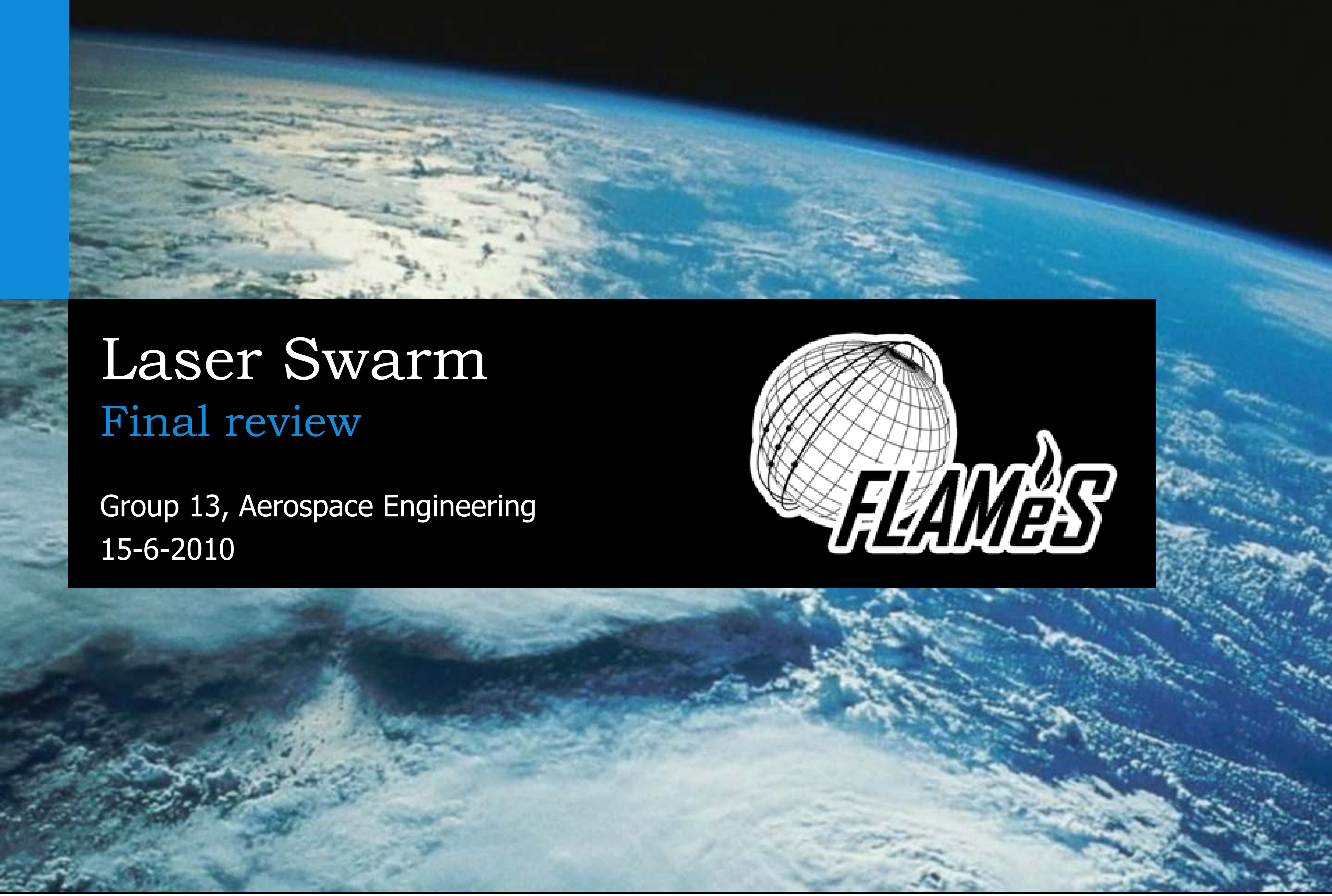


Laser Swarm

Final review

Group 13, Aerospace Engineering

15-6-2010

Laser Swarm

- Swarm of 9 satellites
- SPAD receiver
- 473nm Laser
- Elevation modeling of the earth
- BRDF modeling of the earth

Contents

- Subsystems design
- Orbital design
- Software tool
- Conclusions and recommendations

1.

Subsystem Design

- *Communications*
- *Navigation & data storage*
- *Attitude determination & control system*
- *Electrical power system*
- *Laser*
- *Optics Payload*

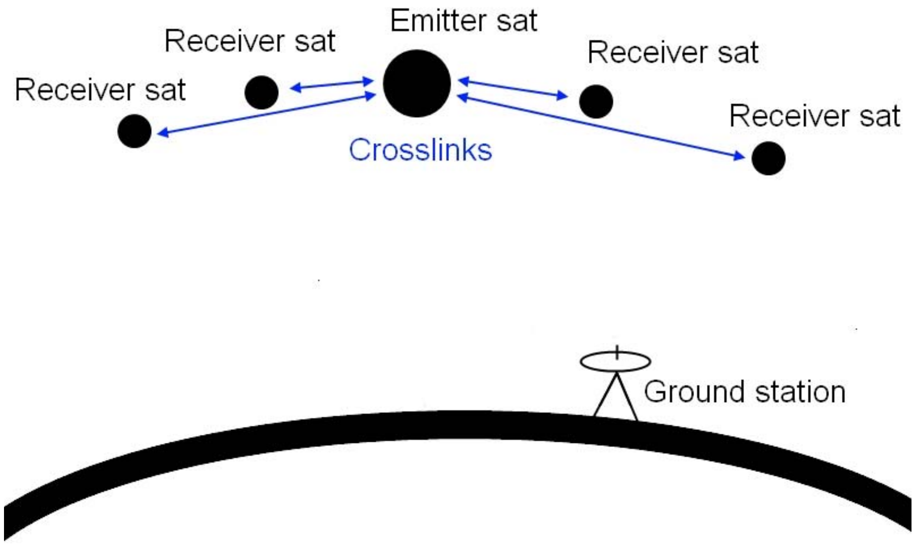
Communications

- Crosslink scientific/housekeeping data (emitter & receiver sat)
- G/S link scientific data (emitter sat)
- G/S link housekeeping data (emitter sat)
- G/S link housekeeping data (receiver sat)

Crosslink scientific/housekeeping data

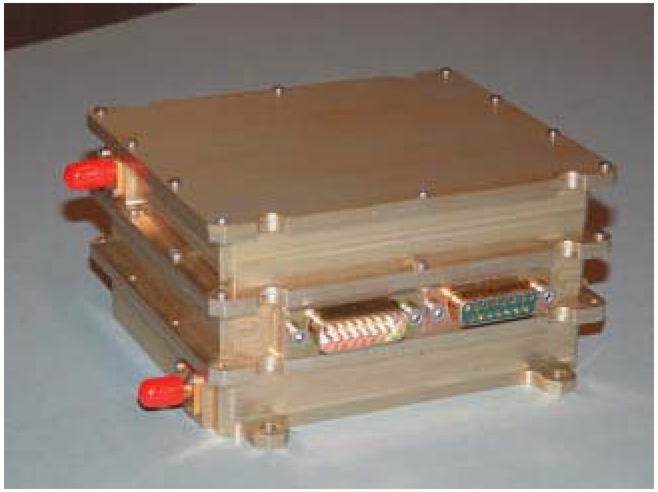
Design parameters

- Two way links
- Frequency: 2 GHz (S-band)
- Max. data rate: 1.62 Mbps
- Max. distance: 261 km
- Modulation: QPSK



Crosslink scientific/housekeeping data

Hardware



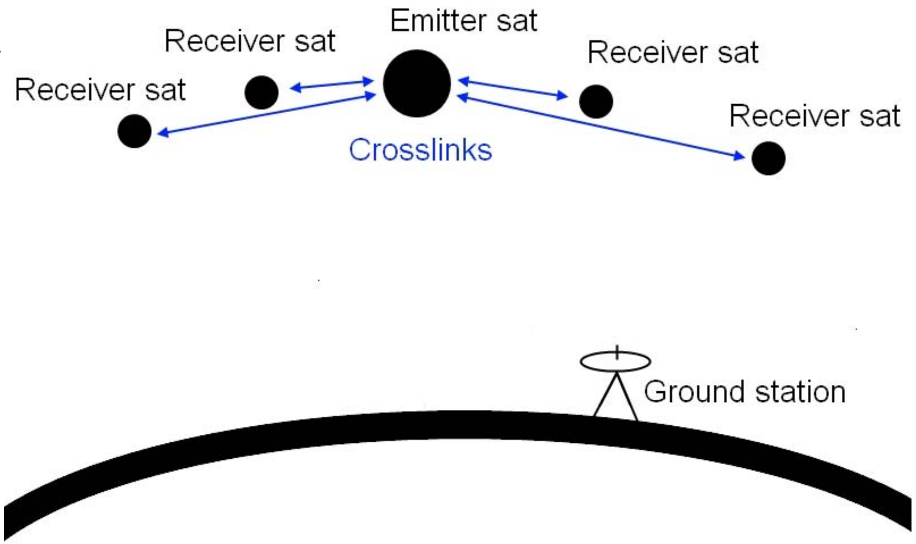
- S-band Transceiver
  - 10 Mbps
  - Max. output 5 Watt
  - 1 kg

- S-band patch antenna
  - 82x82x20mm
  - 80g
  - 4 dBi

Crosslink scientific/housekeeping data

Link budget

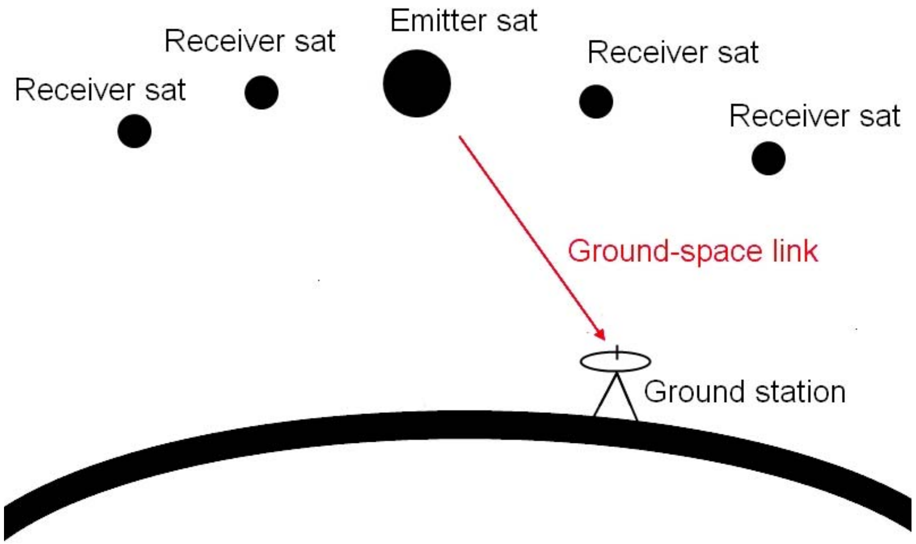
- Input power transceiver: 12 W
- Output power transceiver: 5W
- Required Eb/N0 ratio: 9.6 dB
- Margin: 1.76 dB



G/S link scientific data

Design parameters

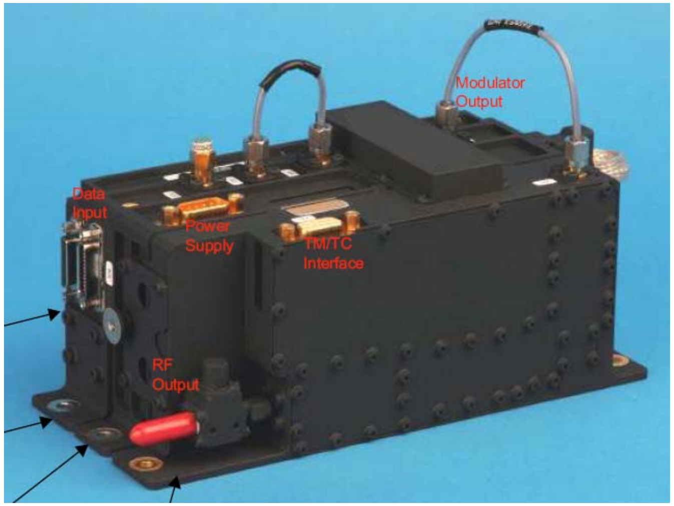
- One way link
- Frequency: 8.2 GHz (X-band)
- Max. data rate: 150 Mbps
- Max. distance: 1000 km
- Modulation: QPSK



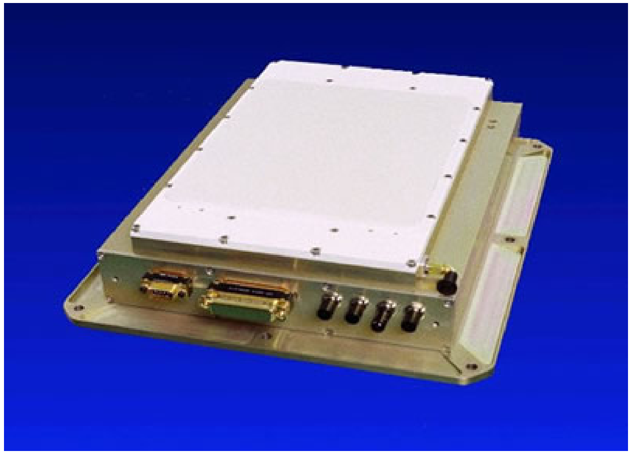
G/S link scientific data

Hardware

- X-band Transmitter
  - 500 Mbps
  - Max. output 6 Watt
  - 1.1 kg



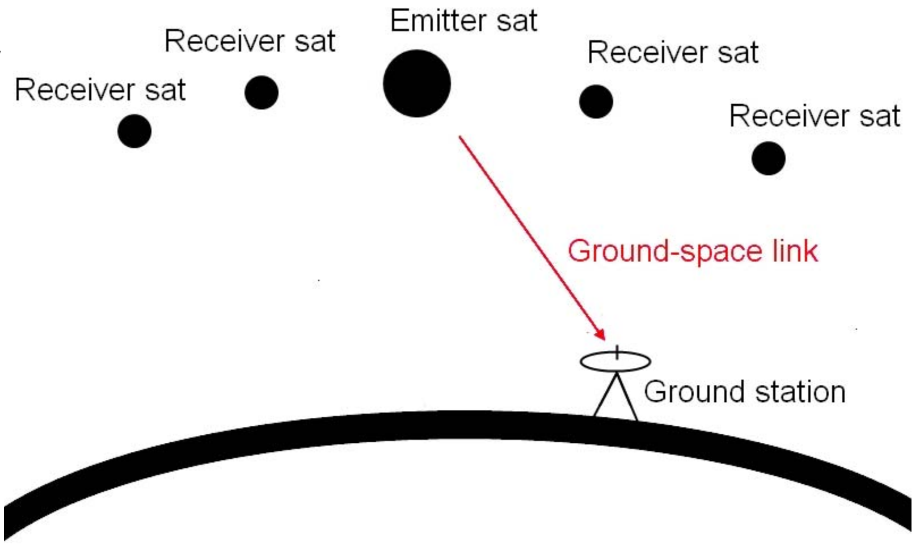
- X-band phased array
  - 330x305x74mm
  - 5.5 kg
  - 23.03 dBi



