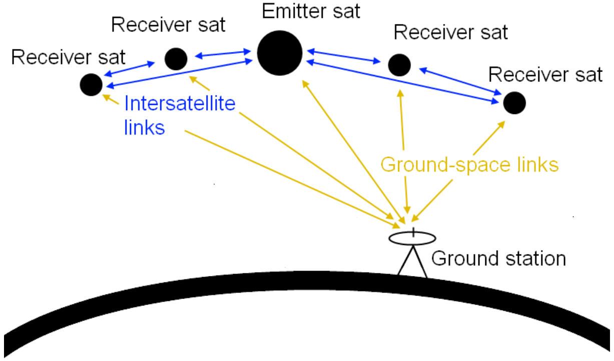
- Advantages
    - Low mass, power consumption & volume receiver sat
    - Scientific data compressed before transmitting to the ground station
- Disadvantages
    - Less robust
    - High mass, power consumption & volume emitter sat
    - High data rate ground-space link

# Communications

## Communications architecture

**Decentralized architecture:**

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

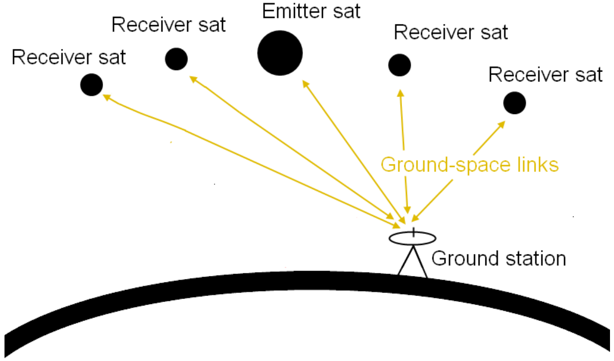



*Decentralized*

# Communications

## Communications architecture

**Extremely decentralized architecture:**




*Extremely decentralized*

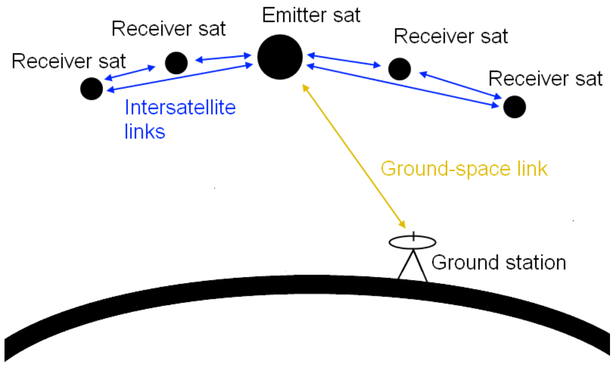
- Advantages
  - Low data rate ground space link
  - No frequency allocation required for intersatellite links
- Disadvantages
  - Higher mass, power consumption & volume receiver sat
  - Desynchronization

# 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

# Communications

## Frequency allocation

**Ground space link:**

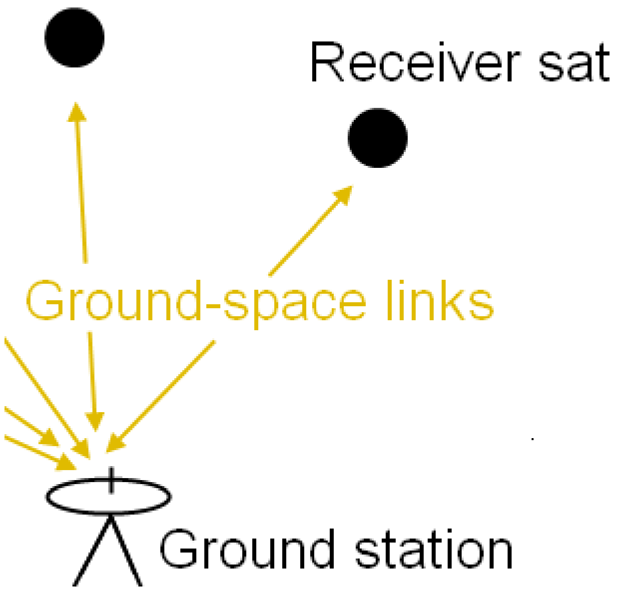
- Possible frequency bands
  - C-band
  - S-band
  - X-band
  - Ku-band
  - Ka-band
  - SHF/EHF-band

# 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

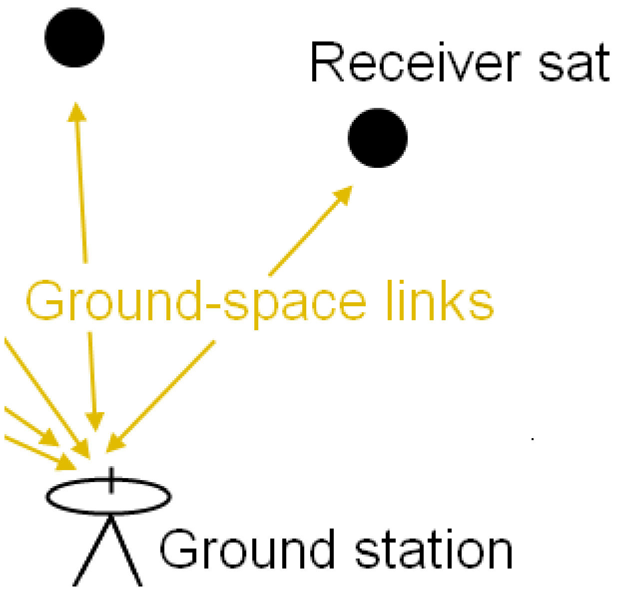


# Communications

## Frequency allocation

**Ground space link:**

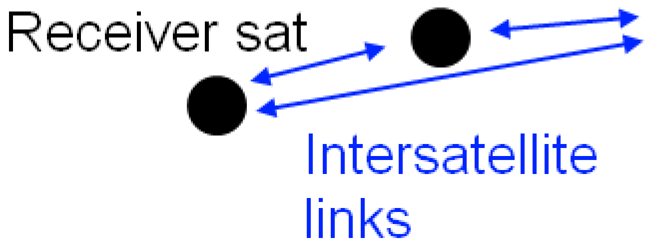
- Possible frequency bands
  - C-band
  - **S-band**
    - Low data rate
    - Good for house keeping data
  - X-band
  - Ku-band
  - Ka-band
  - SHF/EHF-band



# Communications

## Frequency allocation

**Intersatellite link:**

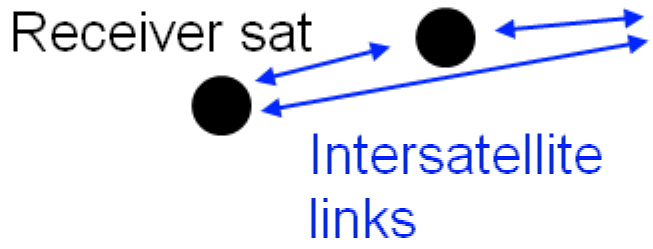



- Possible frequency bands
    - C-band
    - S-band
    - X-band
    - Ku-band
    - Ka-band
    - SHF/EHF-band

# 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

# Communications

## Aspects considered

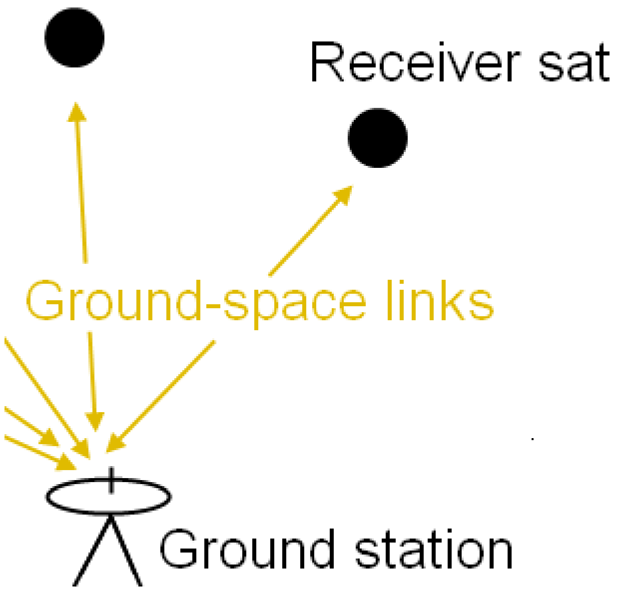
- Communications architecture
- Frequency bands
  - Ground-space link
  - Intersatellite link
- **Antenna configuration**
- Tracking

# Communications

## Antenna configuration

**Ground space link:**

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

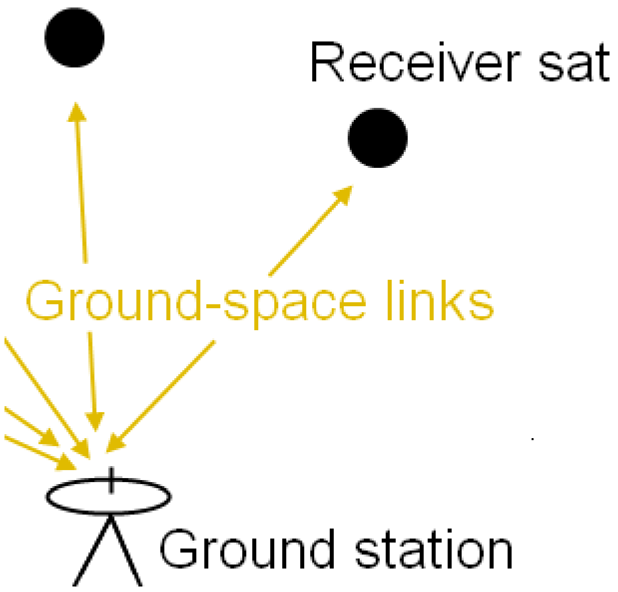


# Communications

## Antenna configuration

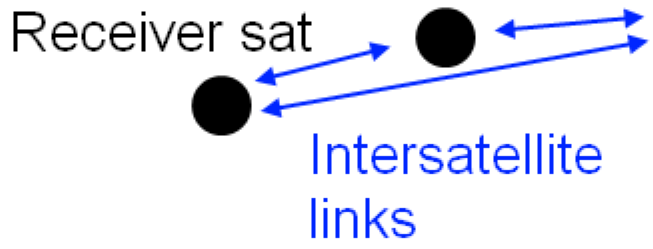
**Ground space link:**

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



# Communications

## Antenna configuration

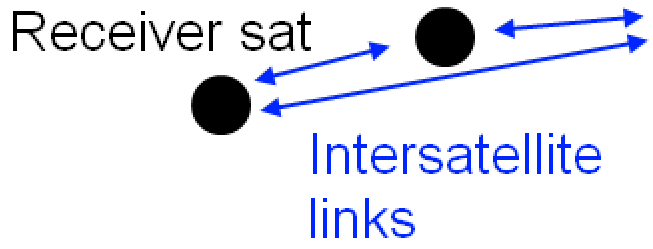



- Intersatellite links
  - Horn antenna
    - Low gain
    - >4 Ghz
  - Helix antenna
    - Low gain
    - <2 Ghz