G/S link scientific data

Link budget

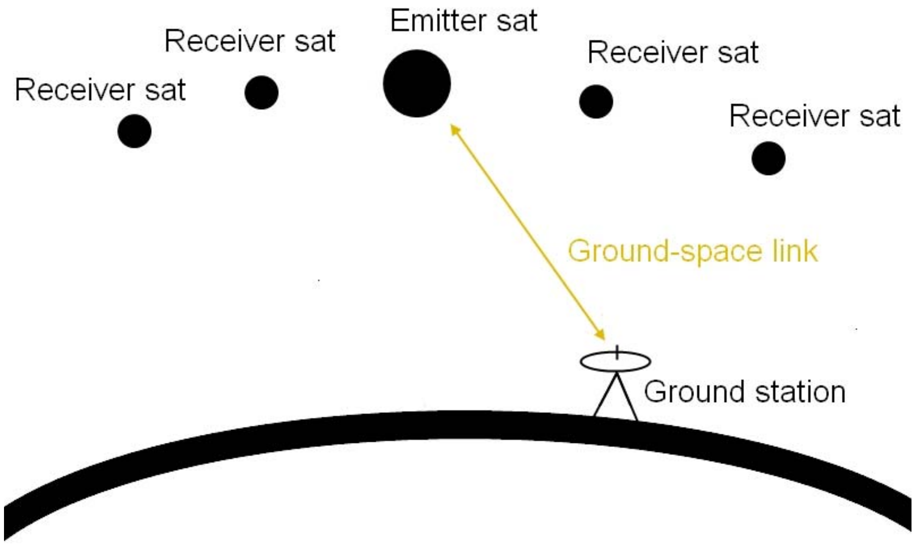
- Input power transceiver: 30 W
- Output power transceiver: 5W
- Required Eb/N0 ratio: 9.6 dB
- Margin: 29.3 dB



G/S link housekeeping data

Design parameters

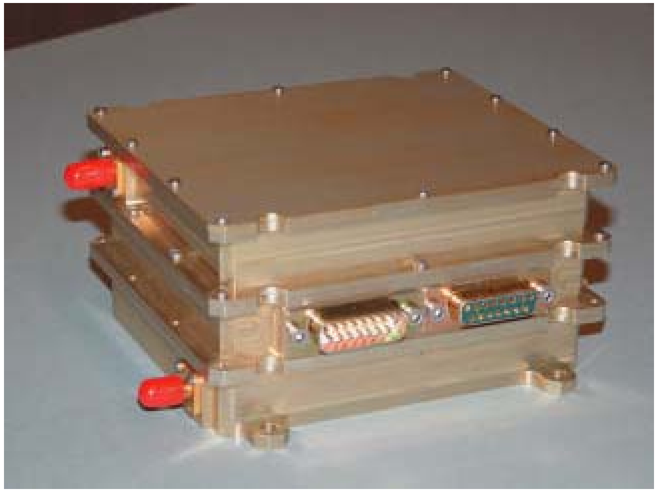
- Two way link
- Frequency: 2 GHz (S-band)
- Max. data rate: 20 kbps
- Max. distance: 1000 km
- Modulation: QPSK



G/S link housekeeping data

Hardware

- S-band Transceiver
  - 10 Mbps
  - Max. output 5 Watt
  - 1 kg

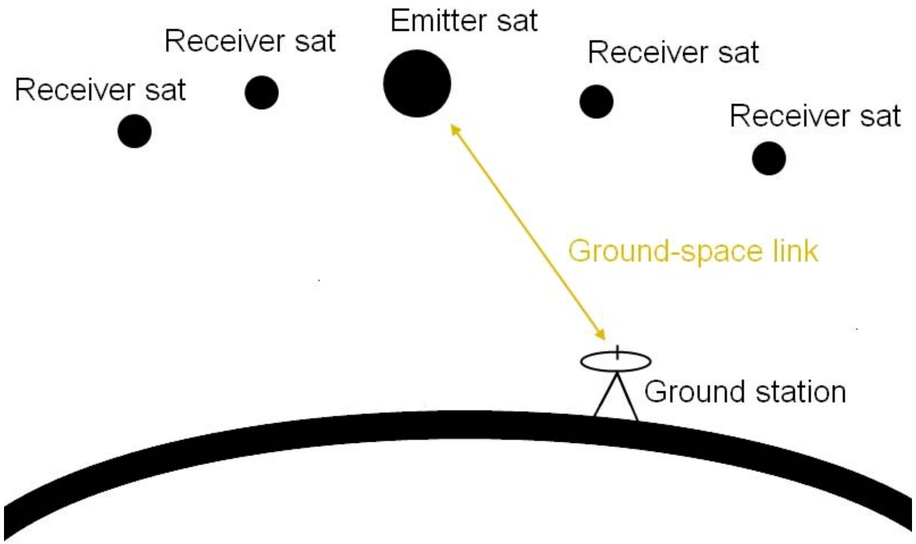


- S-band patch antenna
  - 82x82x20mm
  - 80g
  - 4 dBi

G/S link housekeeping data

Link budget

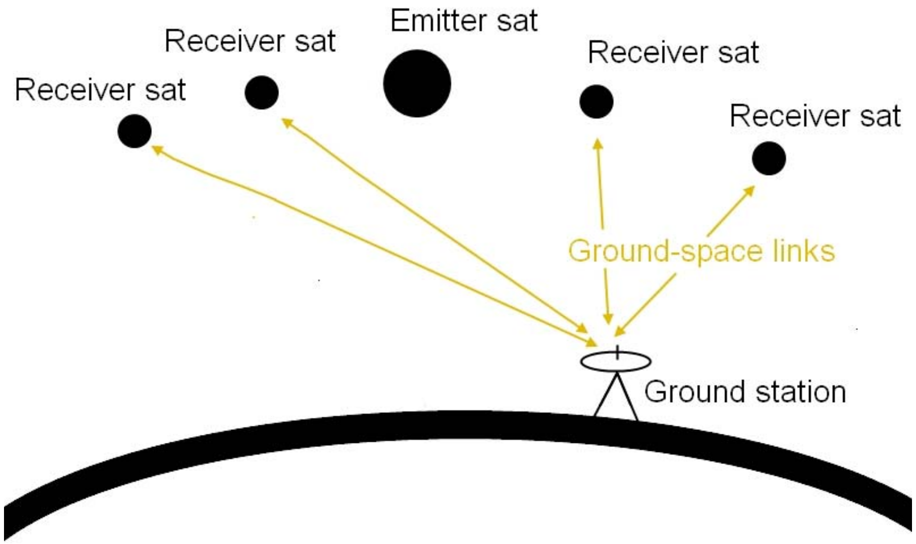
- Input power transceiver: 12 W
- Output power transceiver: 5W
- Required Eb/N0 ratio: 9.6 dB
- Margin: 27.65 dB



G/S link housekeeping data (backup)

Link budget

- Input power transceiver: 12 W
- Output power transceiver: 5W
- Required Eb/N0 ratio: 9.6 dB
- Margin: 27.65 dB



1.

Subsystem Design

- *Communications*
- *Navigation & data storage*
- *Attitude determination & control system*
- *Electrical power system*
- *Laser*
- *Optics Payload*

Data Storage

Overview

- Required amount of data storage
- Downlink rate
- Chosen storage medium
- A word about the receiver memory
- Summary

Data Storage

Required amount of data storage

- The emitter is the only satellite with contact to the Kiruna ground station
- As such it should be possible to store all scientific data on the emitter

- First thing to do is to find how much data has to be stored: What is the longest period without contact to the ground station?

Parameter	Value
Maximum time without contact to ground station	7:35:33
Average time without contact to ground station	1:39:00
Average duration of the contact with ground station	0:08:30

Data Storage

Required amount of data storage - continued

- The total bit rate of all 5 receiver instruments is

  8.13 Mbit/s

- This yields a required storage volume of

  244 Gbit

Parameter	Value
Maximum time without contact to ground station	7:35:33
Average time without contact to ground station	1:39:00
Average duration of the contact with ground station	0:08:30

Data Storage
Can the data be send to earth

- Every **13** or more orbits a long period without contact occurs.
- During these orbit additional data is generated.

- The resulting downlink rate is **111 Mbit/s**
- The available rate is **150 Mbit/s**

Parameter	Value
Maximum time without contact to ground station	7:35:33
Average time without contact to ground station	1:39:00
Average duration of the contact with ground station	0:08:30

Data Storage

Storage medium

64 Gbit flash nand memory module

- Weighs 6.10 grams
- 20.40 x 13.84 x 12.13 mm
- Uses ~ 1 Watt of power
- Space qualified
- 98% survival chance after 5 years

Data Storage

Storage medium - continued

- 244 Gbit / 64 Gbit ⇒ 4 modules
- Extra module added for redundancy

In total:

- ~ 5 Watt of power
- 30.5 grams
- At least 102 x 69.2 x 60.7 mm

Data Storage

Receiver satellite memory

- All science data is to be stored on the emitter
- Memory is still required for housekeeping data and scientific data in emergency
- Each receiver satellite has a 64 Gbit flash nand memory

  (Can allow it to store of up to 7 hours of data)

Data Storage

Summary

- The emitter has 5 x 64 Gbit modules

  320 Gbit available, where 244 Gbit is necessary

- A receiver has 1 x 64 Gbit module

- Communications and data storage

	Emitter satellite	Receiver satellite
Mass [kg]	10.66	3
Power [W]	47	13
Cost [k$]	2940	525

Navigation

Overview

1. Possible options
2. Hardware
3. Accuracy

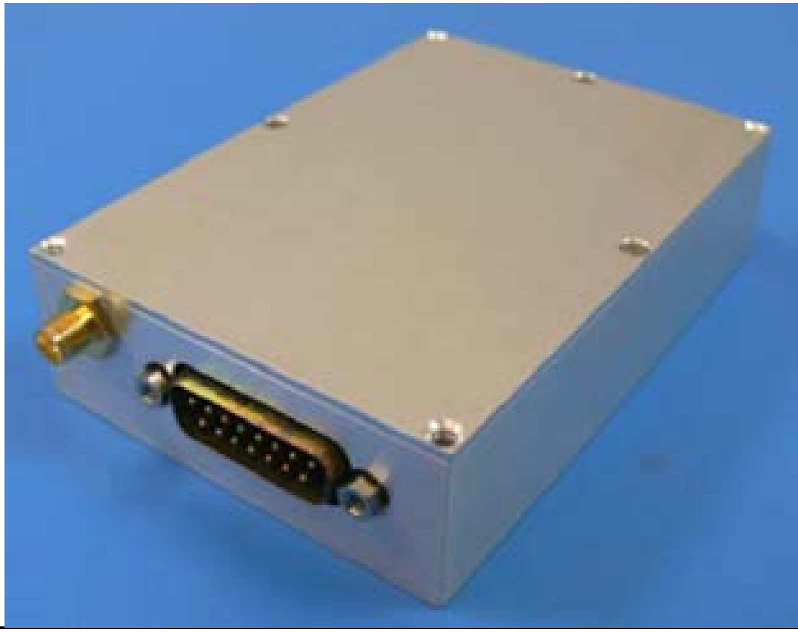
Navigation

The options

1. Utilize the attitude instruments
2. Hybrid communication/navigation system
3. GPS receiver on every satellite

Navigation
Hardware

- Weighs less than 200 grams
- 100 mm x 70 mm x 25 mm
- Requires ~ 1 Watt
- Cost per receiver $25,000



Navigation

Accuracy

What kind of accuracy can be reached?

- ~ 10 m readily available
- ~ 0.9 m after some calculations
- ~ 1.5 mm with post-processing

1.

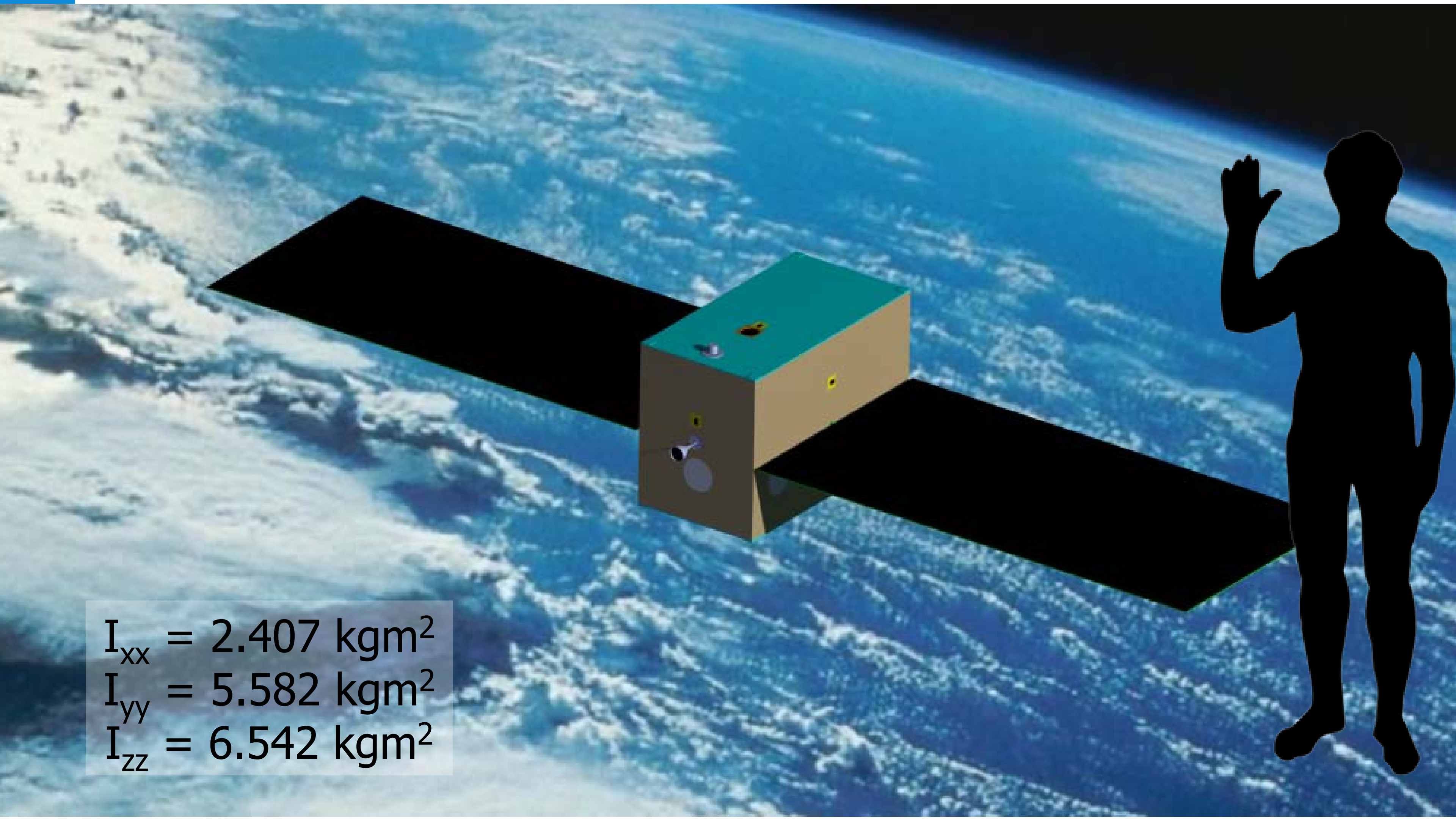
Subsystem Design

- *Communications*
- *Navigation & data storage*
- *Attitude determination & control system*
- *Electrical power system*
- *Laser*
- *Optics Payload*