# Communications

## Antenna configuration

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



# Communications

## Aspects considered

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

# 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

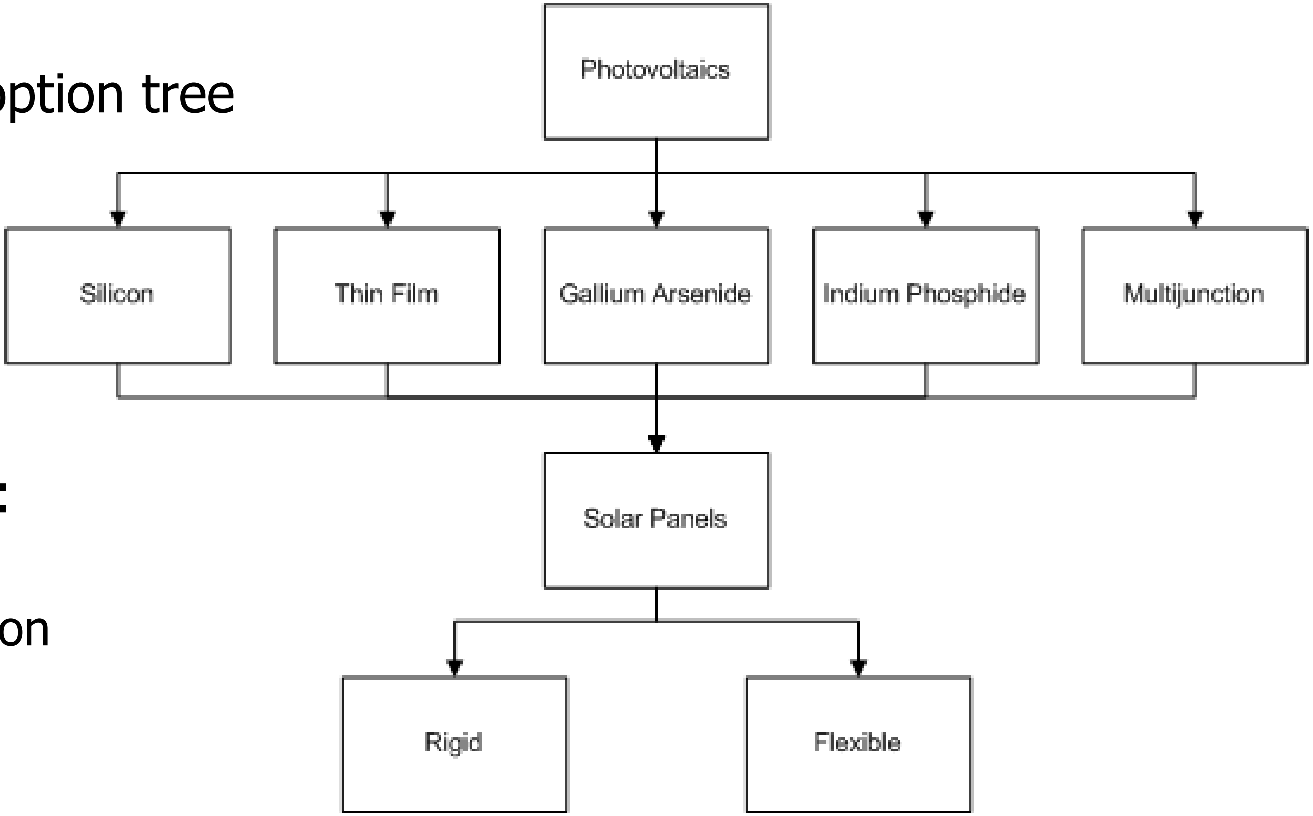
# Communications

## 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

# Electrical Power System

Pruned design option tree

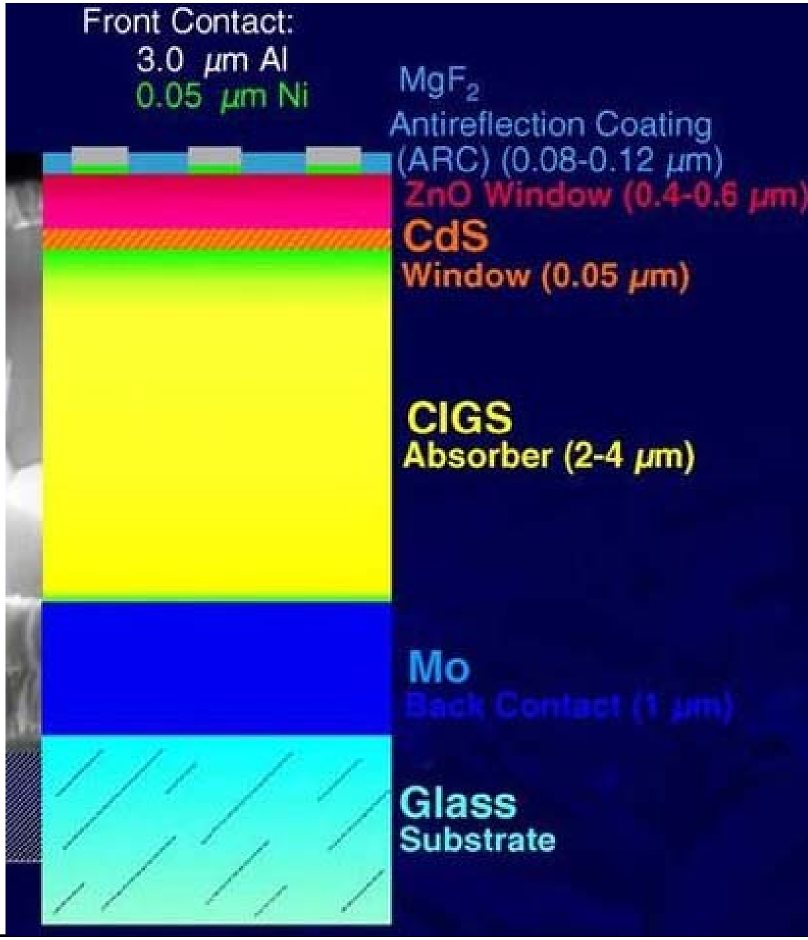



Two candidates:

- Thin film
- Triple junction

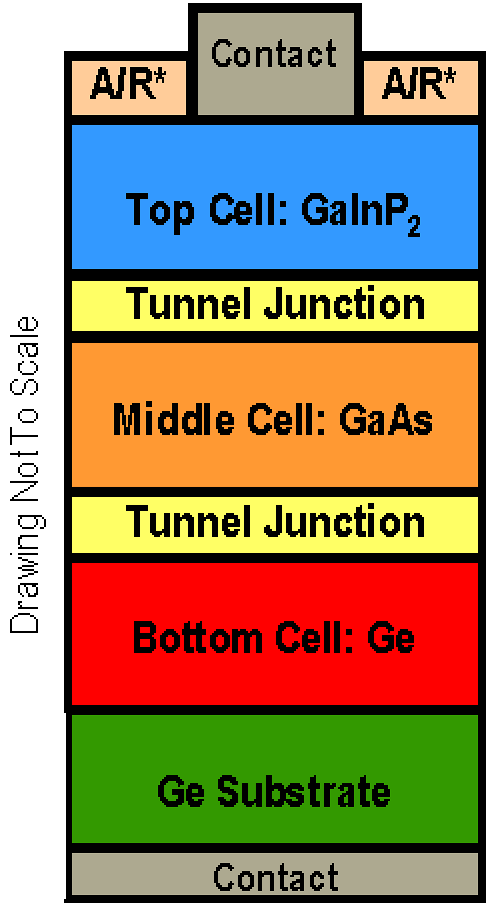
# EPS – Thin Film CIGS

- Multiple layers of thin photovoltaic material
- Copper-Indium-Gallium-Selenium absorber
- Low efficiency
- Low production cost
- High absorptance coefficient



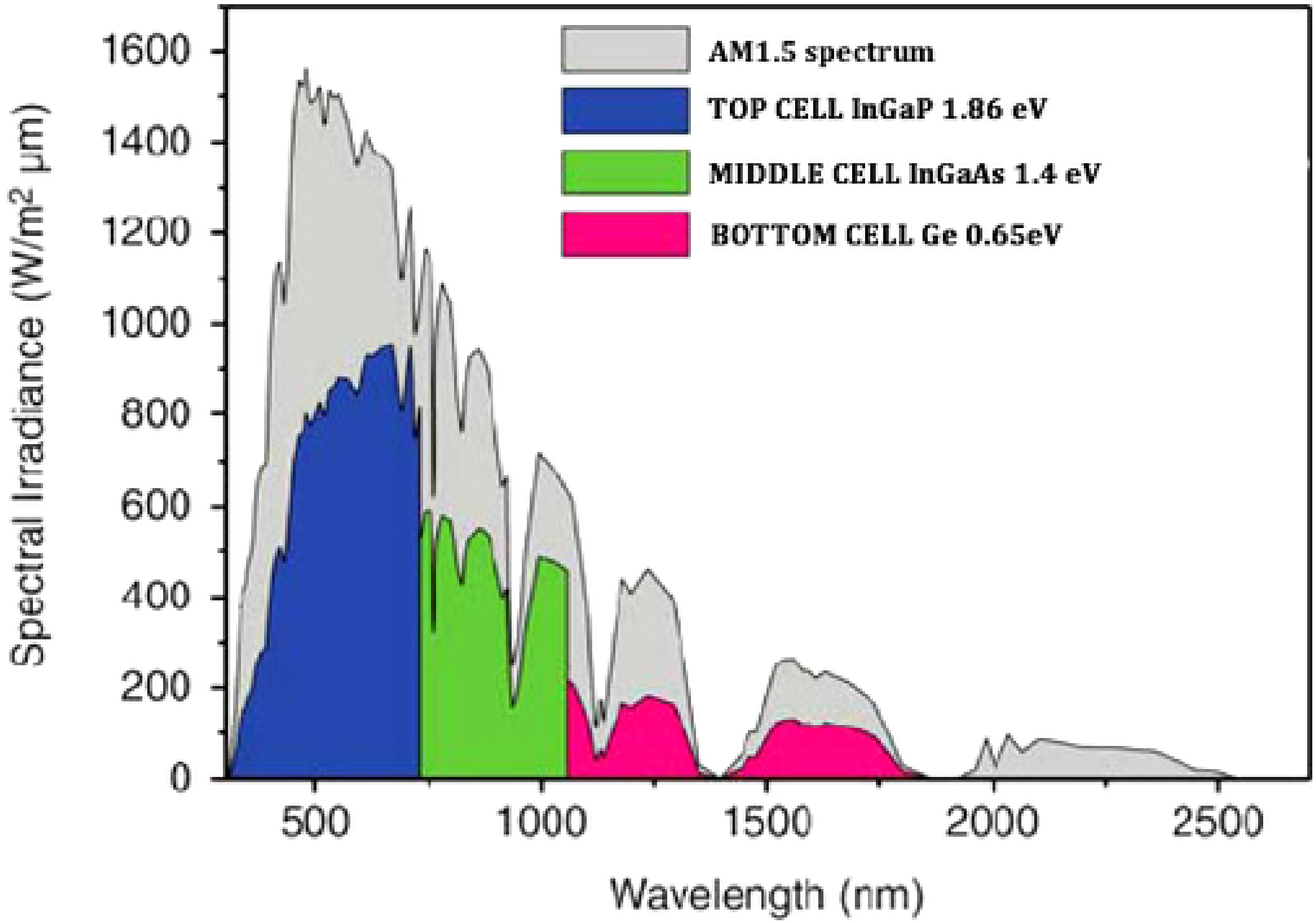
# EPS – Triple Junction

- Multiple pn-junctions
- High efficiency
- High production cost
- Larger covering of the solar spectrum




*A/R: Anti-Reflective Coating

# 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

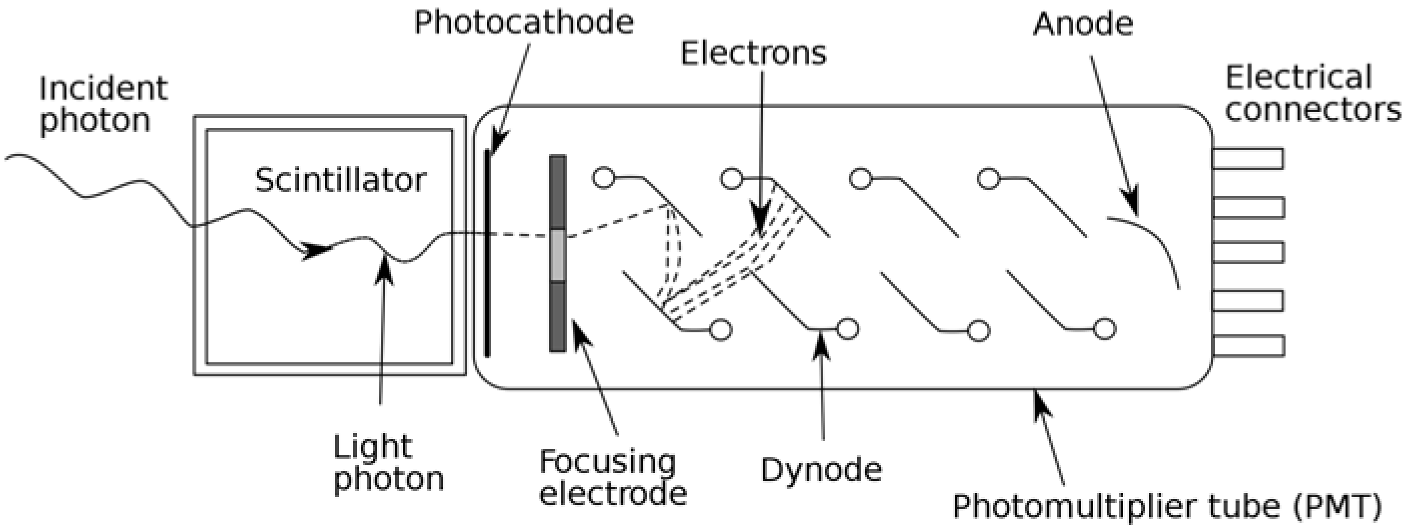
- Single-Photon Detection
  - Photonmultiplier tube
  - Single Photon Avalanche Diode (SPAD)
- Wavelength Estimation
  - Atmospheric transmittance
  - Wavelength ratio

# Optical Receiving Payload

## Single-Photon Detection

- Convert light (photons) to measurable quantity (Voltage or current)
- Multiple ways
  - Photomultiplier tube
  - SPAD
  - Quantum dot (underdeveloped)

# Photomultiplier tube

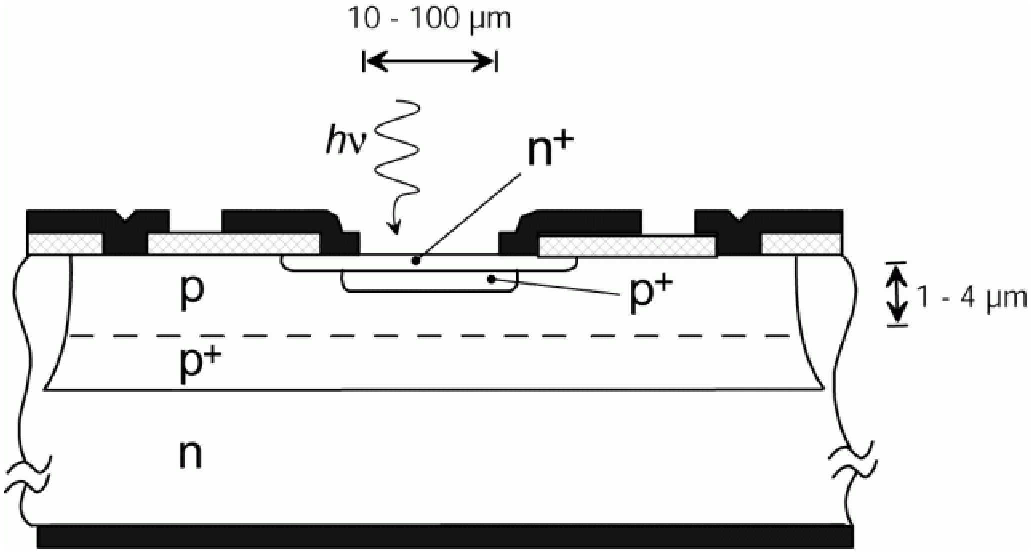



Typically 1000 to 2000 V is used

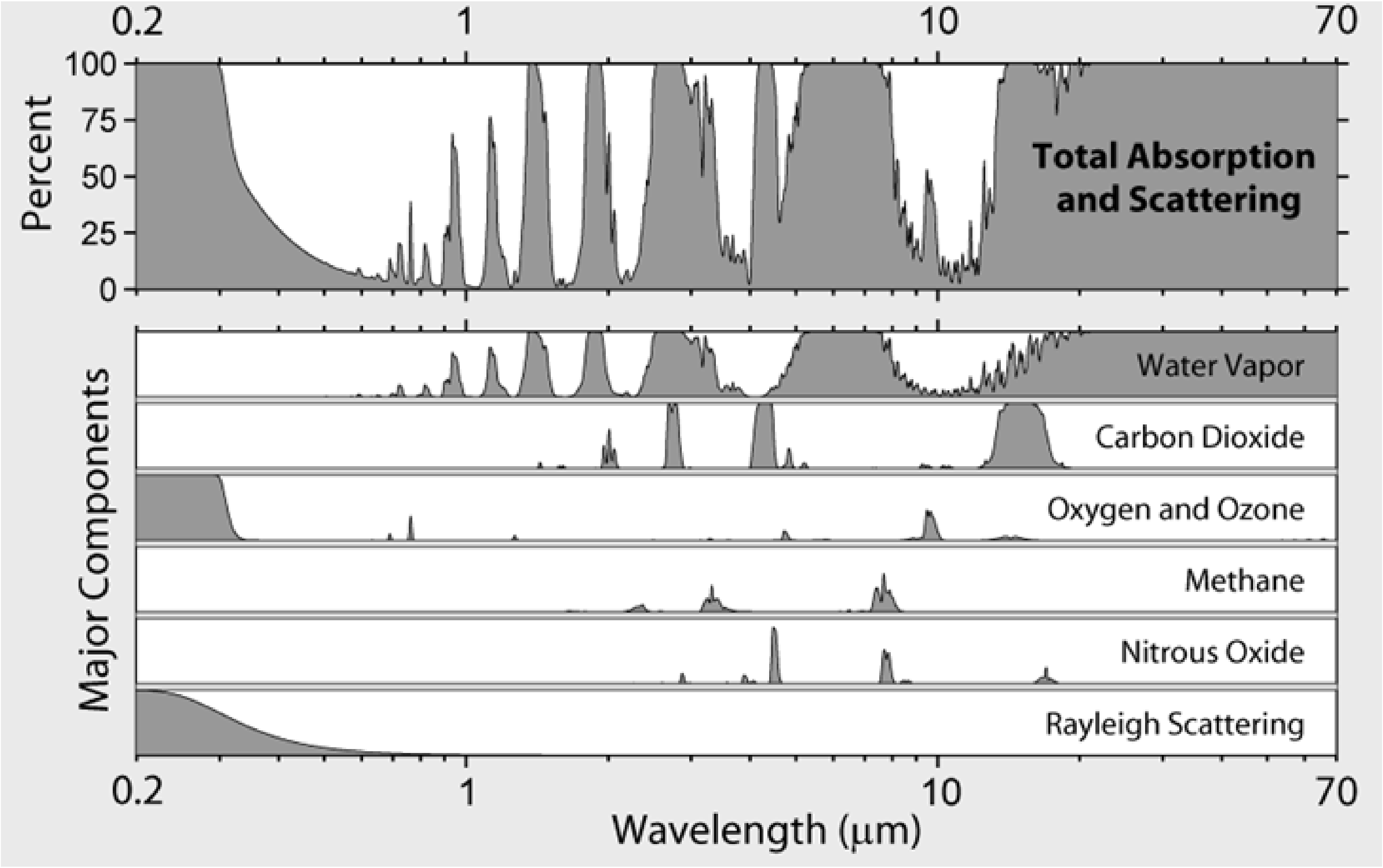
# SPAD

## Single Photon Avalanche Diode

- Based on p-n junction
- Reversed biased voltage
- Sensing avalanche current
- Small size, less power



# Atmospheric Absorption Bands

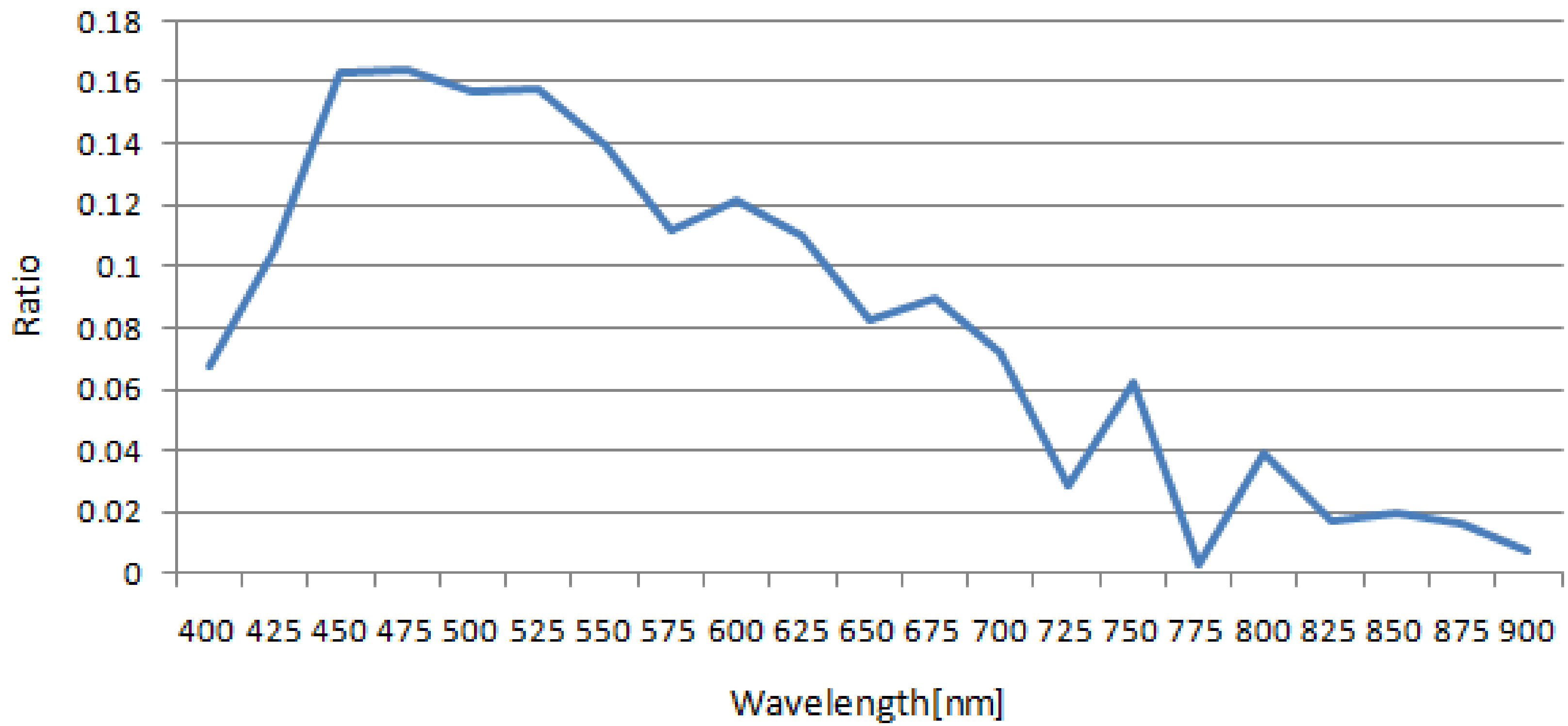


# Wavelength estimation

- General sufficient wavelength range 400nm to 900nm
- Atmospheric transmittance Vs. Photon detection efficiency
- Wavelength ratio

  R = transmittance^2*efficiency

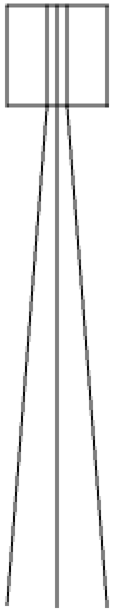
# Wavelength estimation



# Laser Optics

- To get the desired footprint.
- Three options:
  - No optics
  - Two lenses
  - Mirrors

# Laser Optics – No Optics



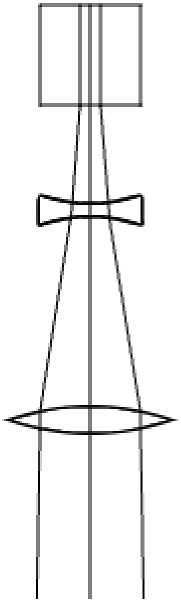
Advantages:

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

Disadvantages:

- Footprint directly depends on:
  - Laser beam divergence
  - Orbit altitude
- 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 orbit altitude a little

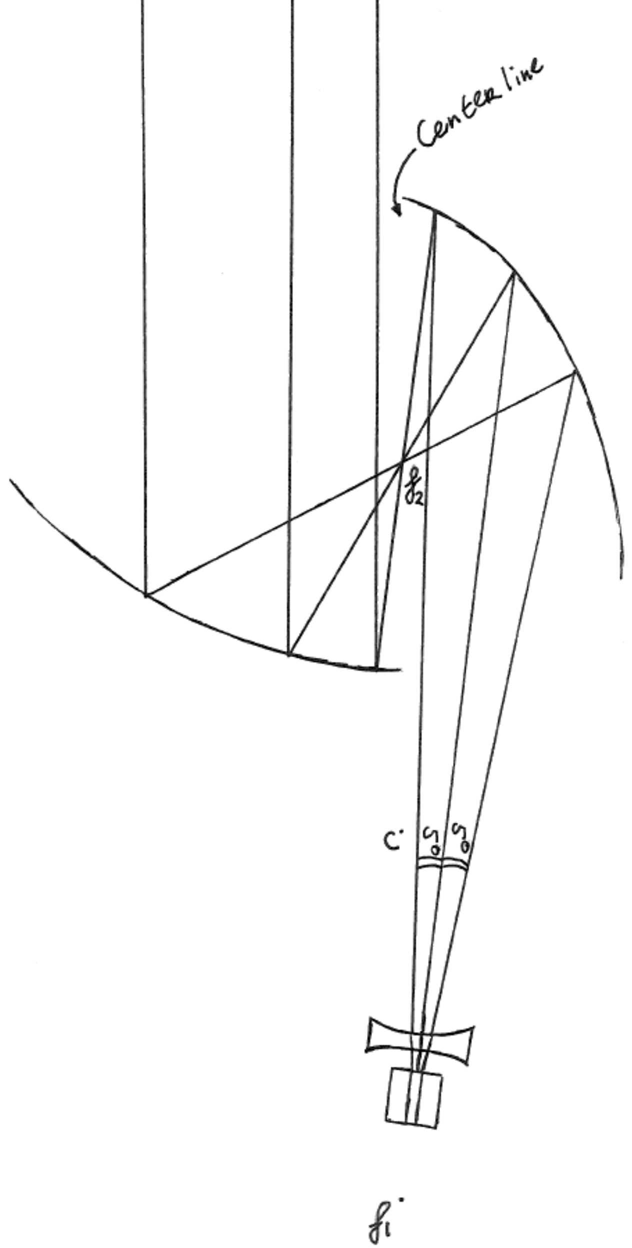
# Laser Optics – Mirrors

Advantages:

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

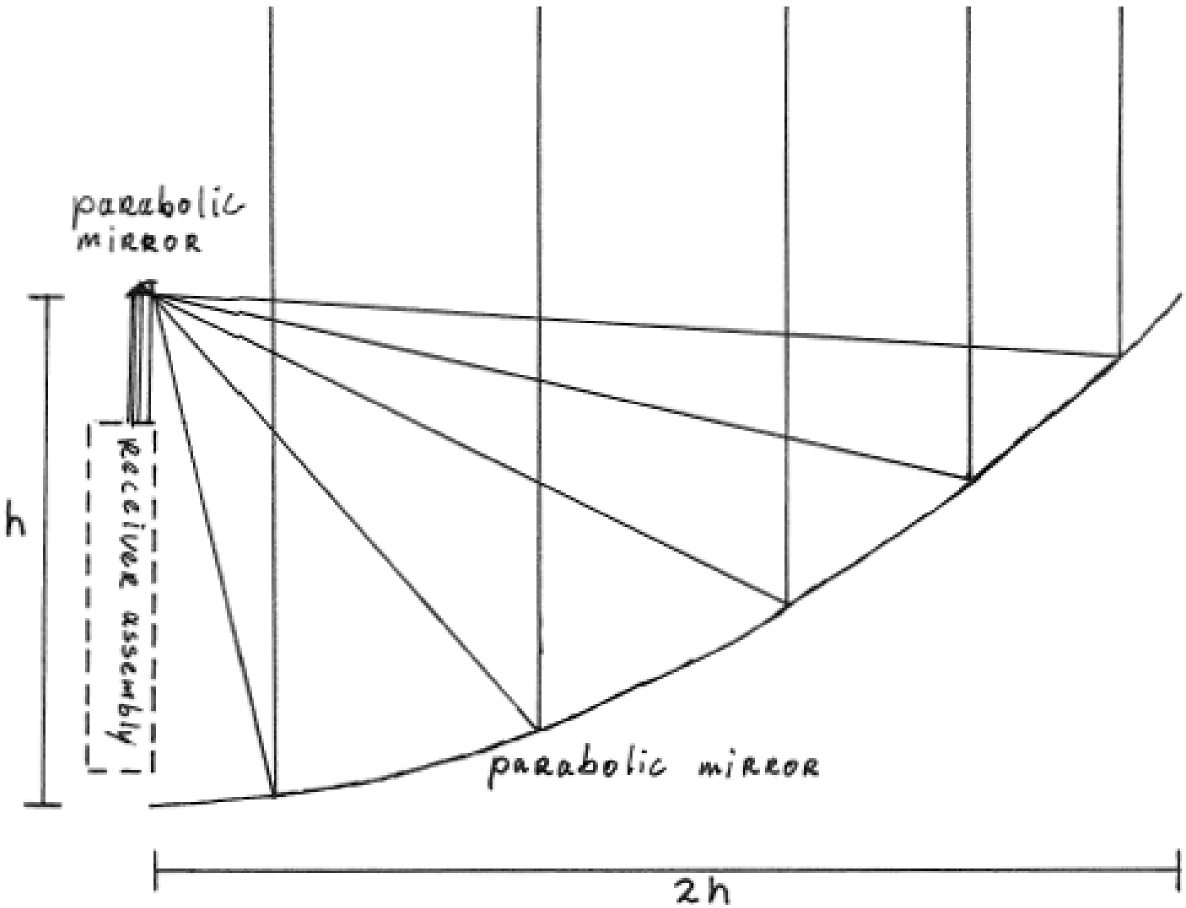
Disadvantages:

- 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.