Attitude and Orbital Determination and Control Subsystem

- Emitter
  - Attitude determination
  - Attitude control
  - Orbit control
  - Pointing
- Receiver
  - Attitude determination
  - Attitude control
  - Orbit control
  - Pointing

Emitter Satellite



$I_{xx} = 2.407\ \mathrm{kgm}^2$
$I_{yy} = 5.582\ \mathrm{kgm}^2$
$I_{zz} = 6.542\ \mathrm{kgm}^2$

Disturbance Torques

- Gravity gradient

$$T_{gg} = \frac{3\mu}{2R^3}\left|I_z - I_y\right| sin(2\theta)$$

- Solar Radiation

$$T_{sp} = \frac{F_s}{c} A_s (1+q)\cos i\,(c_{ps} - cg)$$

- Earth Magnetic Field

$$T_m = DB = D\frac{2M}{R^3}$$

- Aerodynamic Torques

$$T_a = 0.5\rho C_d A V^2 (c_{pa} - cg)$$

Disturbance Torques Emitter

- Gravity gradient

$$T_g = \frac{3 \cdot 398600.4 \cdot 10^9}{2 \cdot 6878000^3} |6.542 - 2.407| \sin(2 \cdot 1°) = 2.652 \cdot 10^{-7} \text{Nm}$$

- Solar Radiation

$$T_{sp} = \frac{1367}{3 \cdot 10^8} 1.58(1 + 0.6)\cos 0° \cdot 0.2 = 2.304 \cdot 10^{-6} \text{Nm}$$

- Earth Magnetic Field

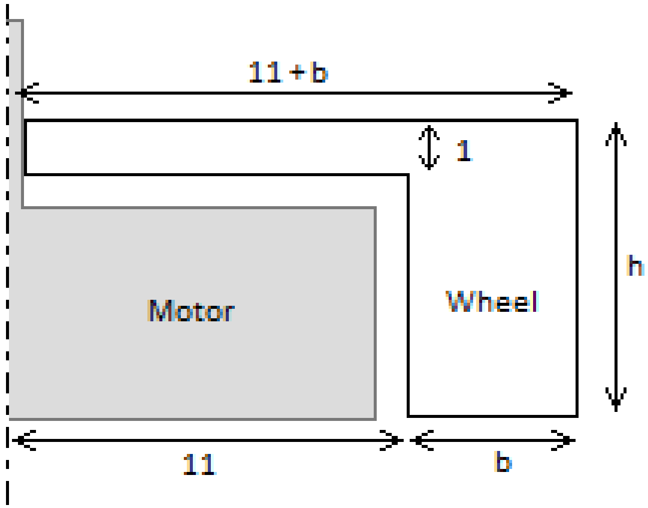
$$T_m = 1 \cdot \frac{2 \cdot 7.96 \cdot 10^{15}}{6878000\text{^}3} = 4.893 \cdot 10^{-5} \text{Nm}$$

- Aerodynamic Torques

$$T_a = \frac{1}{2} 1.80 \cdot 10^{-12} \cdot 2.2 \cdot 1.58 \cdot 7613^2 \cdot 0.2 = 3.626 \cdot 10^{-5} \text{Nm}$$

Reaction Wheels Emitter

- Total disturbance torque $8.776 \cdot 10^{-5}$ Nm
- Safety margin of 2
- Torque requirement $1.755 \cdot 10^{-4}$ Nm



- Angular acceleration 100 rad/s

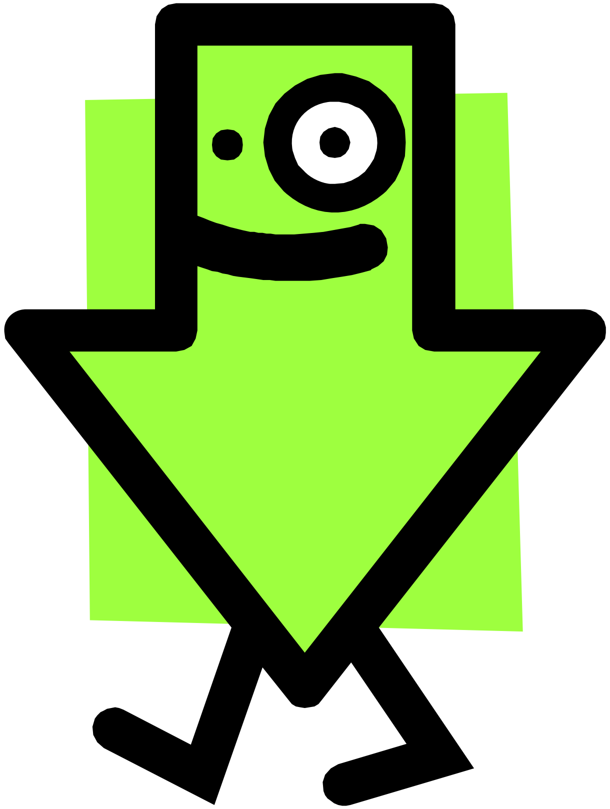
- h = 10 mm
- b = 36 mm
- m = 212 grams

Emitter Thruster

- ΔV requirement 225.38 m/s
- Bipropellant thruster
- I_{sp} = 291 s
- Propellant mass 3.8 kg
  - Monomethylhydrazine 2.88 L
  - Dinitrogen Tetraoxide 1.32 L

Source: http://www.eads.com

Pointing Emitter

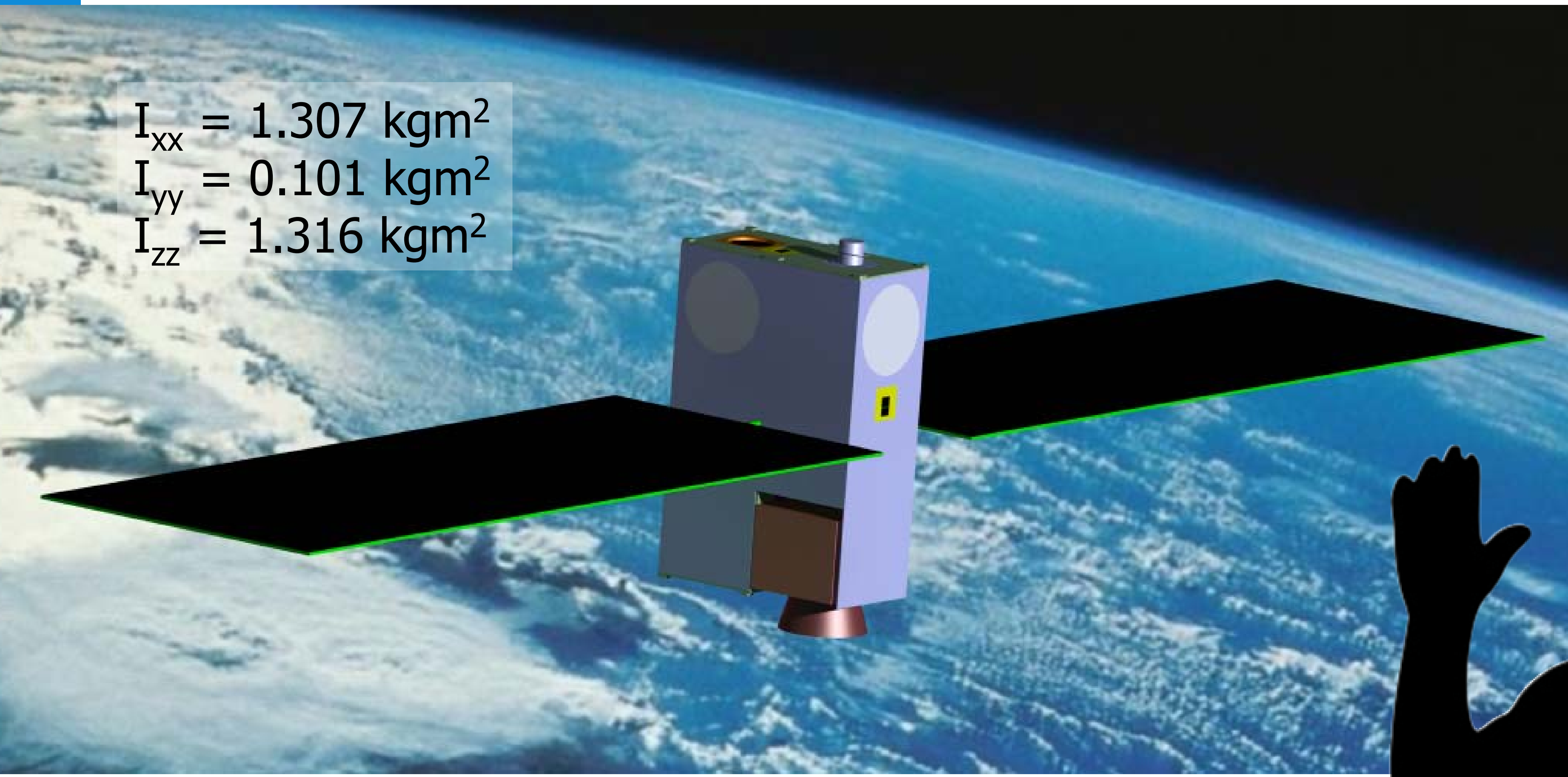


Volumes, Masses and Prices Emitter

Emitter	Number	Dimensions	Mass	Price [€]
Sun sensors	5	30x30x14.5 mm^3	120	55000
Star tracker	1	50x50x100 mm^3	375	75000
Reaction wheels	3	90x90x20 mm^3	135	550
Magneto torquers	3	20x20x150 mm^3	600	9000
Thruster (incl. tanks, etc.)	1	300x200x100 mm^3	1650	400000
Total				309000 [$ FY00]

Receiver Satellite

$I_{xx} = 1.307\ \text{kgm}^2$
$I_{yy} = 0.101\ \text{kgm}^2$
$I_{zz} = 1.316\ \text{kgm}^2$



Disturbance Torques Receiver

- Gravity gradient

$$T_g = \frac{3 \cdot 398600.4 \cdot 10^9}{2 \cdot 6878000^3} \left|1.316 - 0.101\right| \sin(2 \cdot 30°) = 1.933 \cdot 10^{-6} \text{Nm}$$

- Solar Radiation

$$T_{sp} = \frac{1367}{3 \cdot 10^8} 0.53(1 + 0.6)\cos 0° \cdot 0.15 = 5.796 \cdot 10^{-7} \text{Nm}$$

- Earth Magnetic Field

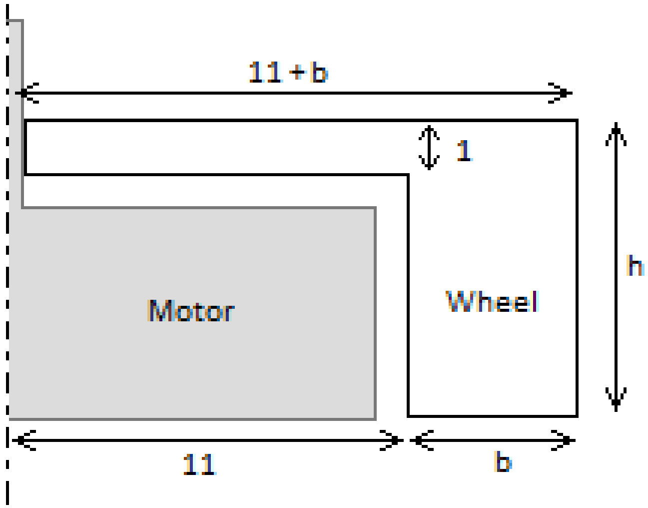
$$T_m = 0.1 \cdot \frac{2 \cdot 7.96 \cdot 10^{15}}{6878000^3} = 4.893 \cdot 10^{-6} \text{Nm}$$

- Aerodynamic Torques

$$T_a = \frac{1}{2} 1.80 \cdot 10^{-12} \cdot 2.2 \cdot 0.53 \cdot 7613^2 \cdot 0.15 = 9.123 \cdot 10^{-6} \text{Nm}$$

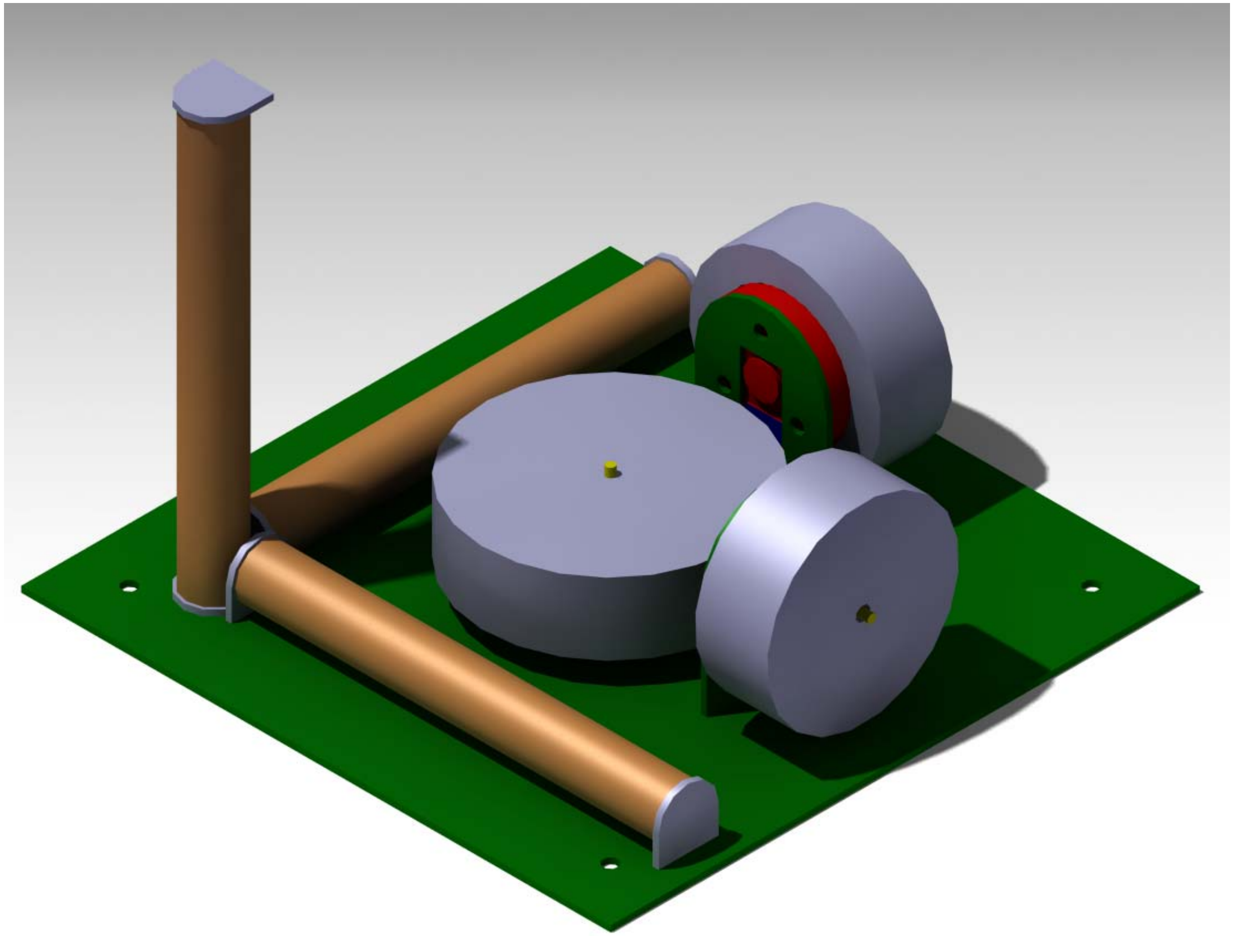
Reaction Wheels Receiver

- Total disturbance torque 1.65 $\cdot 10^{-5}$ Nm
- Safety margin of 2
- Torque requirement $3.31 \cdot 10^{-5}$ Nm