# Receiver Optics – Fill Factor

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

This is clearly unacceptable. 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.

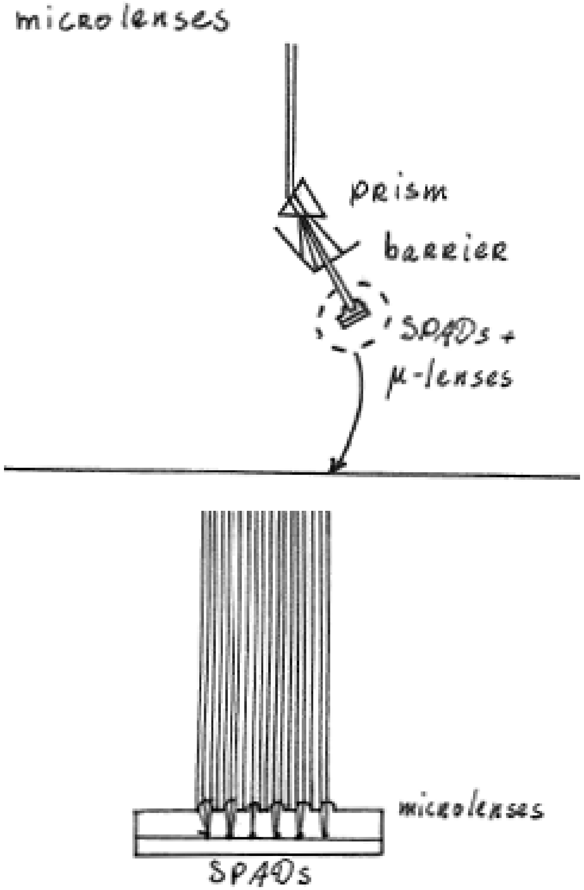
# Receiver Optics – Microlenses

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 unacceptible



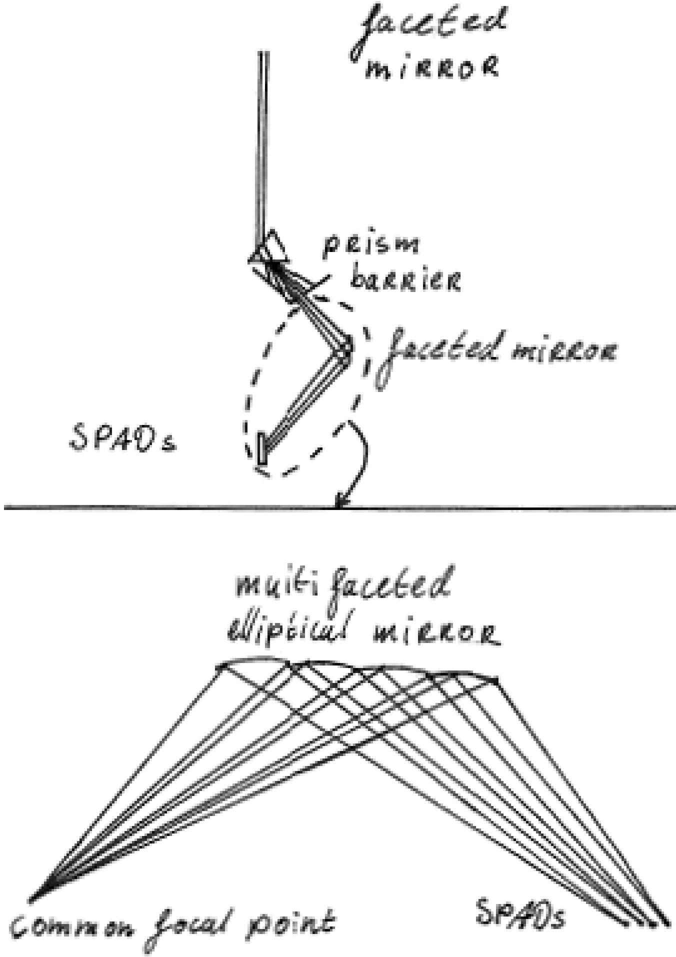
# Receiver Optics – Faceted Mirror

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

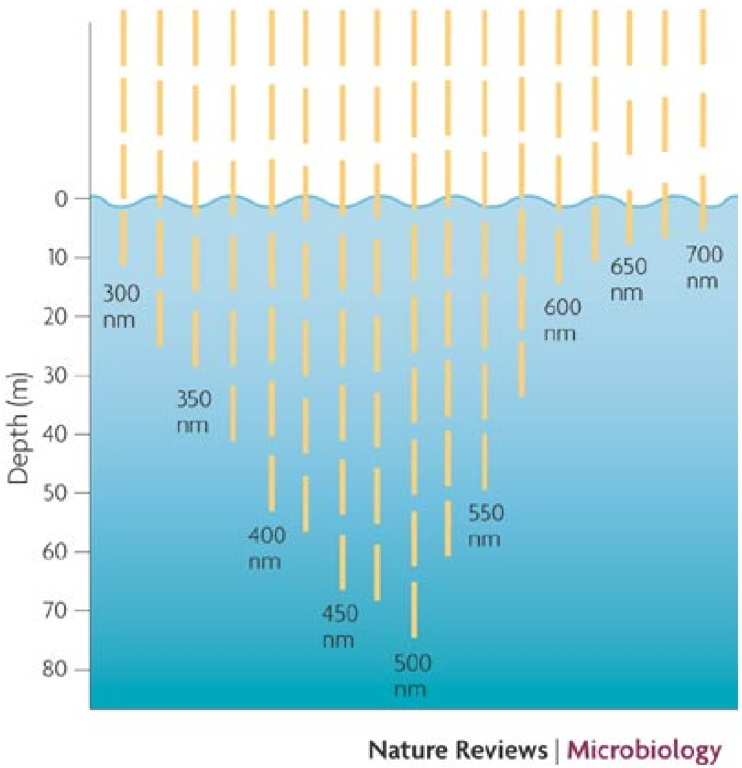


# Receiver Trade-off

| 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 |

# Ocean Reflectance

- Large part of the Earth is covered by water

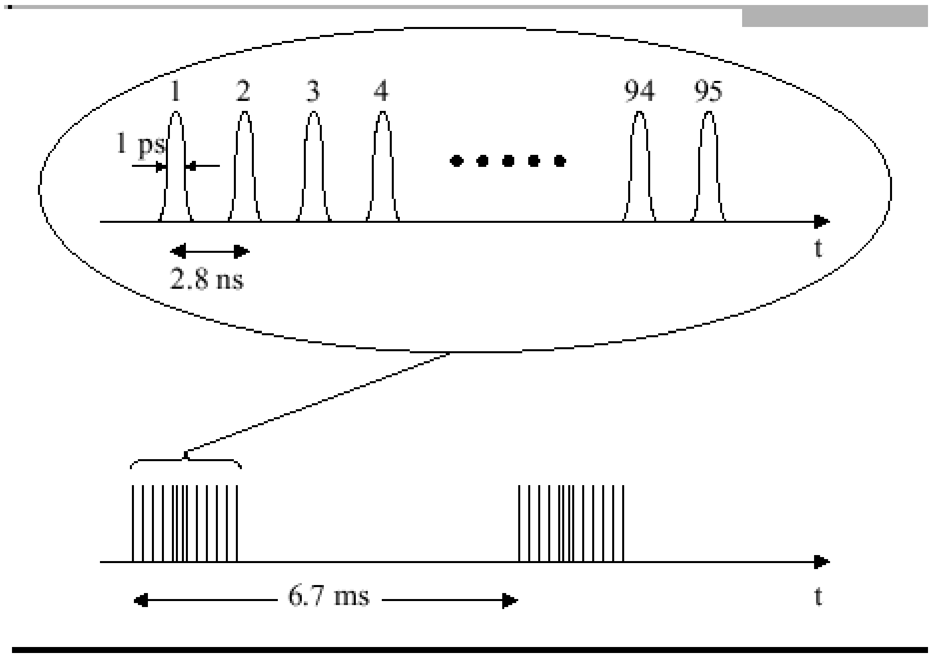



'blue' has the highest absorption depth

However, the fractional reflectance is highest

# Continuous Versus Pulsed Waves

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




Analysis of individual pulses

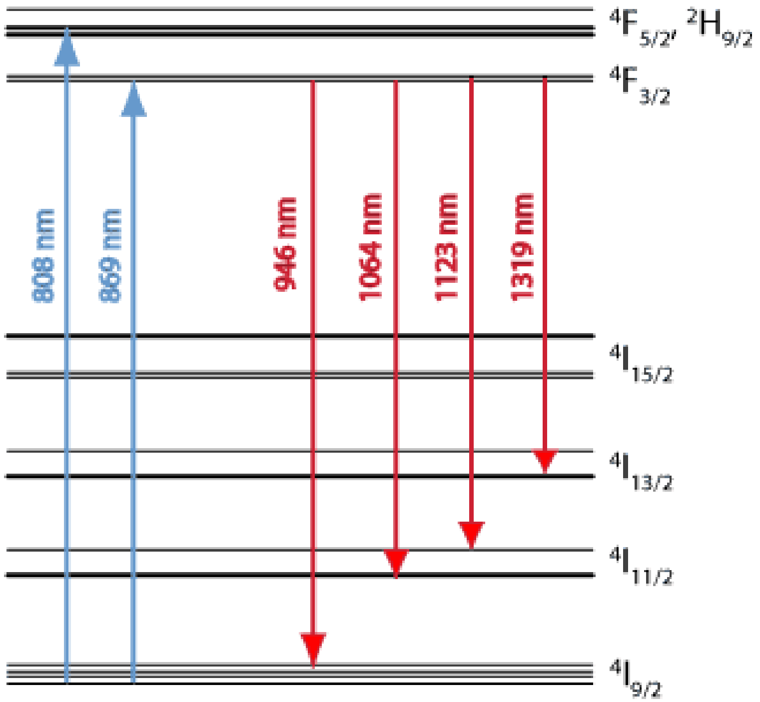
Increased spatial resolution

# 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

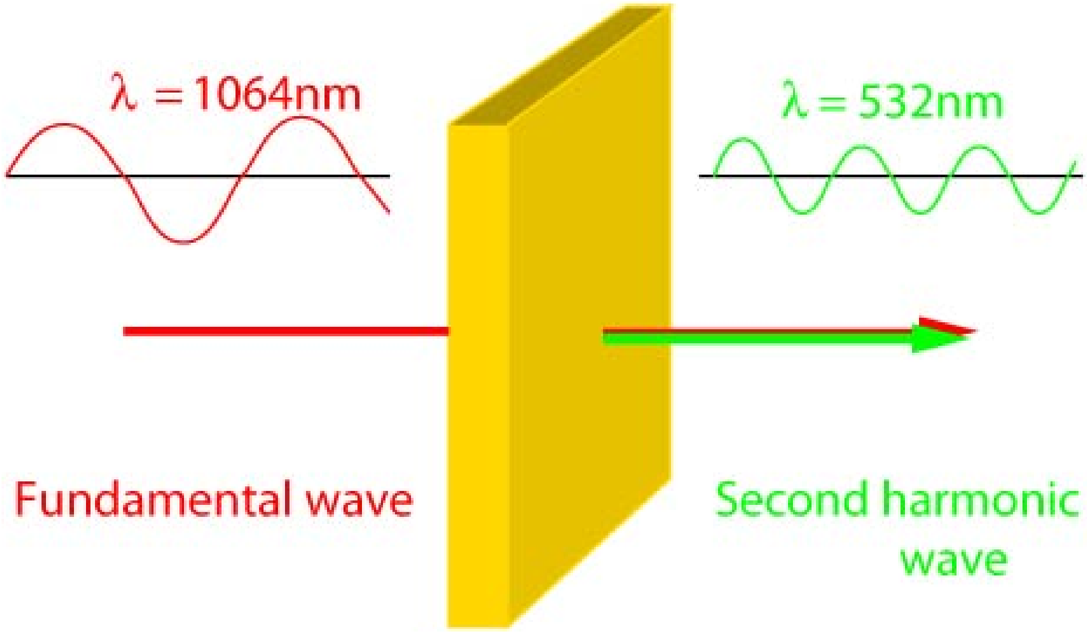
- Second Harmonic Generation (non-linear optics)

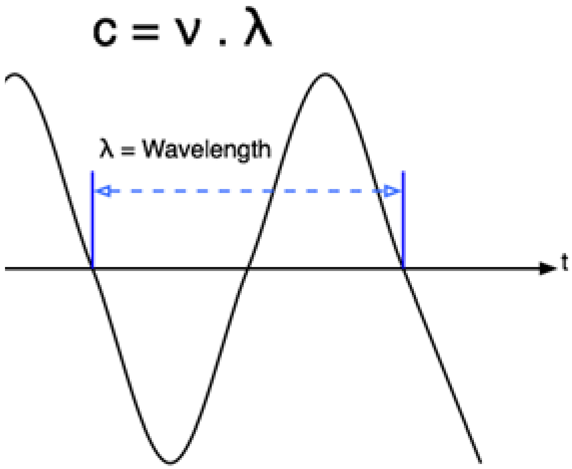



Nd-YAG energy levels

Non-linear (Lithium-Boron) frequency doubling crystal

# From 946 [nm] to 473 [nm]

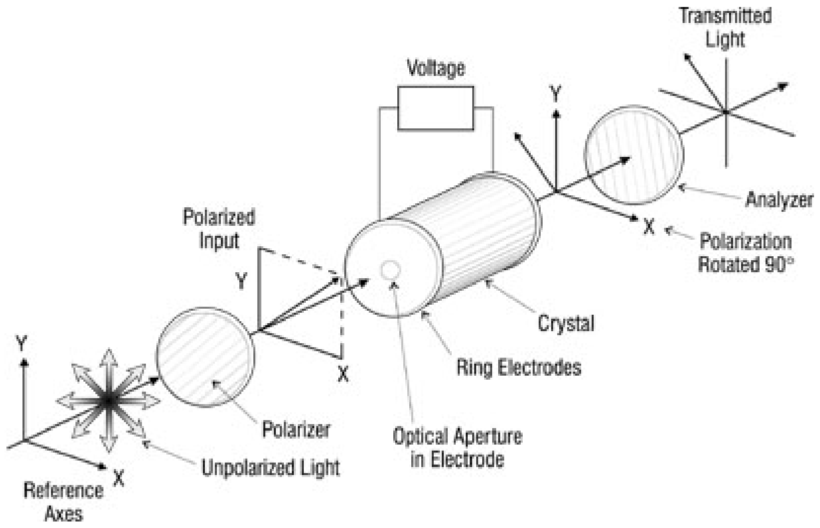


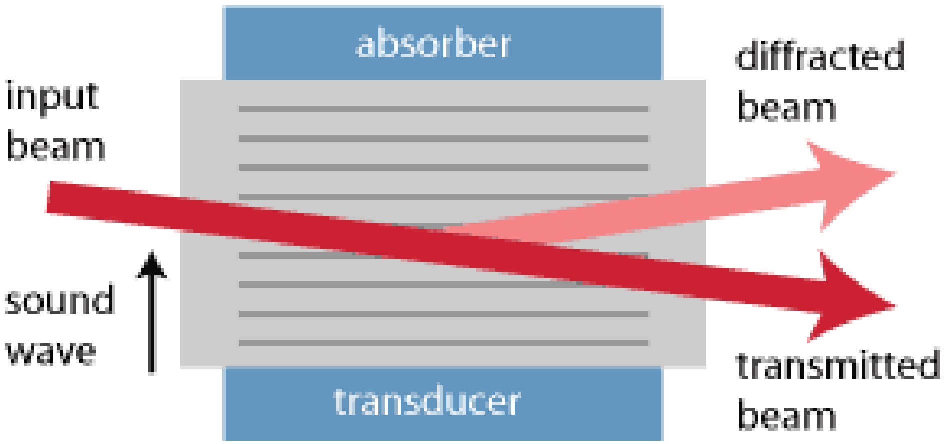
# Pulse Duration Deviation

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

**Pockel Cells** (**E**-field)




**Acoustic-Optic  Switches**
(RF 25 – 50 MHz)



# 5.

## *Orbit design*

# Special orbits types

- Polar orbit
- Repeat orbit
- Sun Synchronous orbit
- Frozen orbit

# 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

# 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

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

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

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

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

# 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

$$\frac{di}{dt} = 0$$ for any a, i or ω

# 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

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

$$F = 1$$

# 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

# 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

# Special orbits types

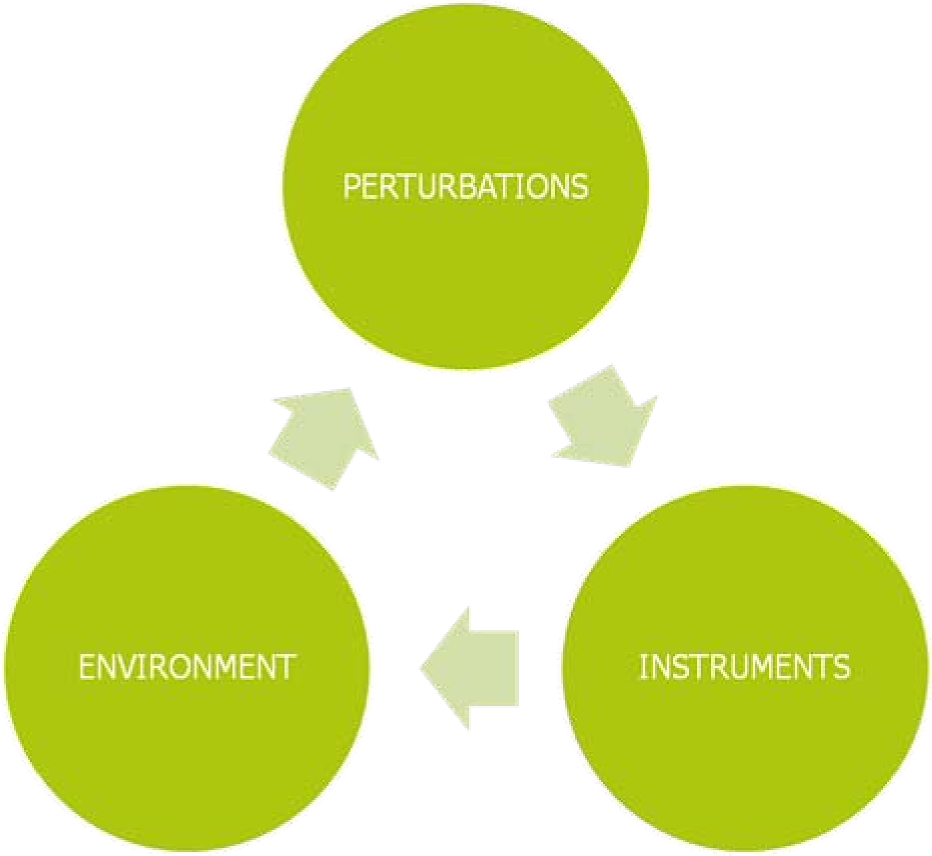
## Summary

- Sun synchronous is not required
- Repeat orbit is unfeasible
- The end result is a

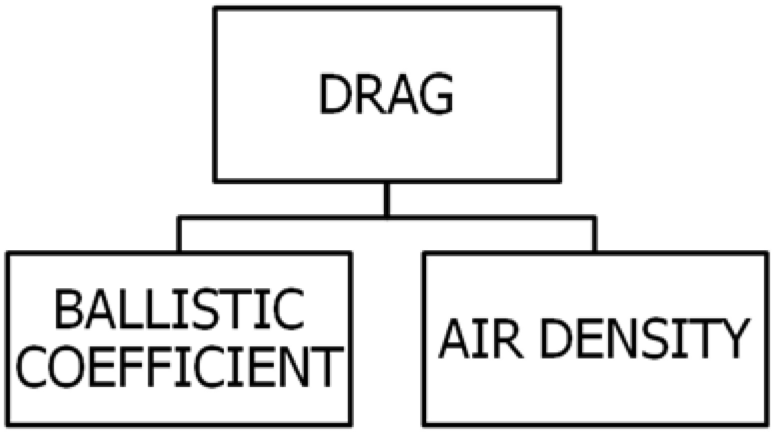
Frozen, polar orbit with

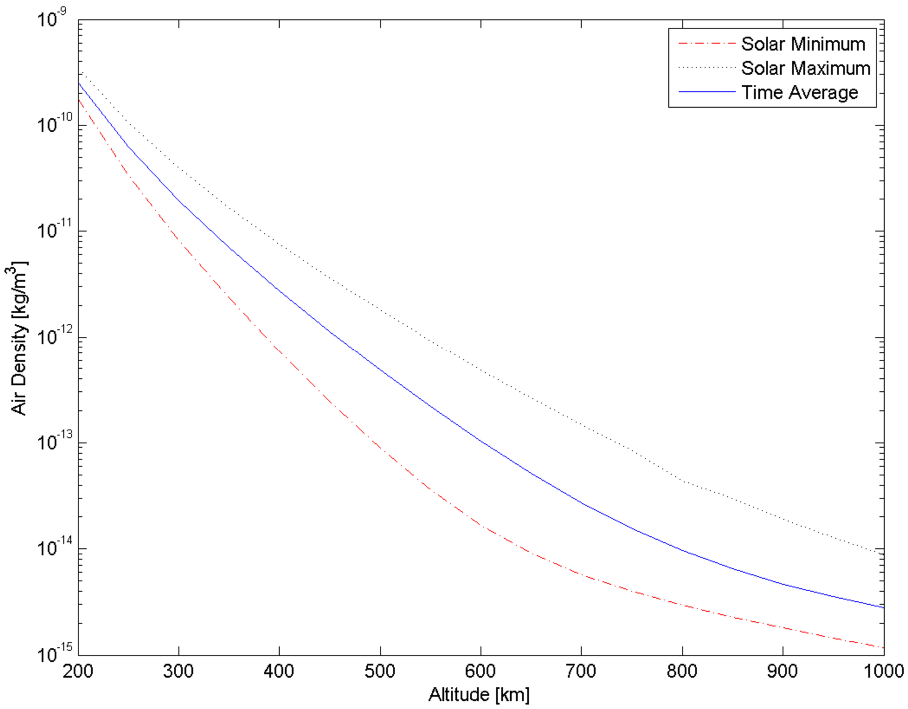
- e = 0 degrees
- i = 90 degrees
- ω = 90 degrees