- Angular acceleration 100 rad/s
- h = 10 mm
- b = 11 mm
- m = 36 grams

Attitude Control Receiver

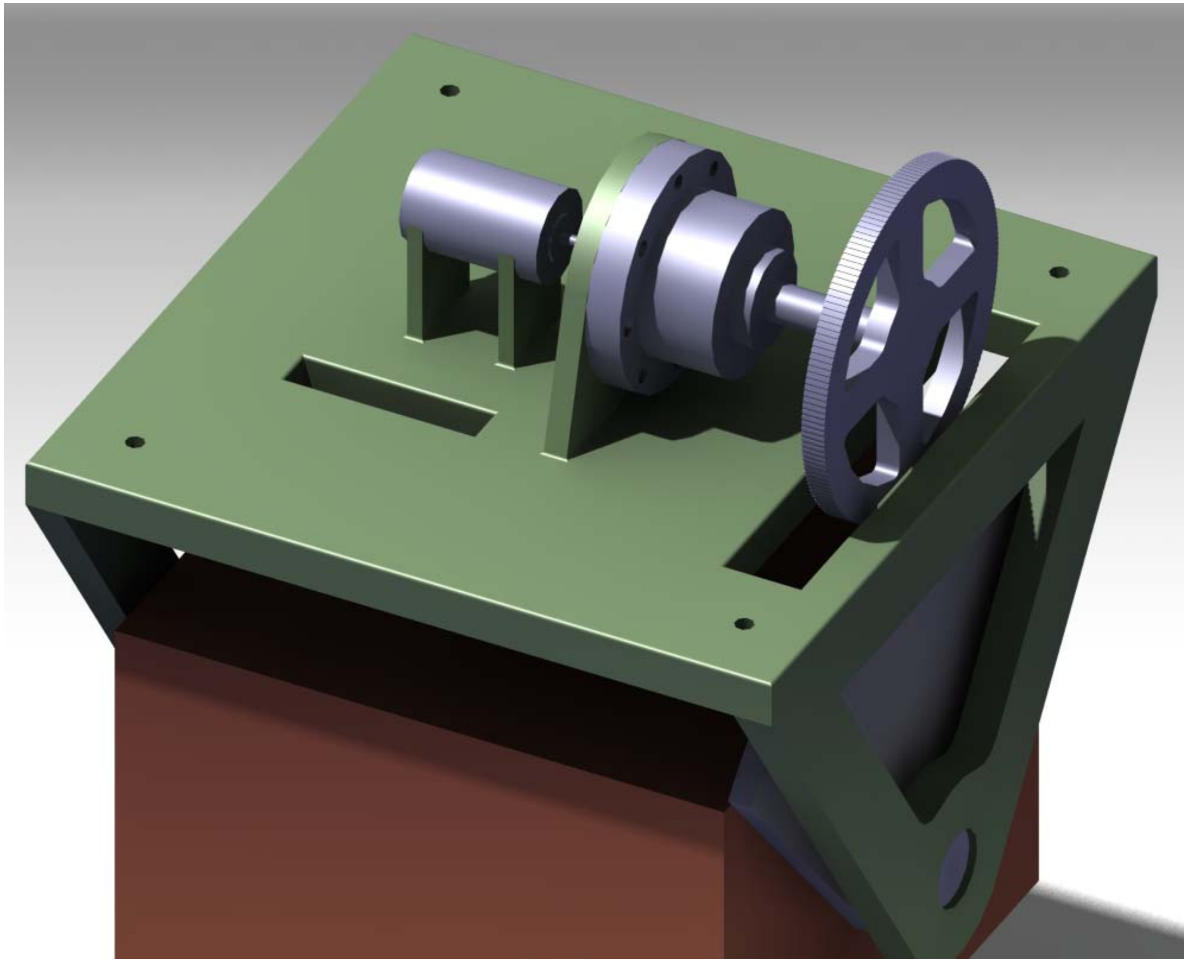


Receiver Thruster

- Maximum ΔV requirement:
  165.14 m/s
- Mono propellant thruster
- I_{sp} = 120 s
- Maximum Propellant mass 1.77 kg
  - Hydrogen Peroxide 1.23 L

Source: http://www.micro-a.net

Pointing Receiver



Volumes, Masses and Prices Receiver

Emitter	Number	Dimensions	Mass	Price [€]
Sun sensors	4	30x30x14.5 mm^3	120	44000
Star tracker	1	50x50x100 mm^3	375	75000
Reaction wheels	3	45x45x15 mm^3	135	550
Magneto torquers	3	9x9x70 mm^3	600	3450
Thruster (incl. tanks, etc.)	1	100x100x150 mm^3	1650	250000
Total				214000 [$ FY00]

1.

Subsystem Design

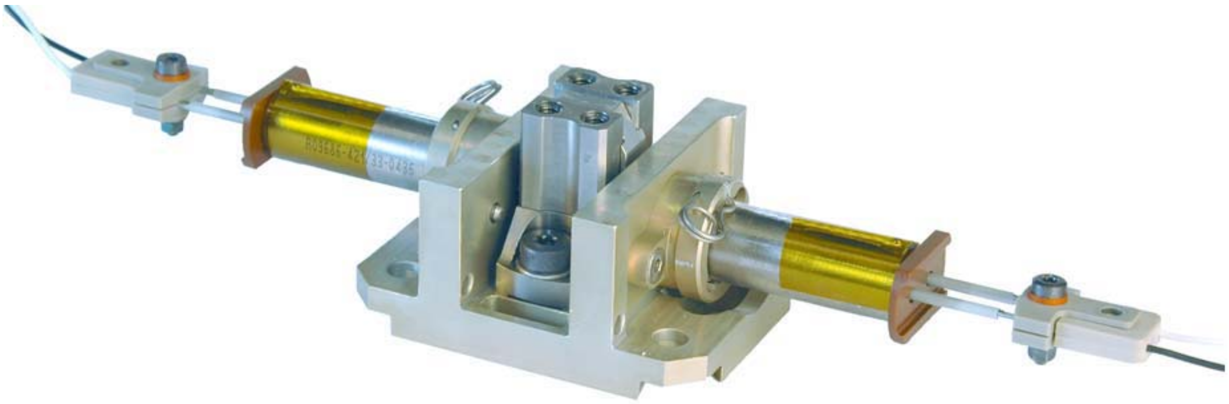
- *Communications*
- *Navigation & data storage*
- *Attitude determination & control system*
- *Electrical power system*
- *Laser*
- *Optics Payload*

EPS Final Design

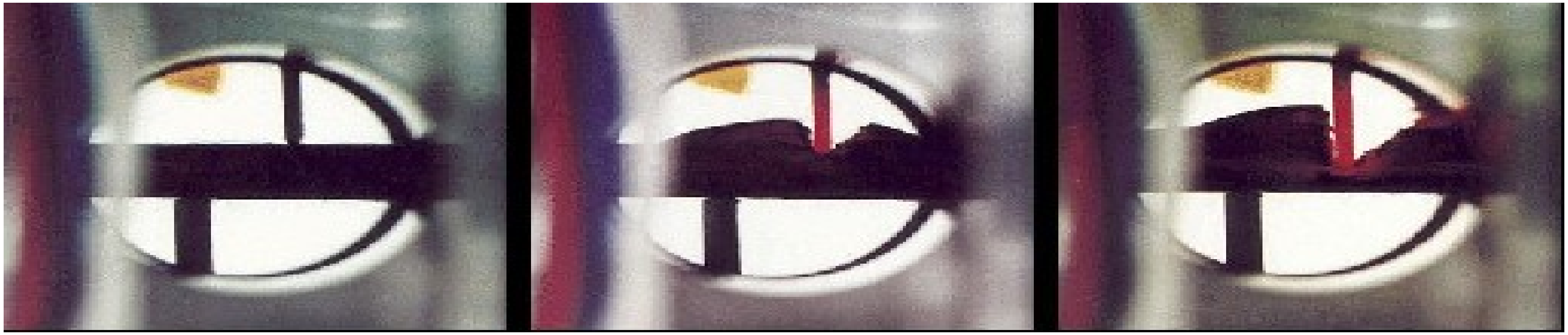
- Solar panel hold down and release mechanism
- Solar panel deployment
- Pointing driver
- Bus regulation
- Battery
- Solar panels
- Summary

Hold down and release mechanism

- DutchSpace Thermal Knife
- Dyneema wires
- “Cutting” by thermal knife
- Low shocks
- High reliability



Hold down and release mechanism



Solar panel deployment

- Use of shape memory alloys
- High reliability
- No pyrotechnic shocks

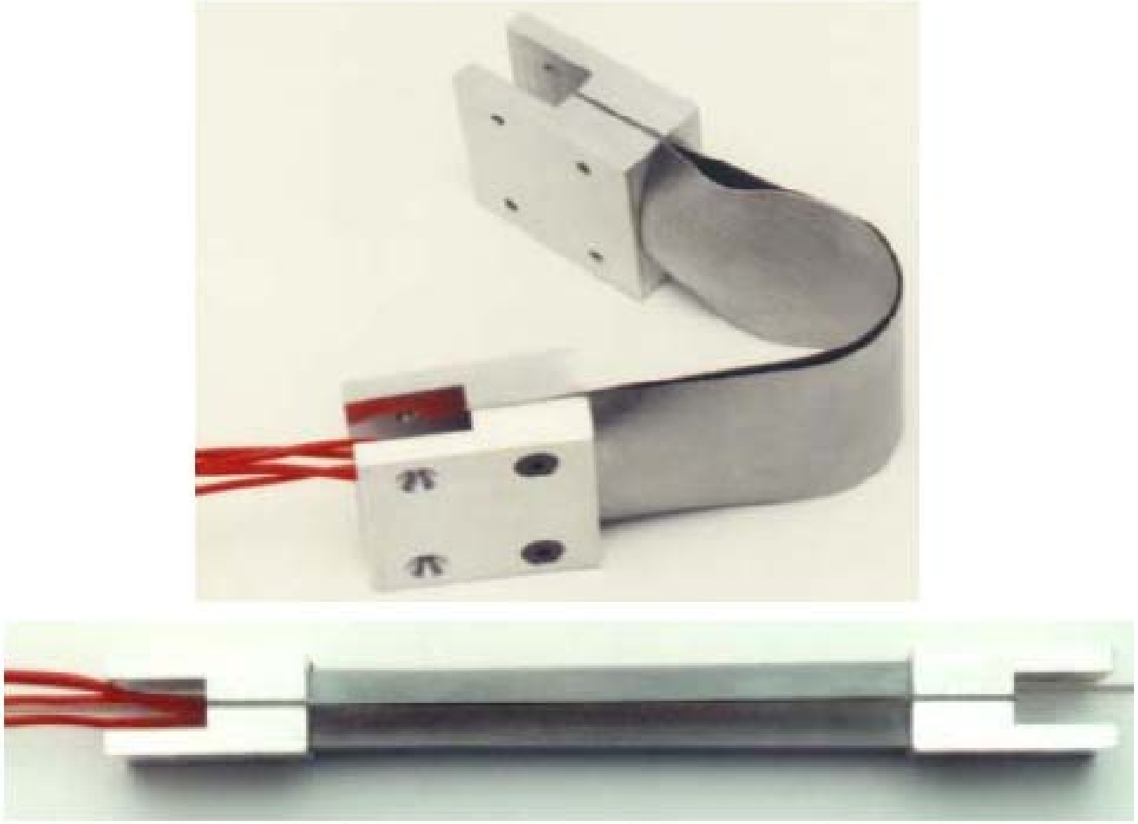
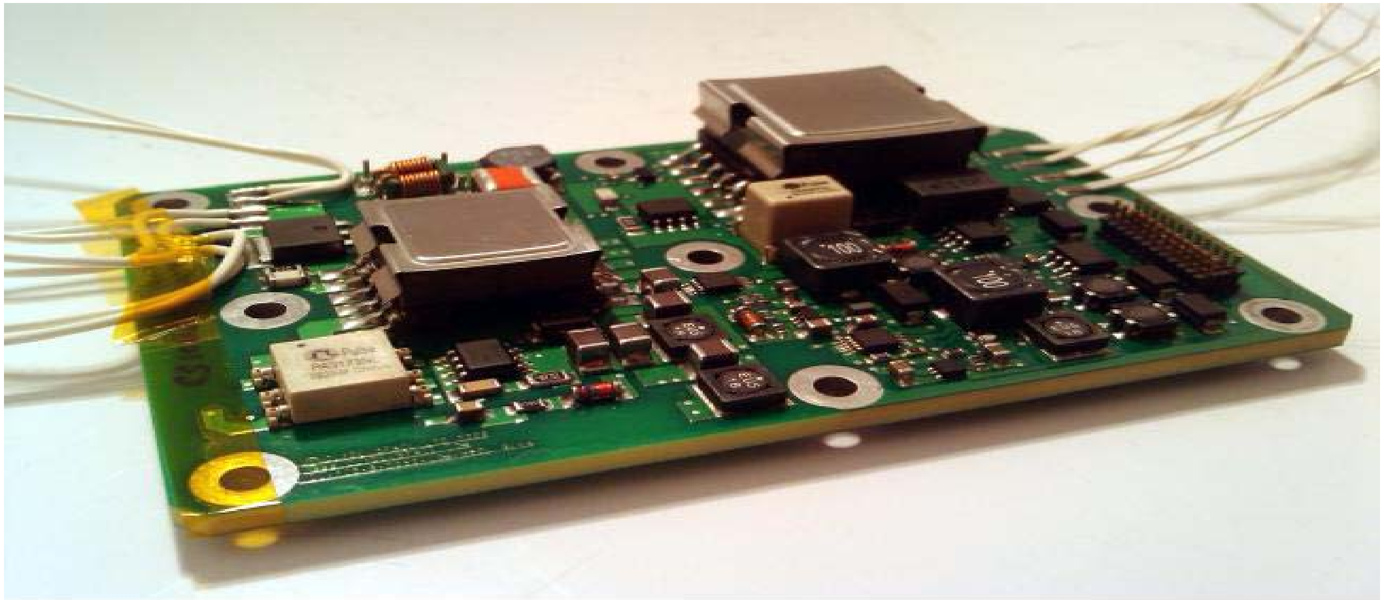


Figure 2. Shape-Memory Alloy Hinges, Stowed (Top), and Deployed (Bottom).