# Orbit Altitude Analysis



# Orbit Altitude Analysis - Perturbations



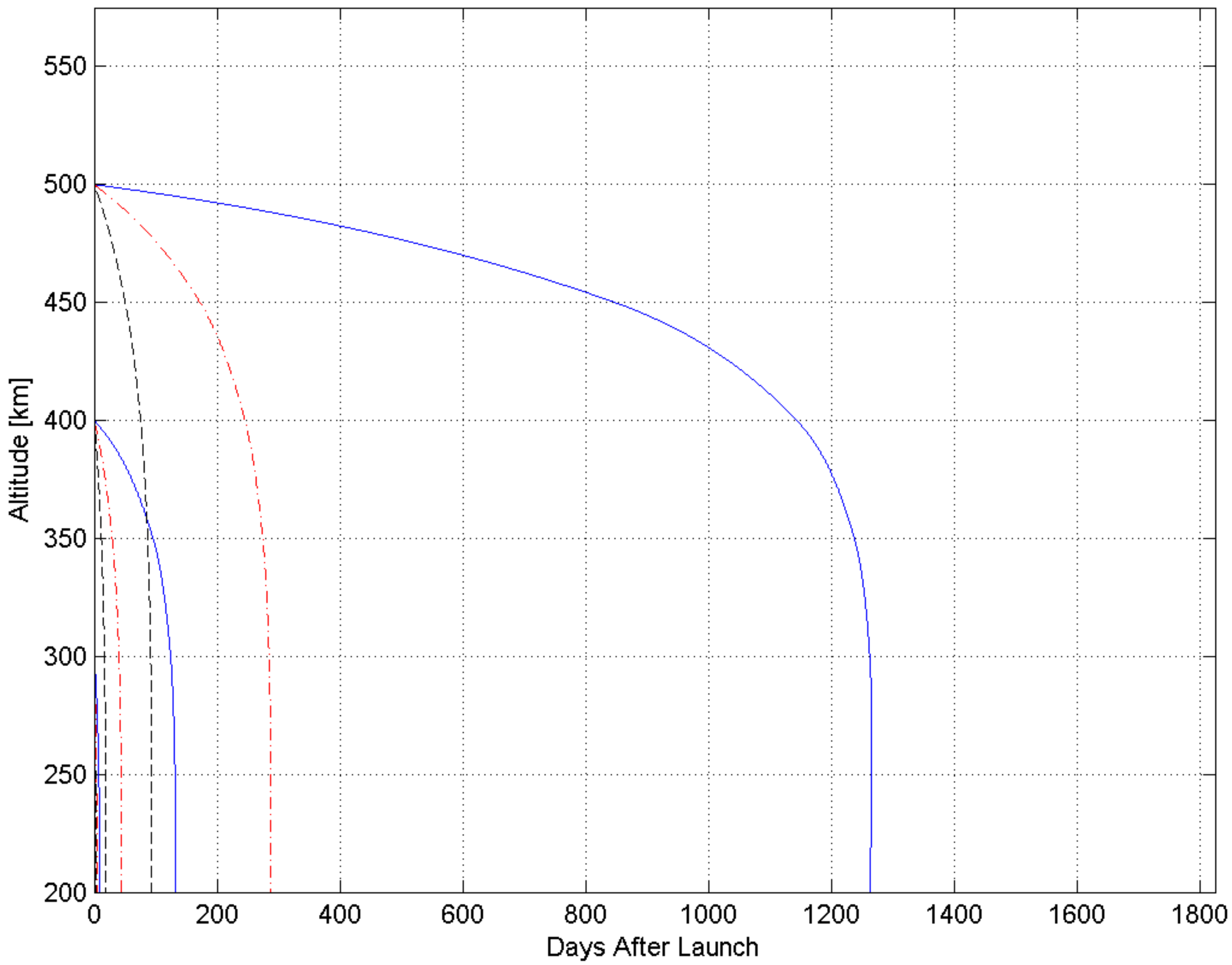



# Drag

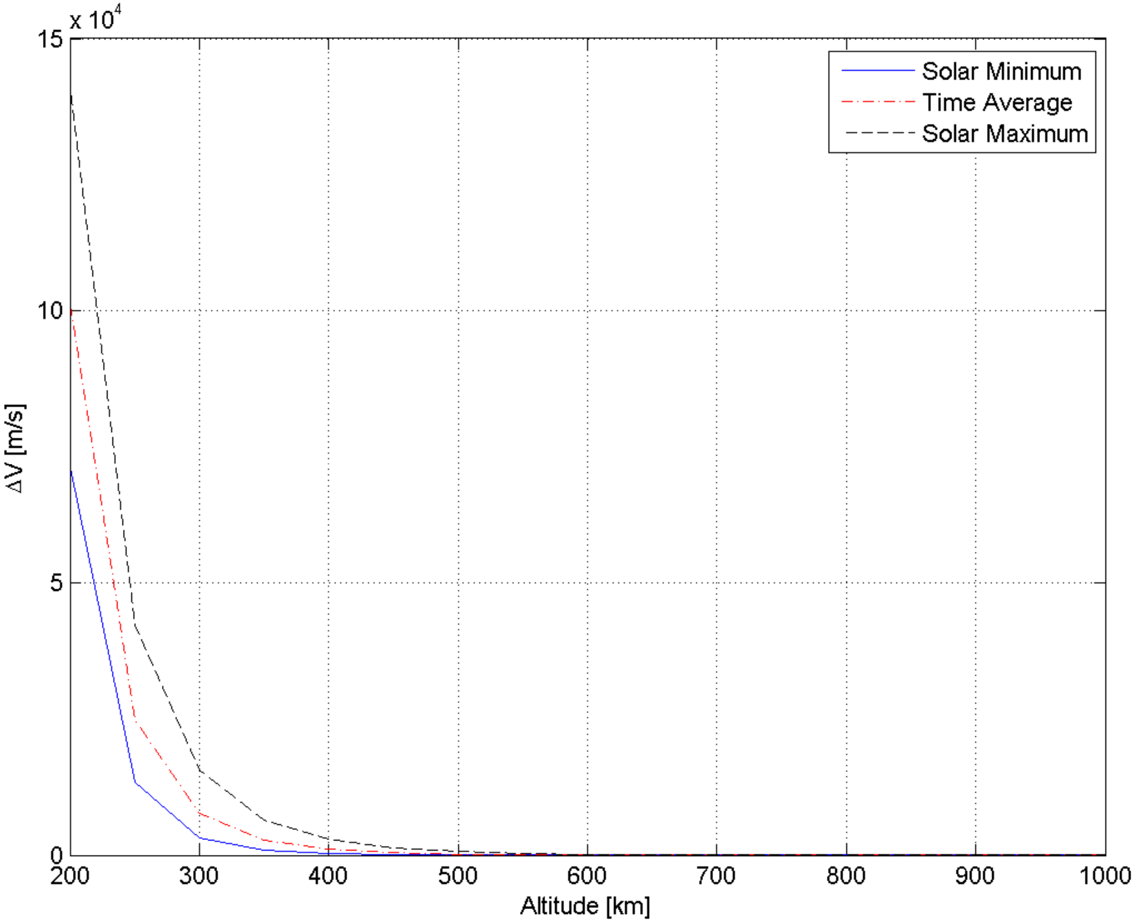
$$\Delta a = -2\pi \left( C_D \frac{A}{m} \right) \rho a^2$$

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

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

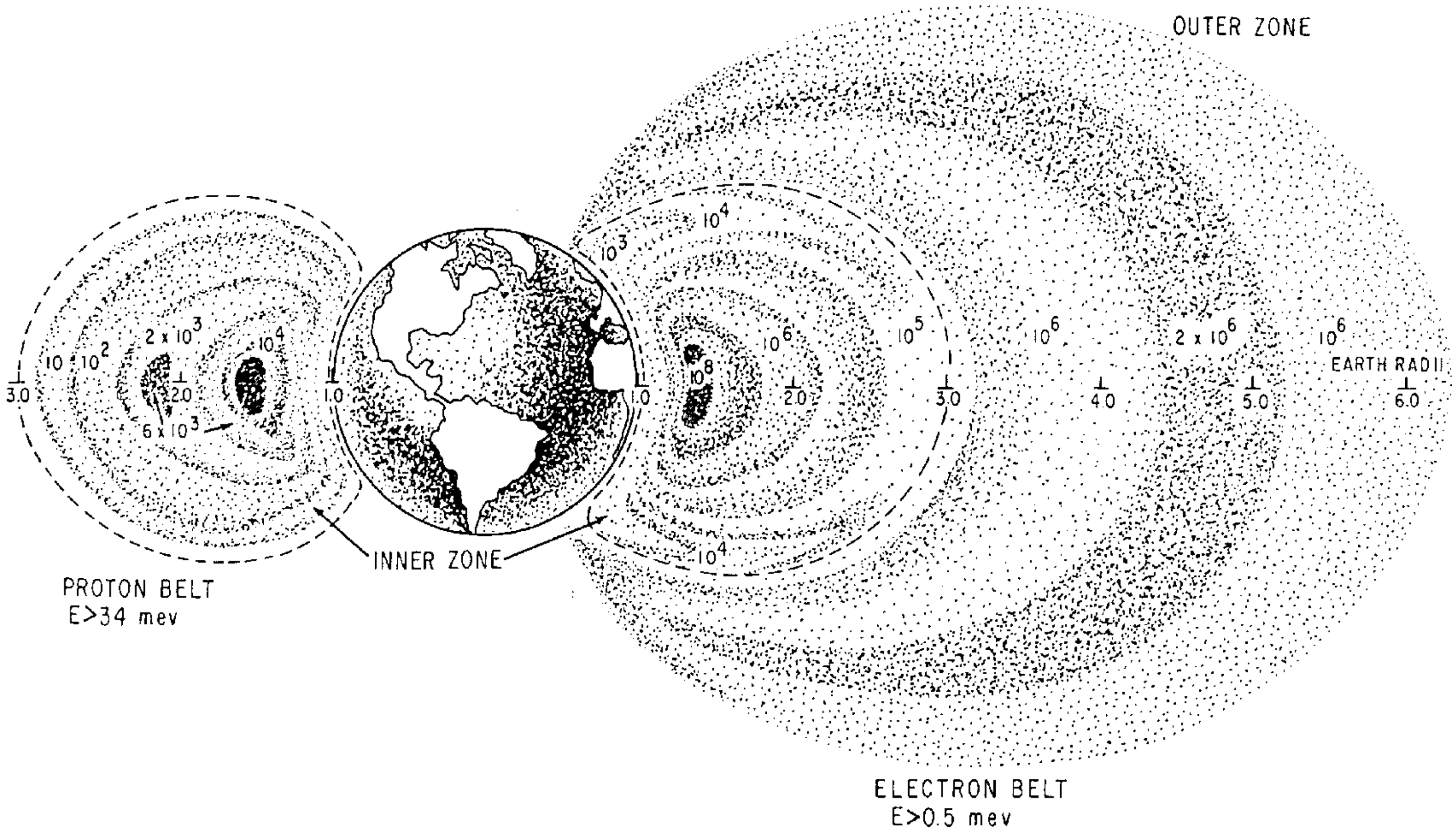


# Drag - ΔV



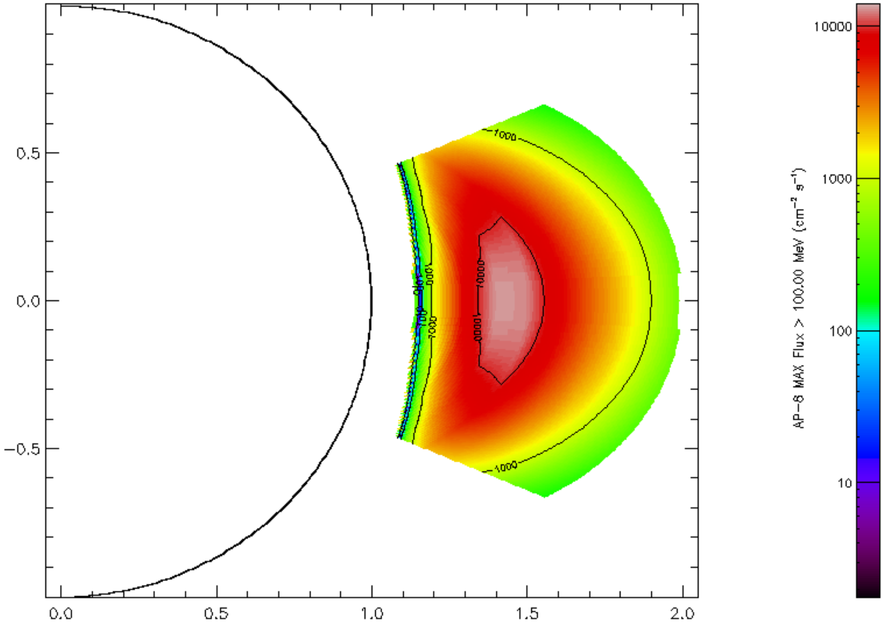
x 10^4
15
10
5
0
200
300
400
500
600
700
800
900
1000
ΔV [m/s]
Altitude [km]
Solar Minimum
Time Average
Solar Maximum

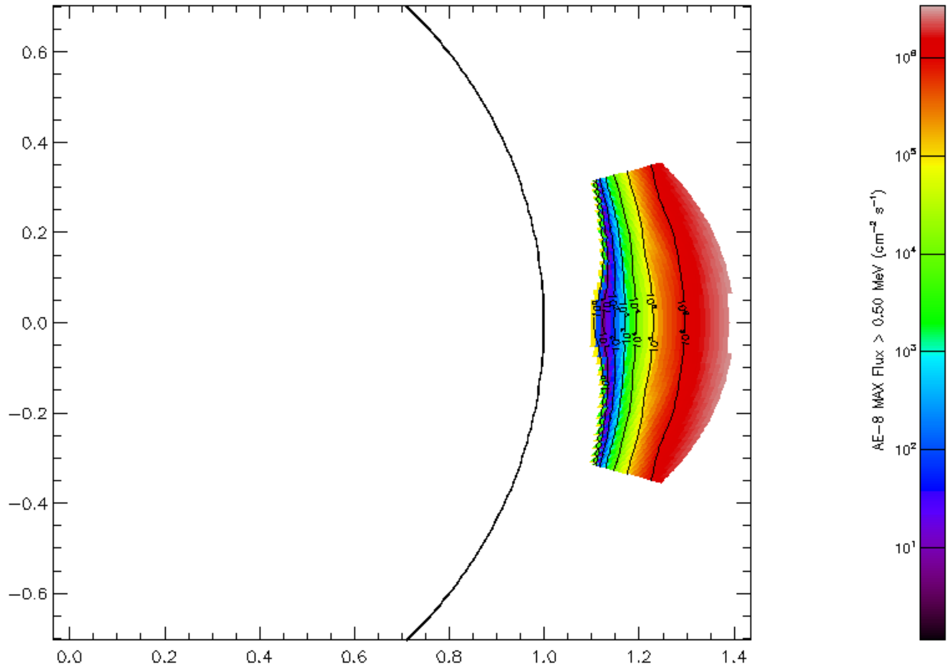
# Environment
## Trapped particle radiation