Pointing driver

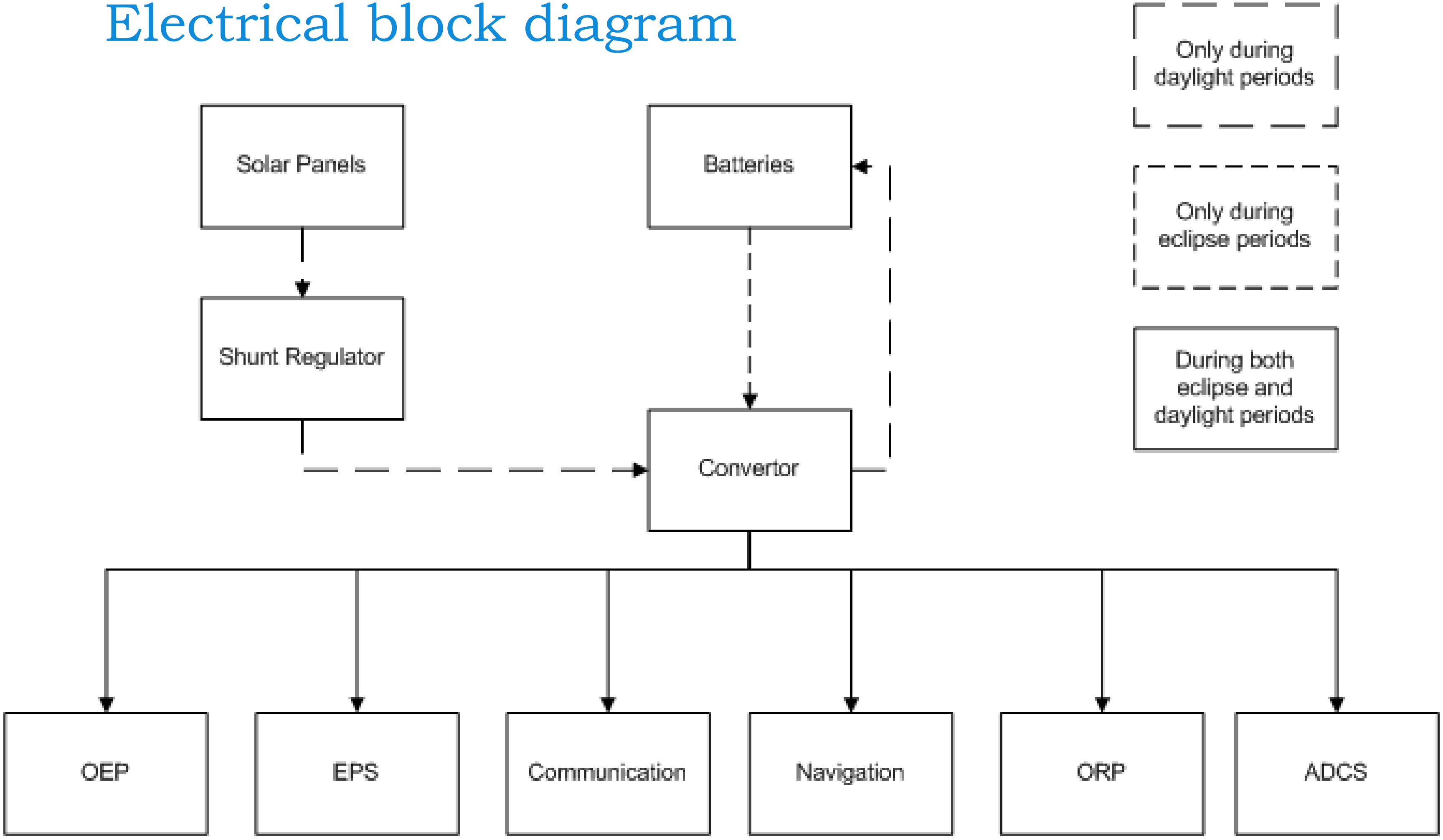
- To fully point solar panels towards the Sun
- Driven by stepper motor
- Increased accuracy by using gear head

Bus regulation: DC/DC convertor



Bus regulation: DC/DC convertor

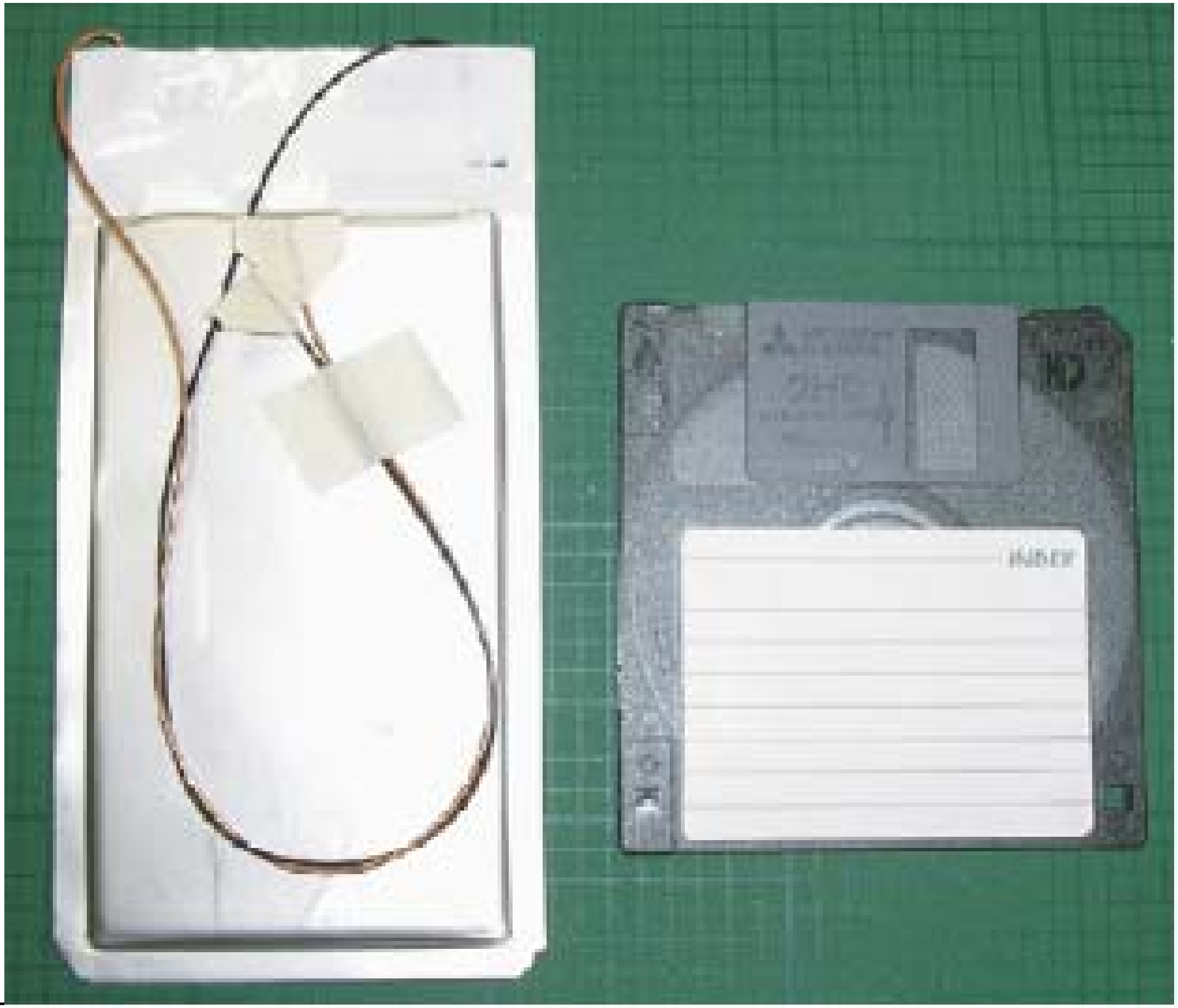
Electrical block diagram



Battery

- Lithium-ion cells
- 158 Wh/kg
- Module consists of 7 cells connected in series
- Battery consists of 2 modules connected in parallel
- 28 Vdc at 6Ah
- 1 battery for the receivers, 3 for the emitter

Battery



Solar panels

- Triple-junction cells
- Receiver area: 0.5 m^2
- Emitter area: 1.4 m^2

Summary - receiver

Part	Dimensions [mm]			Weight [g]	Power [W]
	Length	Width	Height		
Driver	30	6	60	21.4	1
Battery	168	102	10	1000	0
Deployment	120	50	10	120	4*
Convertor	95	60	17	80	1.5
Shunt regulator	2.8	2.6	1.05	0.1	0.5
Thermal knife	60	50	38	280	15*
Wiring	-	-	-	230	0.28
Solar Panels	500	500	0.36	723	0
* One-time application					

Summary

- Receiver:
  - Mass: 3.6 kg
  - Cost: $ 266 000

- Emitter:
  - Mass: 5.8 kg
  - Cost: $ 541 000

1.

Subsystem Design

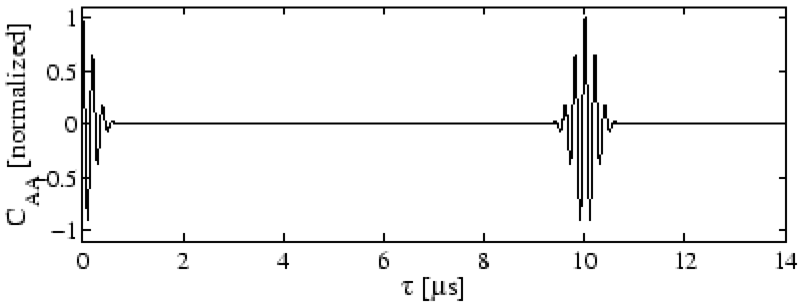
- *Communications*
- *Navigation & data storage*
- *Attitude determination & control system*
- *Electrical power system*
- *Laser*
- *Optics Payload*

Optical Emitting Device

Performance characteristics set by simulation

Desired characteristics:

- Wavelength: 473 [nm]
- Pulsed wave form: (Repetition rate ~ 5,000 [Hz])
- Pulse energy: ~1 [mJ]
- Pulse length: ~1 [ns]



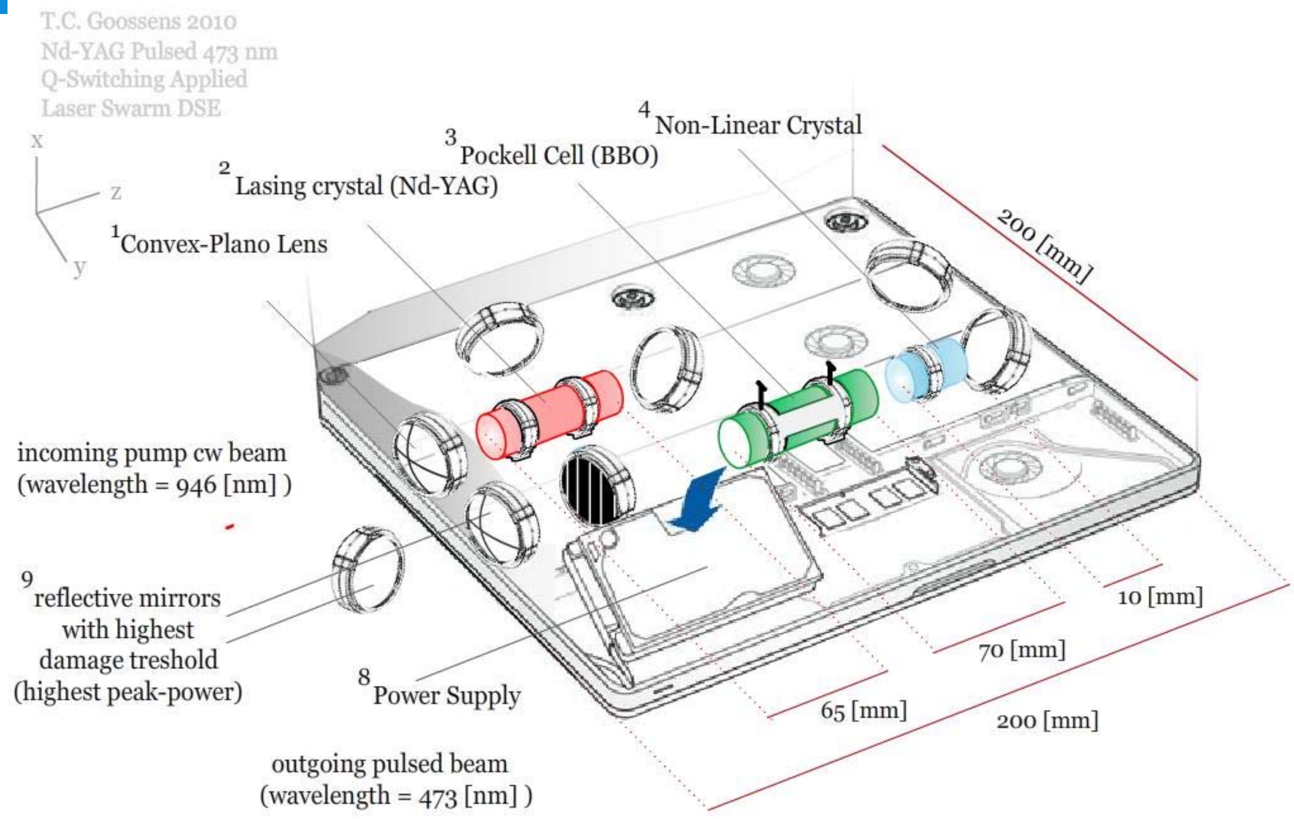
Laser Cavity

- Starting from Nd:YAG 946 [nm] to 473 [nm]
- From continuous to pulsed waveform
- Initializing Nd:YAG population inversion (diode pumps)
- Lifetime considerations

Diode pumped Nd:YAG Configuration

Configuration flown on NASA missions (GLAS, MOLA)

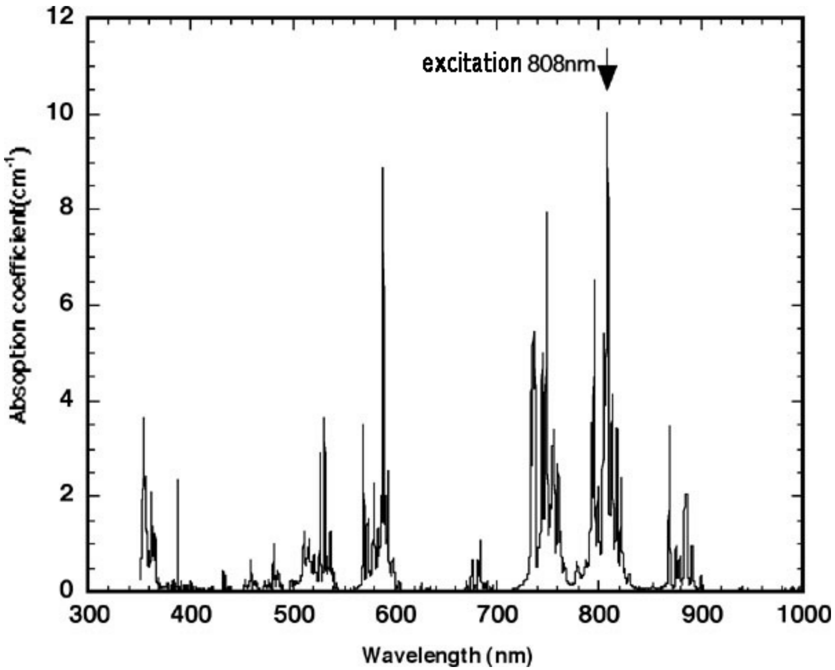
Wall plug efficiency	~ 12	[%]	[2004]
	~ 20	[%]	[2015]



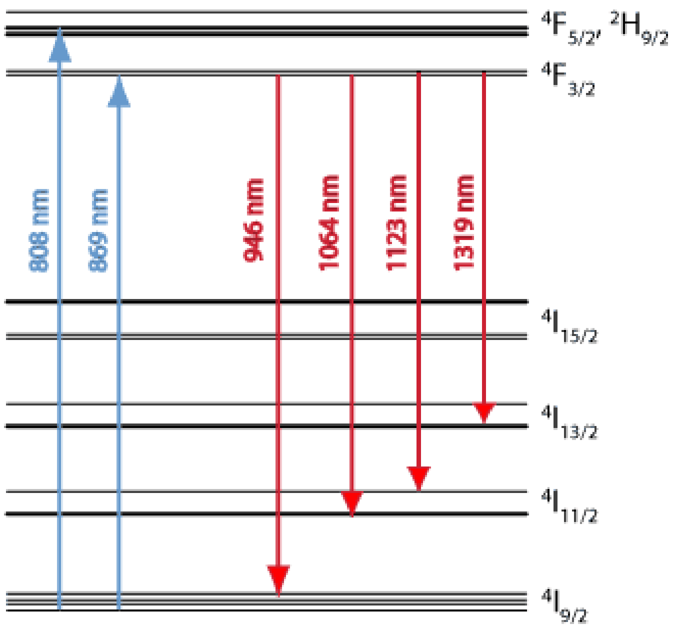
Diode pumped Nd:YAG Configuration

Desired wavelength Nd:YAG 946 [nm]

E = hv (inverse relation with wavelength)



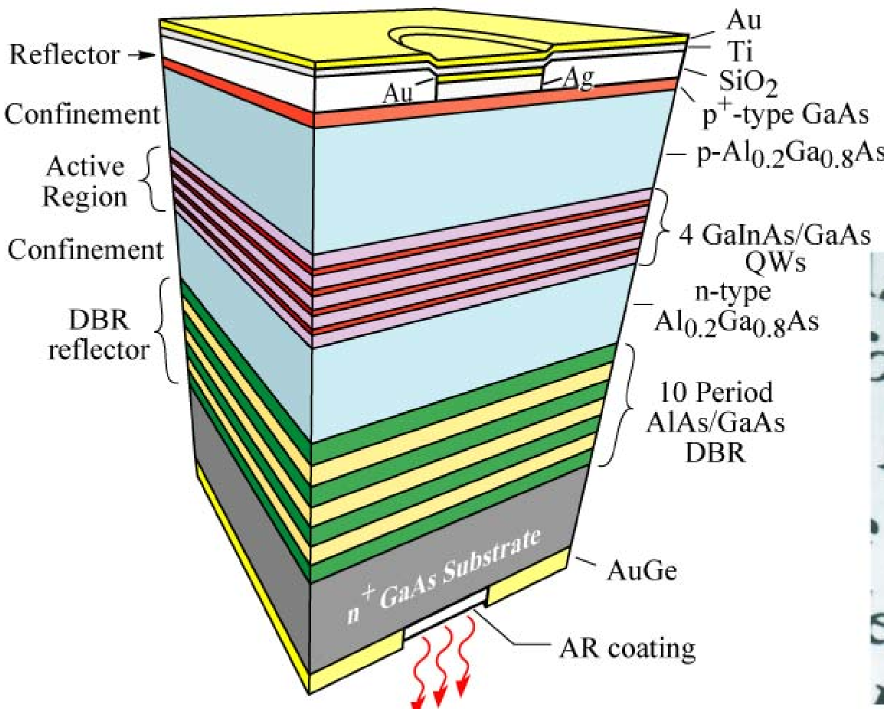
Nd $^{3+}$ ions exhibit large absorption at 808 [nm]



Quantum level trajectory: $F_{5/2} > F_{3/2} > I_{9/2}$
Lasing action: $F_{3/2} > I_{9/2}$

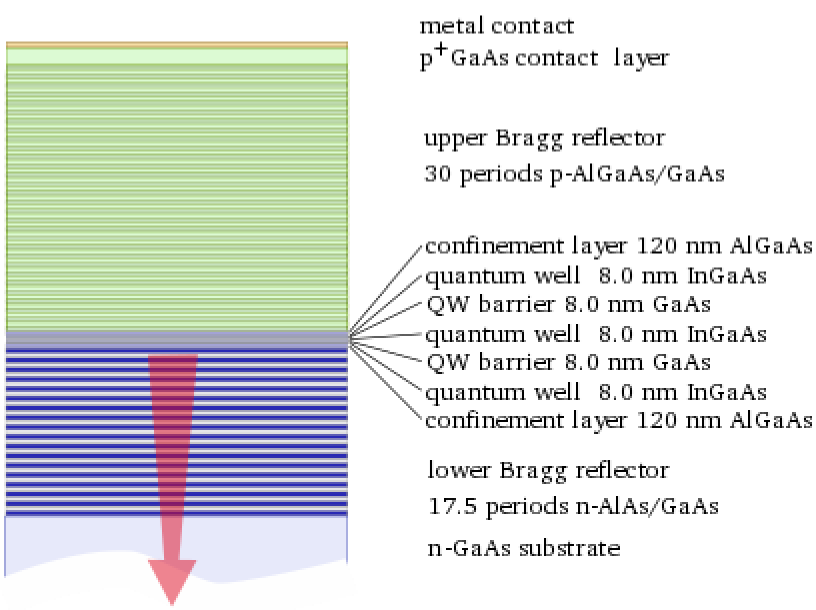
Diode Pumping

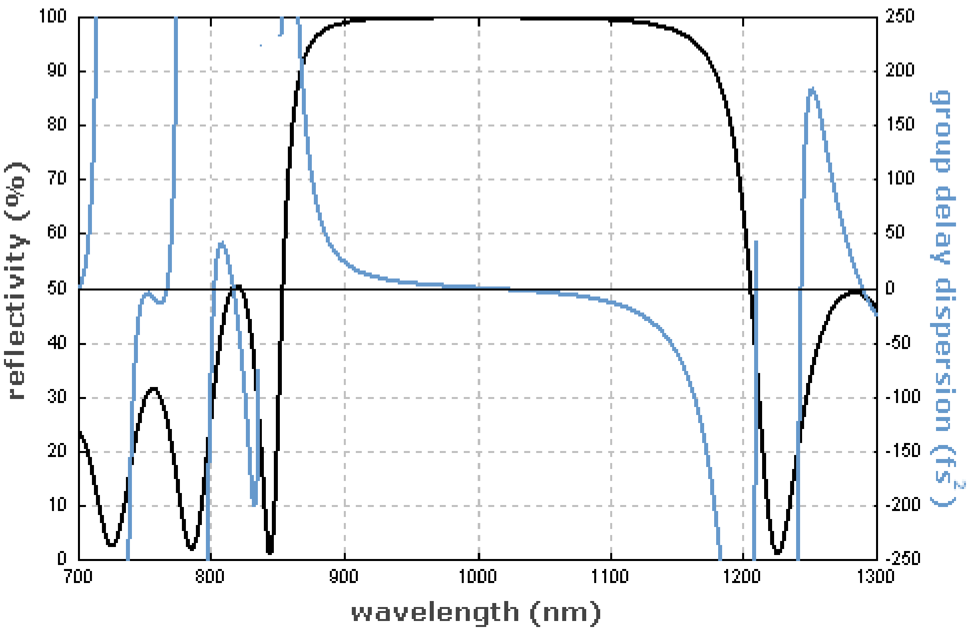
- Used as pump medium (poor beam quality)
- Diode lasers use Distributed Bragg Reflectors (DBR)
- Power up to ~100 [W]; Wall plug efficiency ~ 51 [%]



Distributed Bragg Reflectors

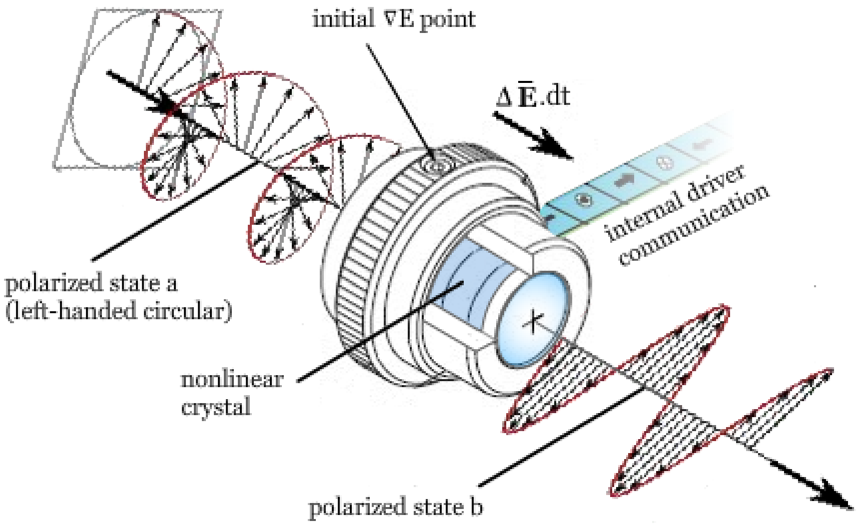
- Designed For Specific Range of Wavelengths
- High Optical Amplification On Small Area



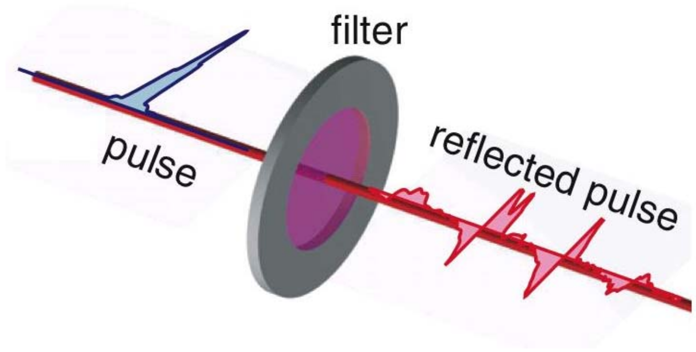


Pulse Generation (Q-Switching)

Pockel Cell + Polarizer Disk



General Pockel Cell Layout

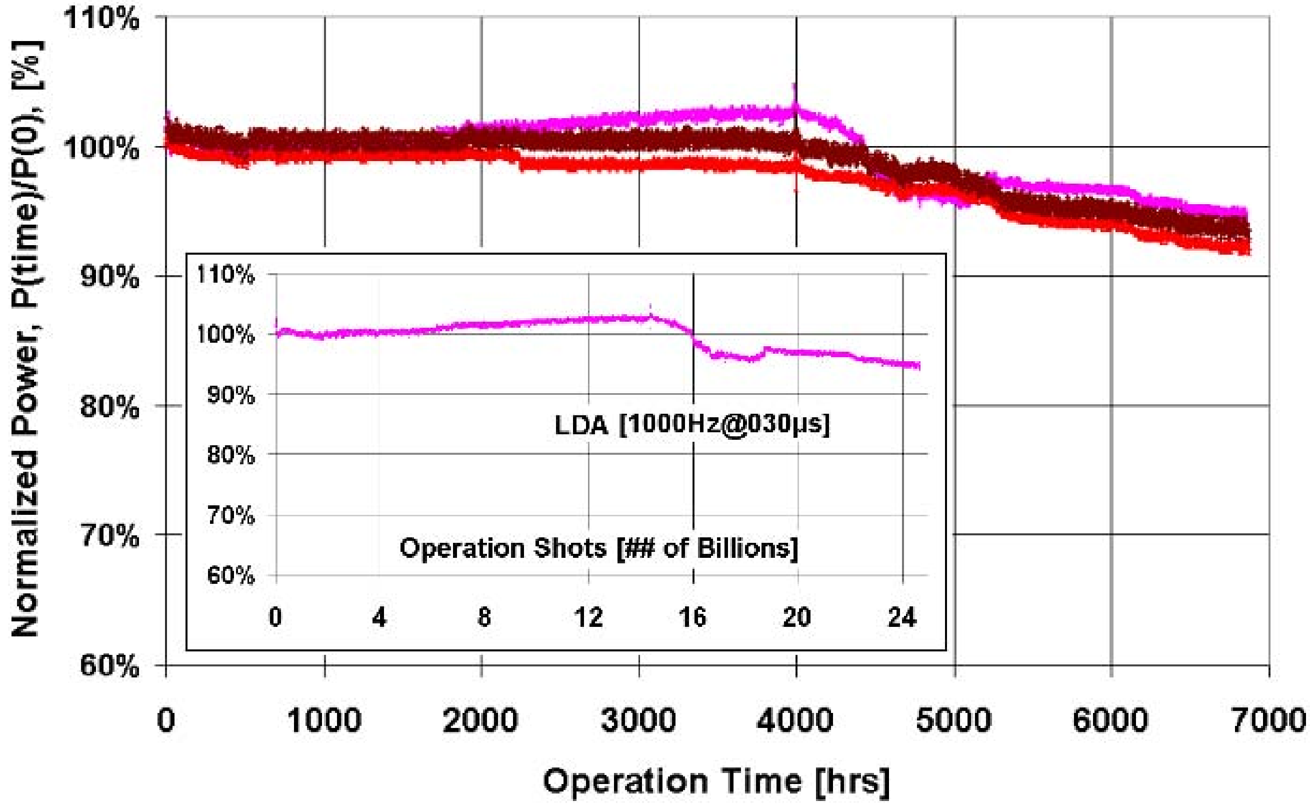


Polarizer Disk Acting As Filter To Create Pulses

Generation of pulses creates high peak powers ~ 100,000 [W]. Laser components should be designed to withstand high energetic loads.