# Environment

## Trapped particle radiation

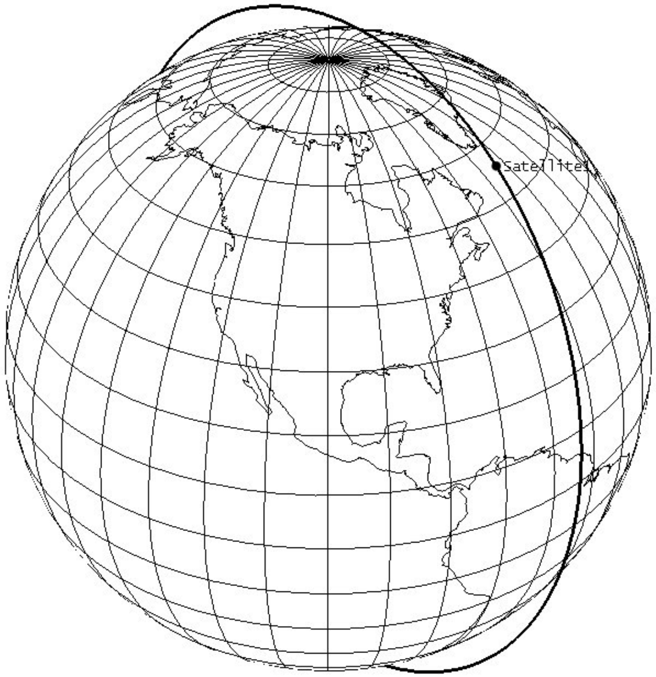


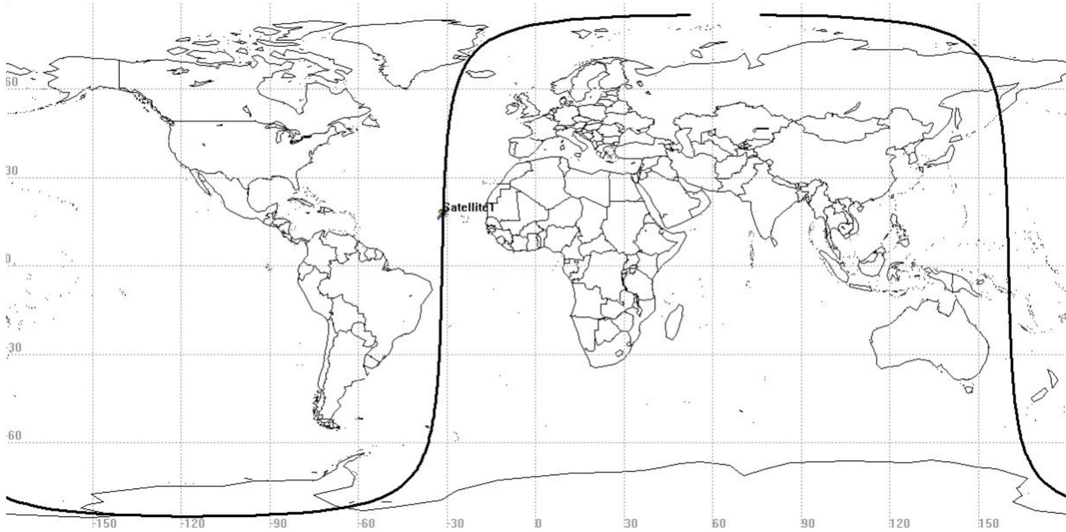



# Orbit Altitude
## Summary

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

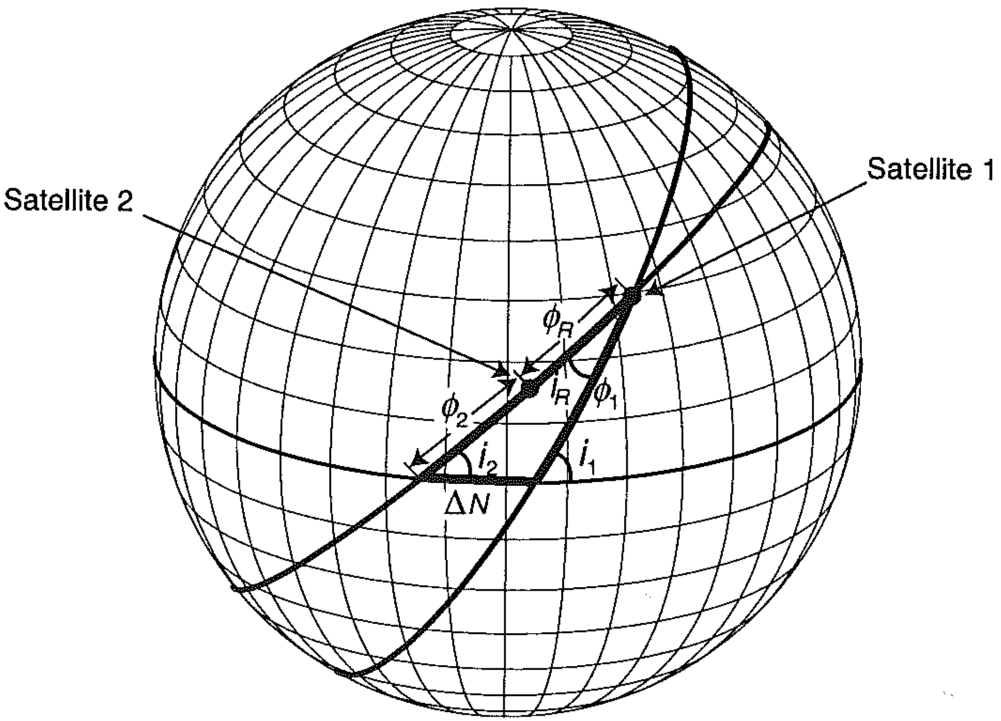
# Orbit Altitude
## Summary

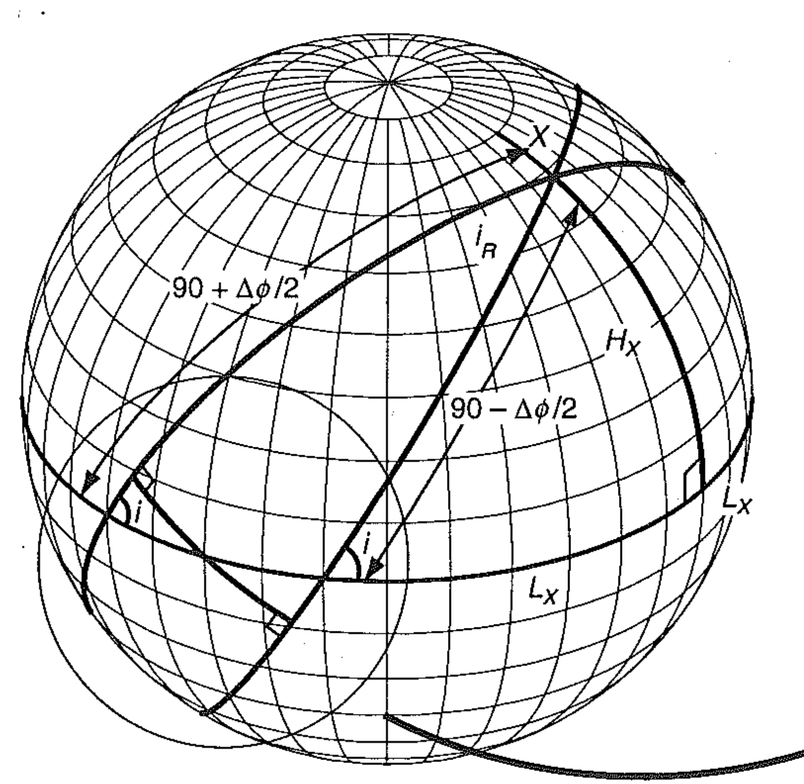


# Formation Design

SWARM



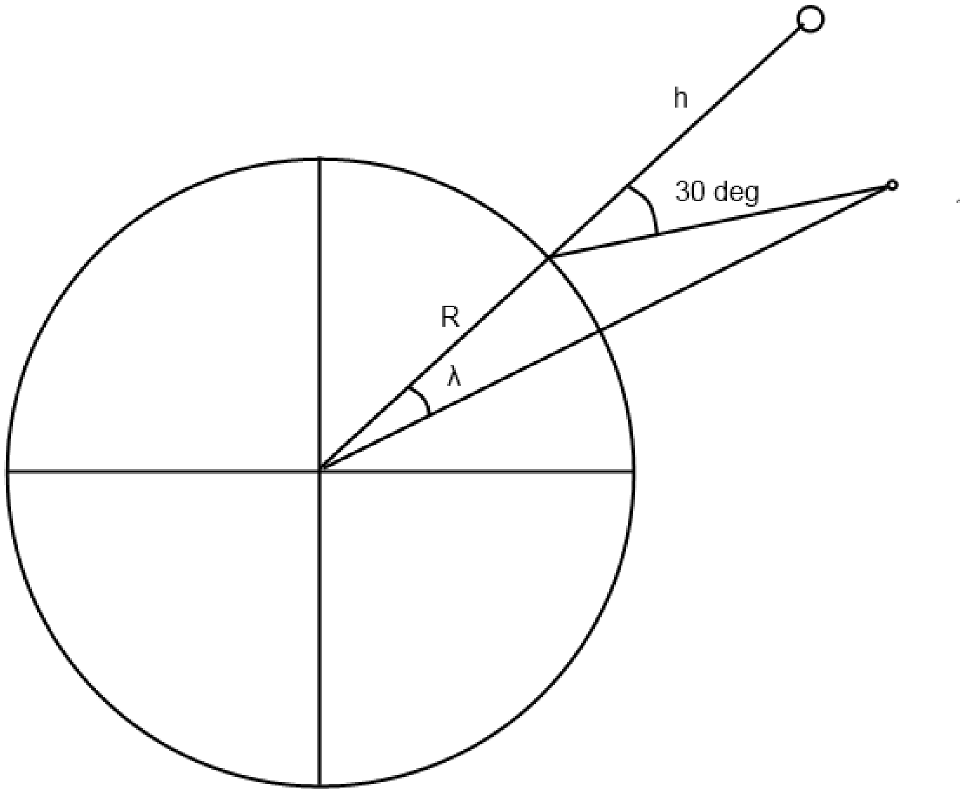



# Formation Design

SWARM

$\lambda = 2.18°$

$i_R = 2.18°$



# Formation Design

## Stationkeeping

Keeping the general constellation to insure better measurement data.

**What affects it?**

- Perturbations
- Differences in initial conditions

# Formation Design

Stationkeeping

**What can be done?**

- Nothing
- Relative Stationkeeping
- Absolute Stationkeeping

# Formation Design

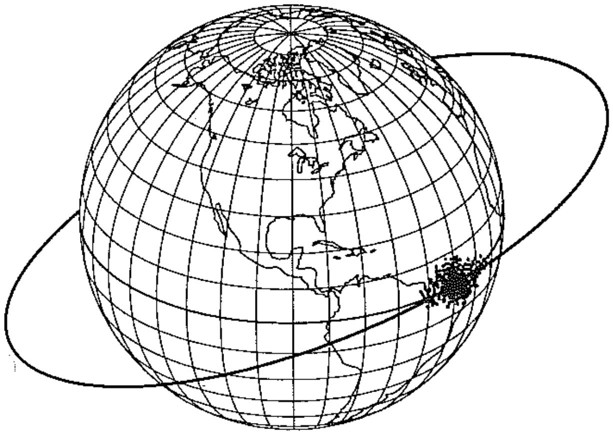
## Collision Avoidance

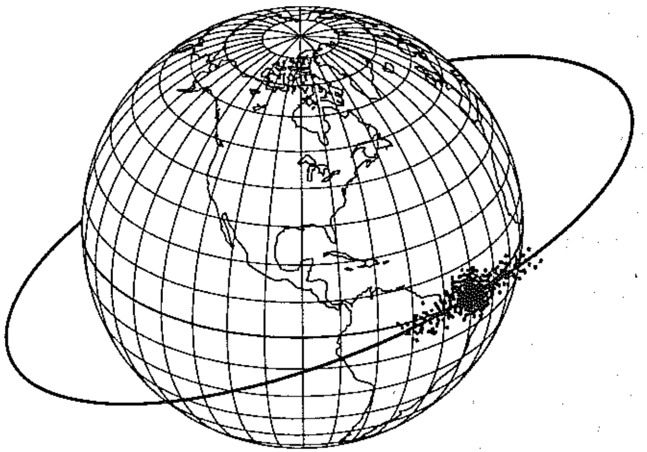
**Why is it important?**

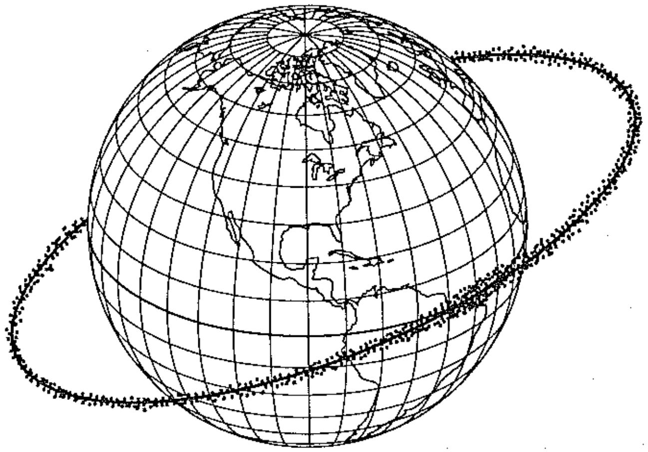
- Loss of 2 satellites, possibly vital
- Increased possibility of collision due to debris spread