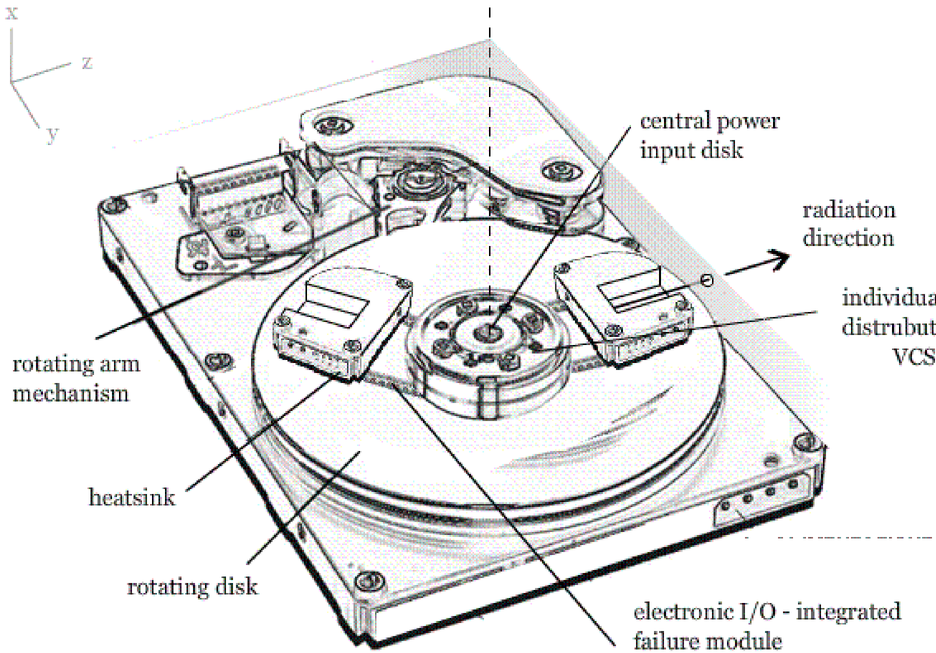
Expected Diode Laser Lifetime

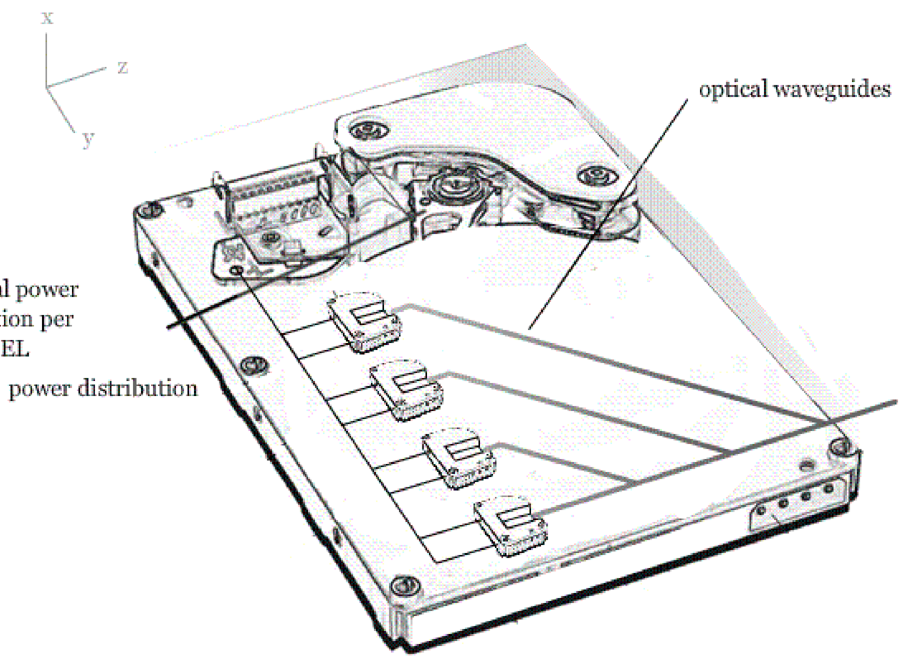
With a repetition rate of 5,000 [Hz] 788.4 billion pulses are needed



Multiple Laser Diodes : Laser Diode Arrays

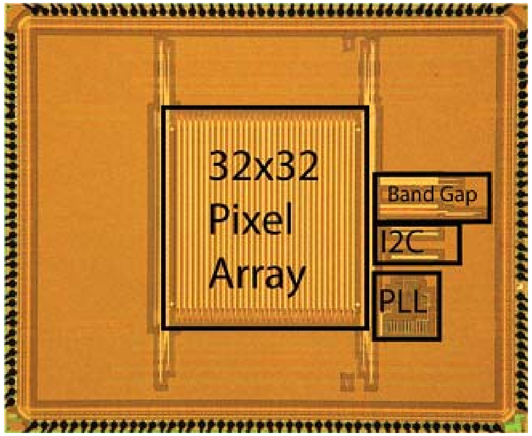
5 year in-orbit means ~ 800,000,000,000 shots
1 laser diode array ~ 30,000,000,000 shots
Number of laser diode arrays on matrix = 800/30 ≈ 27

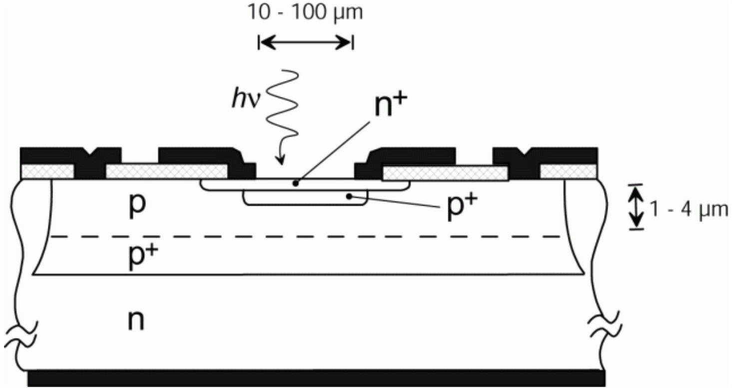




Single Photon Avalanche Diodes

- Space-graded reversed biased PN-junction
- Applied voltage (Va) above breakdown voltage (Vb)
- Single photons create detectable current due to avalanche

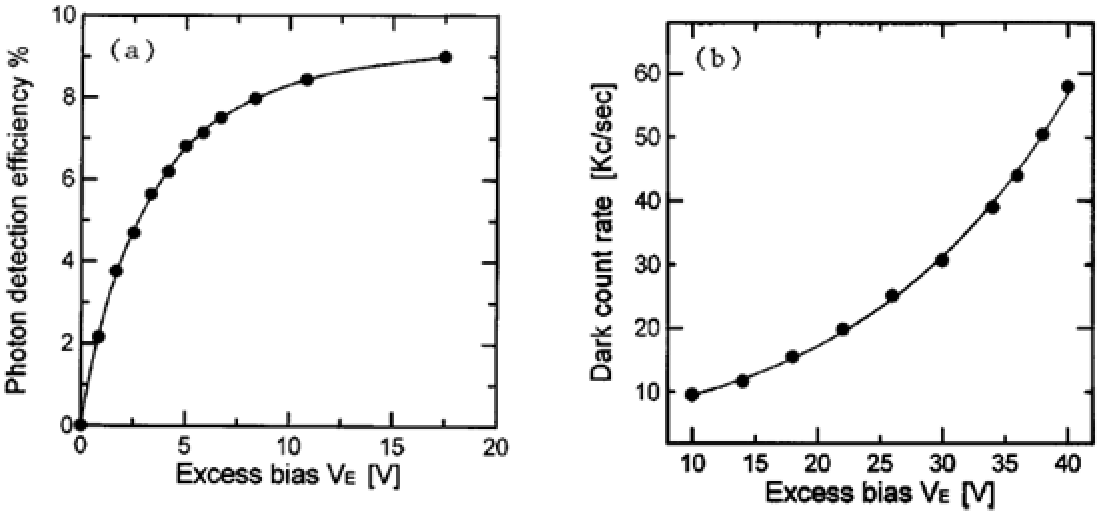




Single Photon Avalanche Diodes

- Excess electrical field Ve determines characteristics
- Ve = (Va – Vb)

- Increase in temperature causes increase in dark count rate



1.

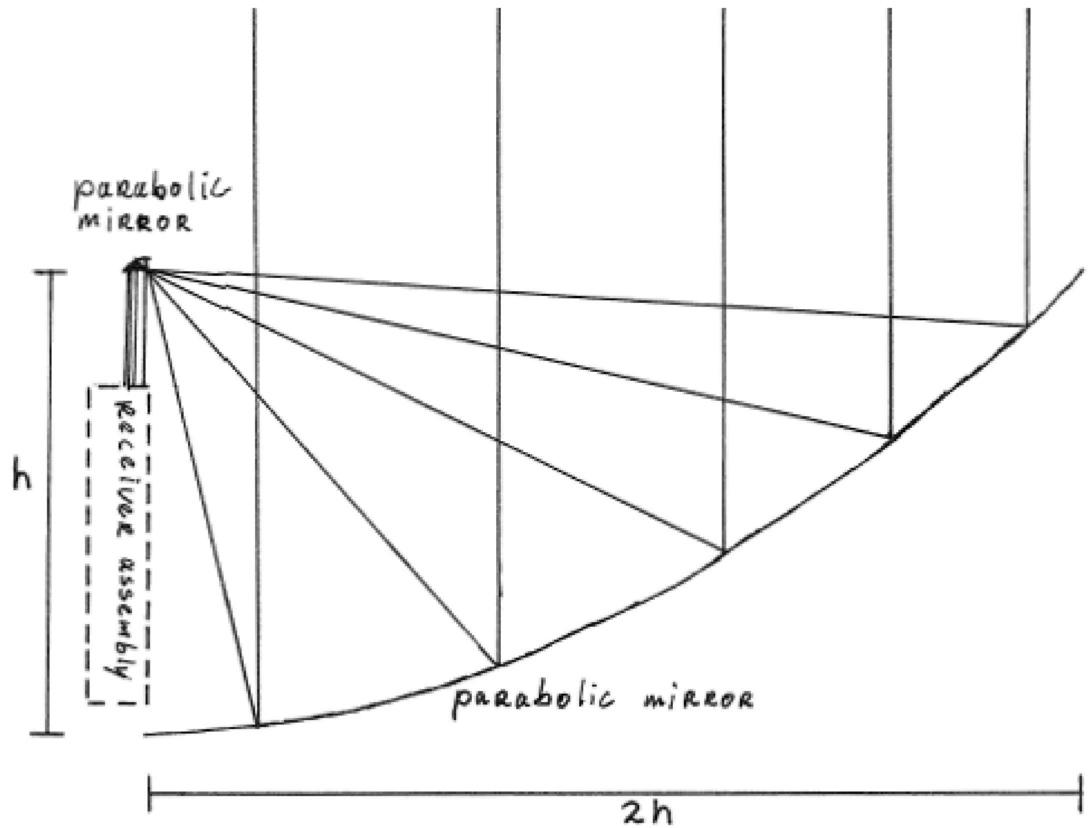
Subsystem Design

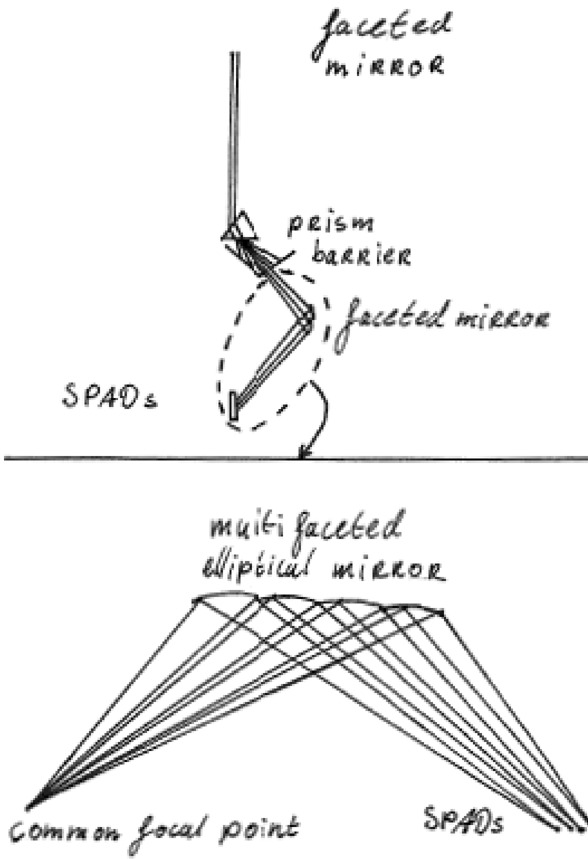
- *Communications*
- *Navigation & data storage*
- *Attitude determination & control system*
- *Electrical power system*
- *Laser*
- *Optics Payload*

Optics Payload

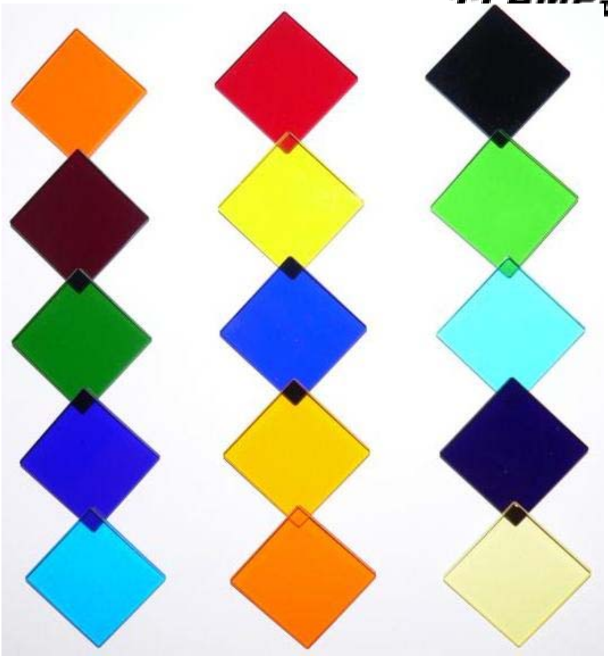
- Prism Design
  - Optical filter
  - Prism variables
  - Angle calculation
- Optical Focus
  - Idea
  - Results
- Payload cost (emitter and receiver)

Optical System





Prism Design



Optical Filter

- Simple
- Accuracy in terms of 10nm (minimum 8nm)
- Low transmittance for high accuracy (50%-60% for 10nm)