# 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

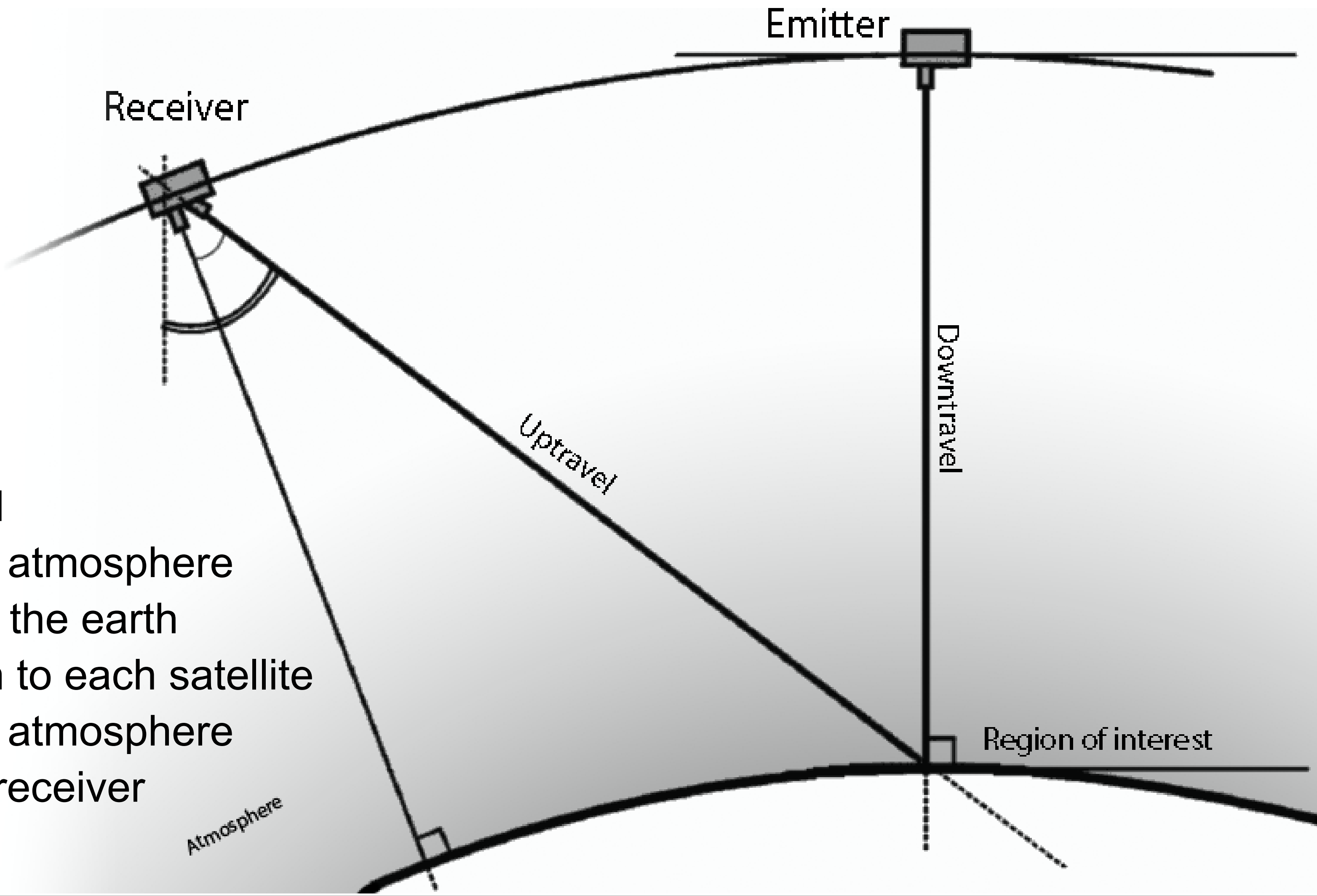
- Simulation

  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.

# Simulation




Pulse cycle

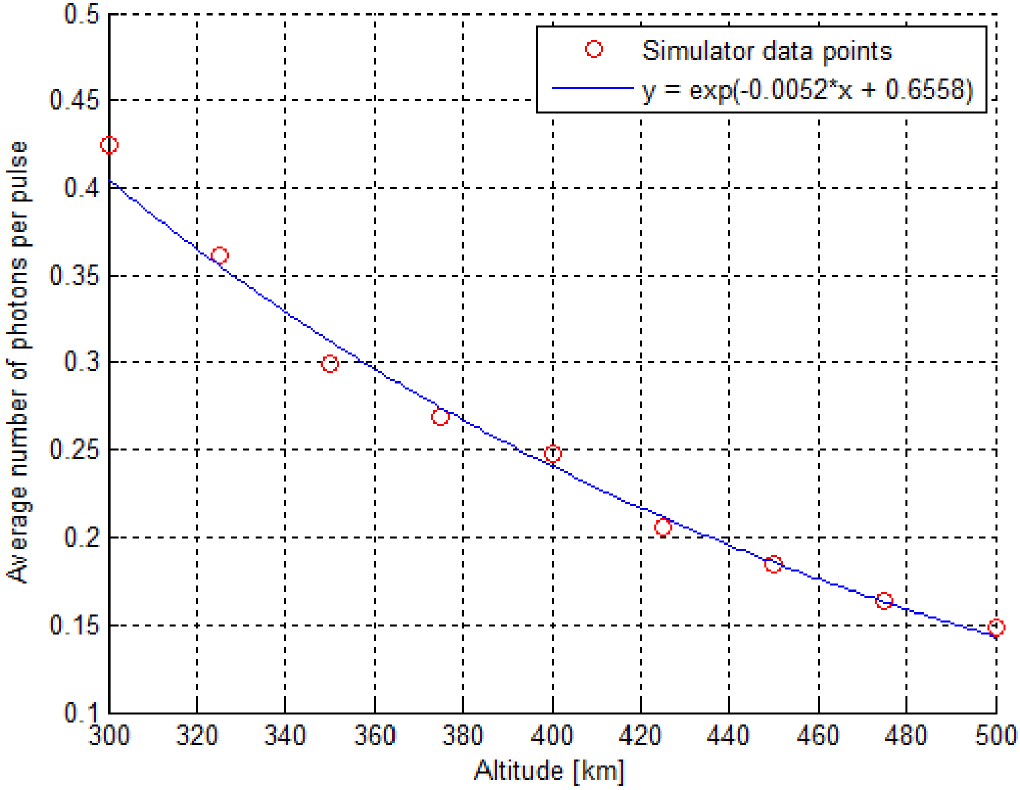
- Pulse emitted
- Absorption in atmosphere
- Scattering on the earth
- Small fraction to each satellite
- Absorption in atmosphere
- Received by receiver

# 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

# 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, 10 nm filter

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

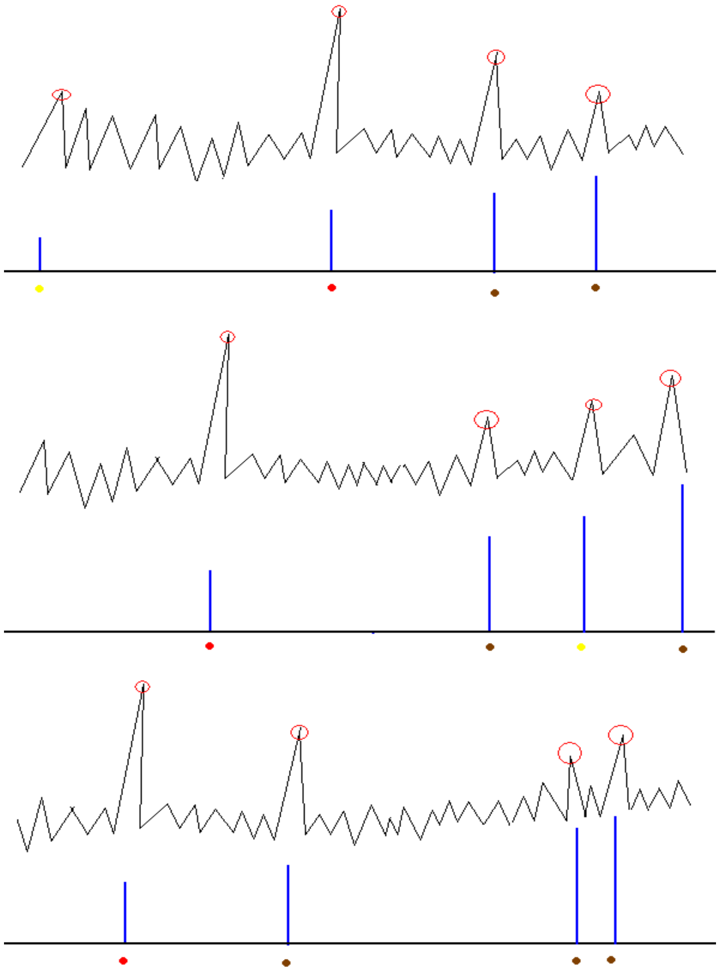
- Define time range
- Find the peaks
- Calculate altitudes
- Find the most common altitude

# Defining Range

- Known:
  - Time pulse sent
  - Time <u>SOME</u> pulse received
- Window : 1/5000 sec = 200 micro sec
- Offset: 500km/c*2 = 3.333 milliseconds travel time
- Height range: 60 km

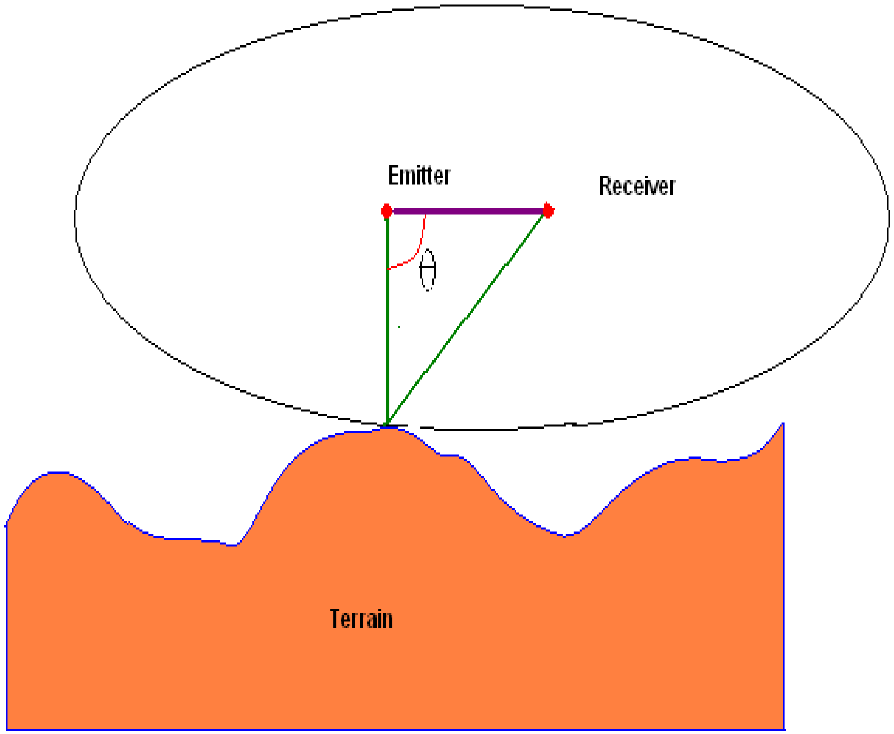
# Find the Peaks

- The peaks correspond to received pulses
- Noise introduced creates “false” peaks
- N*mean threshold
- Intermediate step for BRDF determination



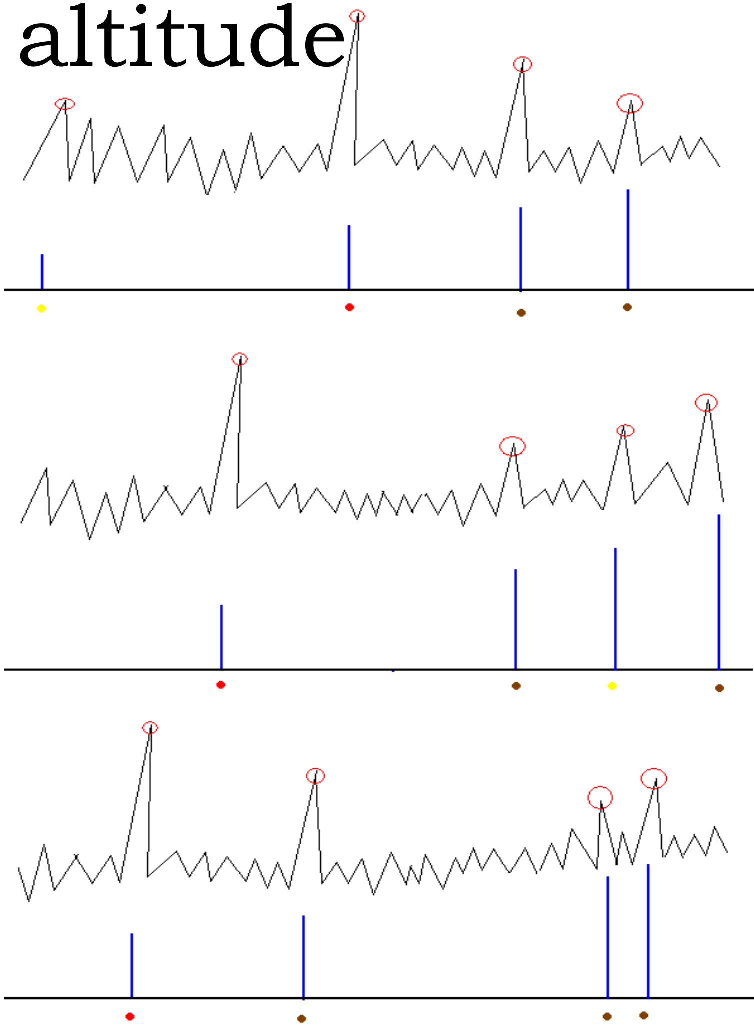
# Calculate altitudes

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



# Finding most common altitude

- Filtering noise
- Peak = specific altitude
- Least standard deviation configuration



# 7.

## *Summary and conclusions*

# Summary

| | |
|---|---|
| • ADCS | Sun sensor & star tracker<br>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° |