Prism Design

α = Incident angle

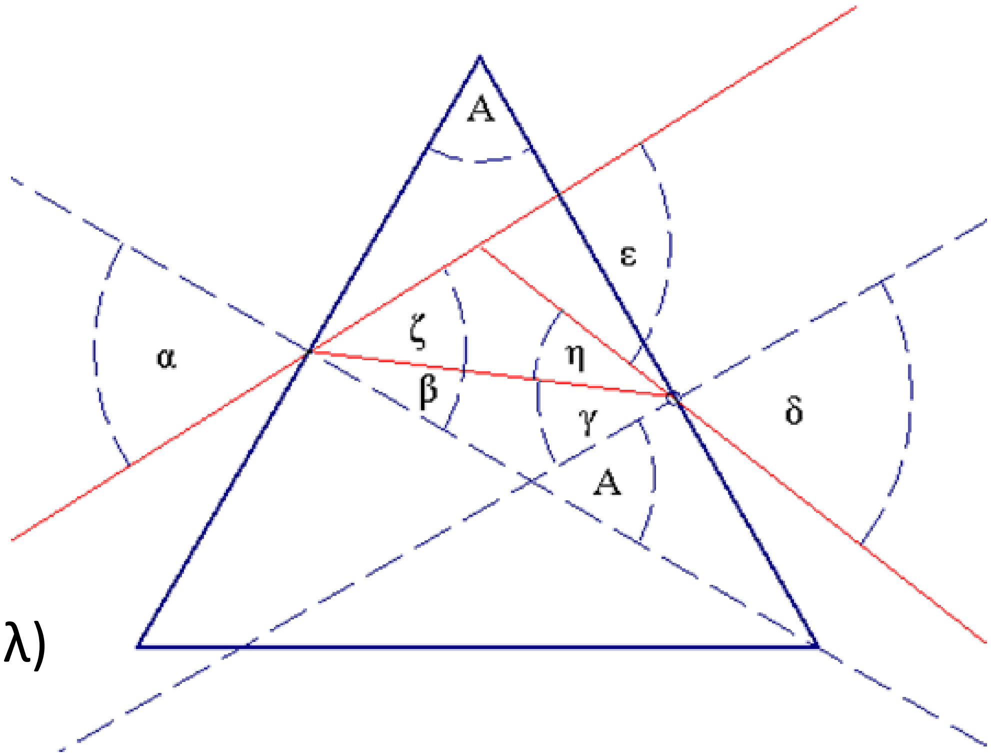
A = Apex angle

n = Index of refraction = f(λ)

ε = Deviation angle = f(α, A, λ)

Different λ leads to different ε

Maximize: $d\varepsilon/d\lambda$



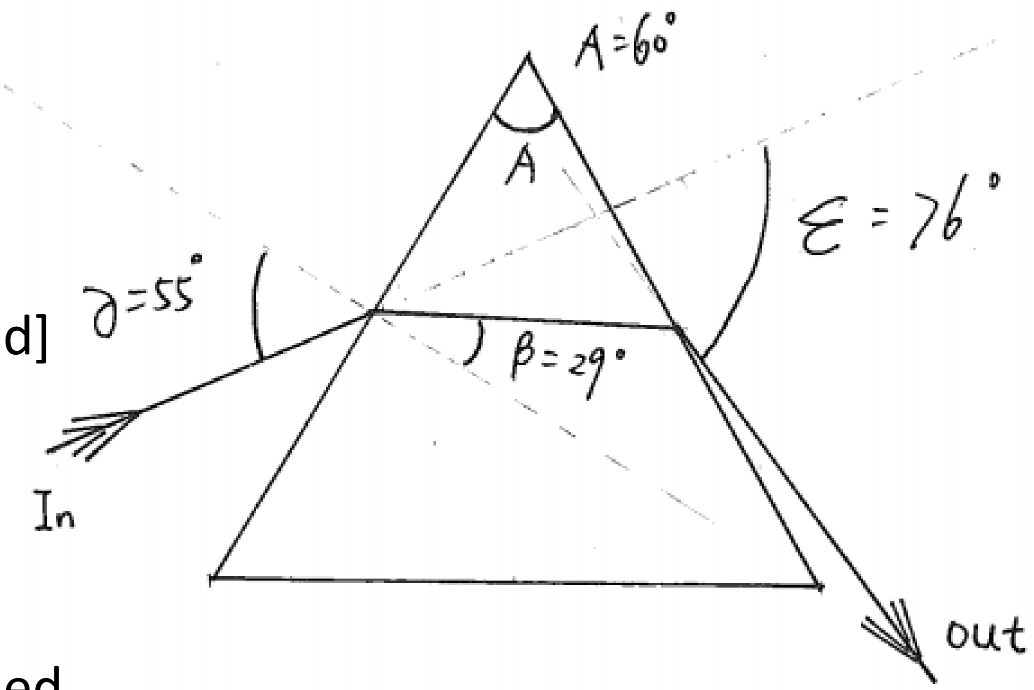
Prism Design

Glass SF11

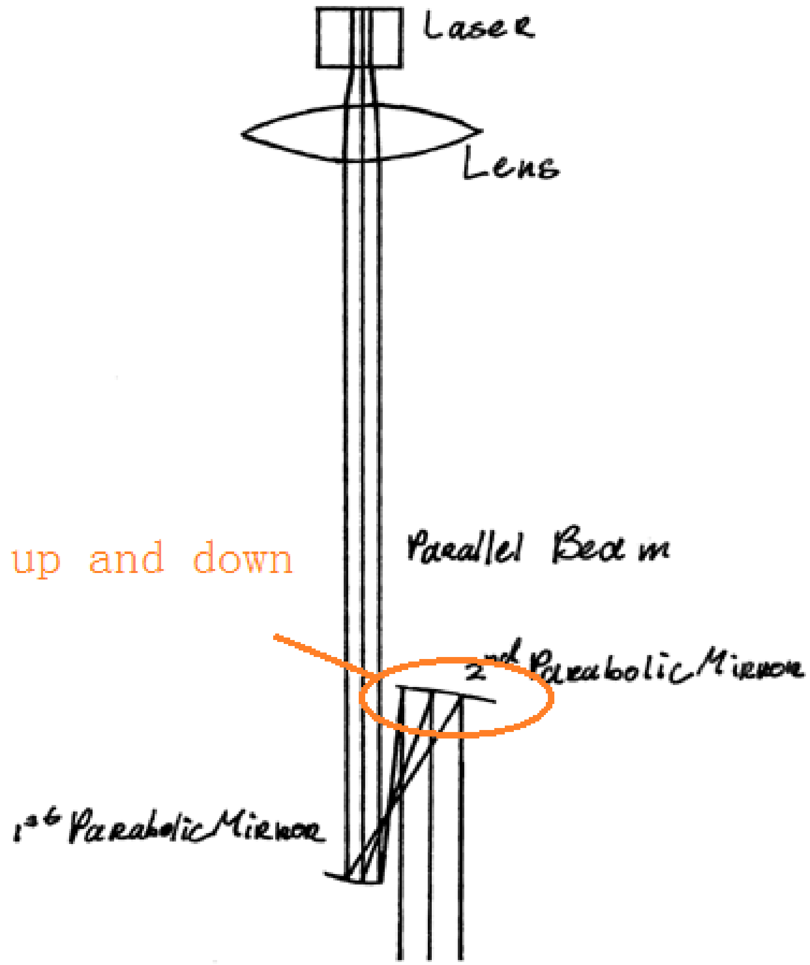
Largest dε/dλ = 2.14[mrad]

1 mm beam width
467mm distance

Flat mirrors are still needed



Laser Optical Focus

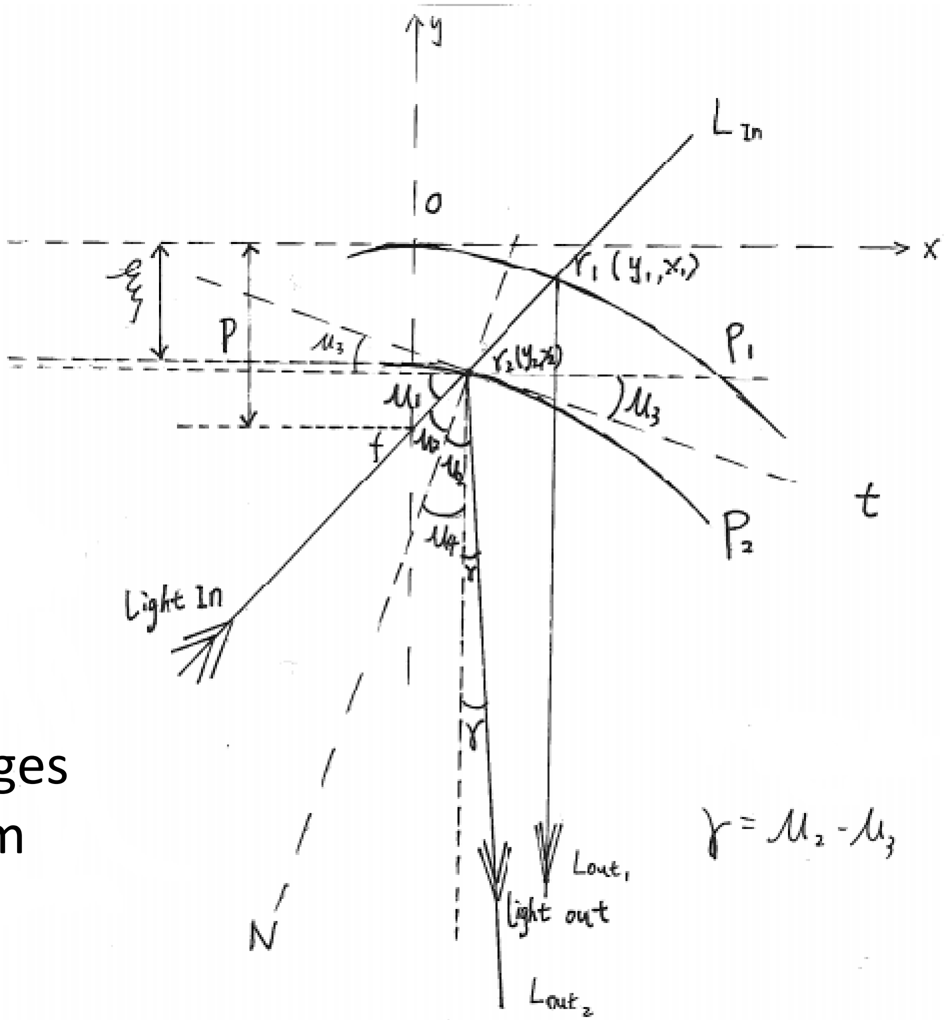


Laser Optical Focus

p = Focus length

γ = Divergence

ξ = Movement length



Changing ξ by 1 mm changes the footprint size by 20.4 m
(not considering diffraction)

Payload Cost Estimation

	Electrical Engineering	System Engineering	Quality Engineering	Material Engineering	Software Engineering	Mechanical Engineering	Optical Engineering	Thermal Engineering	Assessment Manager	General Manager	Subtotal [M$]
SPAD	2	1	1	1	2	1	0	0	1	1	1.8357
Optics	0	1	1	2	0	1	1	0	1	0	0.97904
laser	3	1	2	2	2	2	3	1	1	1	2.32522
Cost [M$]	0.61	0.37	0.49	0.61	0.49	0.49	0.49	0.12	0.73	0.73	5.13996 (a)

	Integration and Test	Space Qualification Test	Product Assurance	Material Cost	Facilities/Machine	Subtotal [M$]
Receiver [M$]	0.24	0.3	0.15	0.01	0.5	1.2
laser [M$]	0.72	0.3	0.15	0.05	0.5	1.72
Cost [M$]	0.96	0.6	0.3	0.06	1	2.92 (b)

	Unit Cost	5 Receiver	9 Receiver
Receiver [M$]	0.034	0.15	0.26
laser [M$]	0.122	0.34	0.34
Cost [M$]	0.156	0.49 (c)	0.6 (d)
Total [M$]		8.55	8.66
Total [FY00M$]		6.98	7.07

8. 66 [M$]

Summary

- Prism is used
- Parabolic mirrors are used to adjust footprint size

2.

Orbital Design

Astrodynamics

- Launch Segment
- Space Segment
- Environment

Launch Segment

Launch vehicle

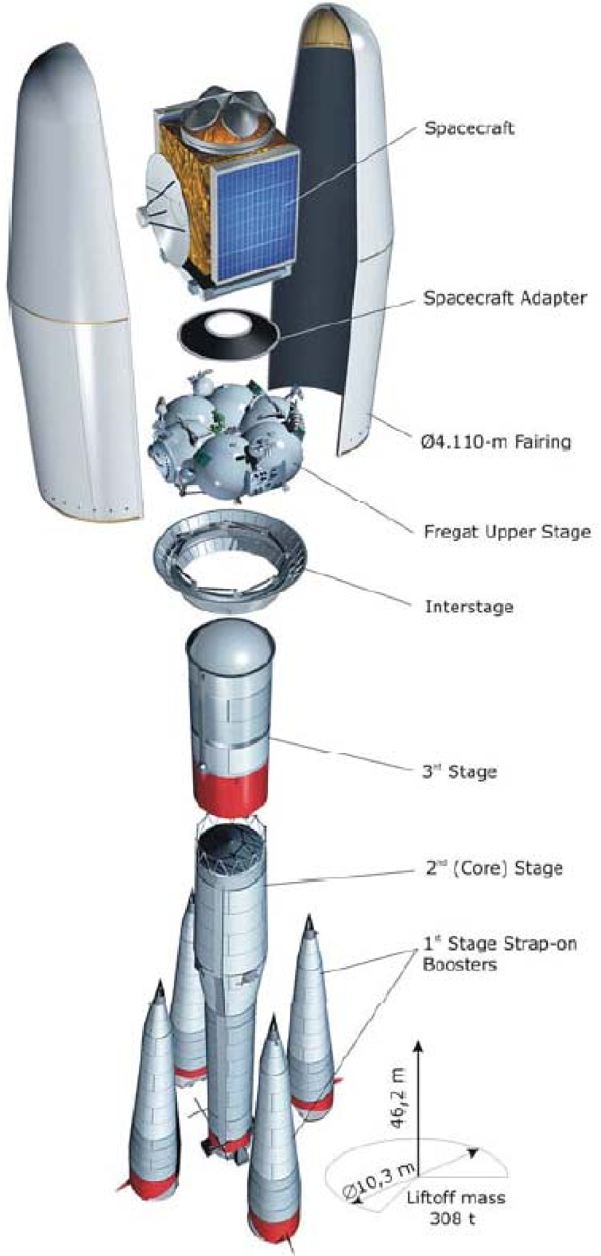
- Payload mass capability
- Payload space capability
- Orbit insertion accuracy
- Safety
- Reliability
- Cost

Launch Segment

Launch vehicle

Soyuz ST

- 4000 kg to LEO
- Large fairing to accommodate all satellites
- Inclination at 0.03 degree accuracy
- Low vibrations
- Over 1700 successful launches
- $ 18 million launch



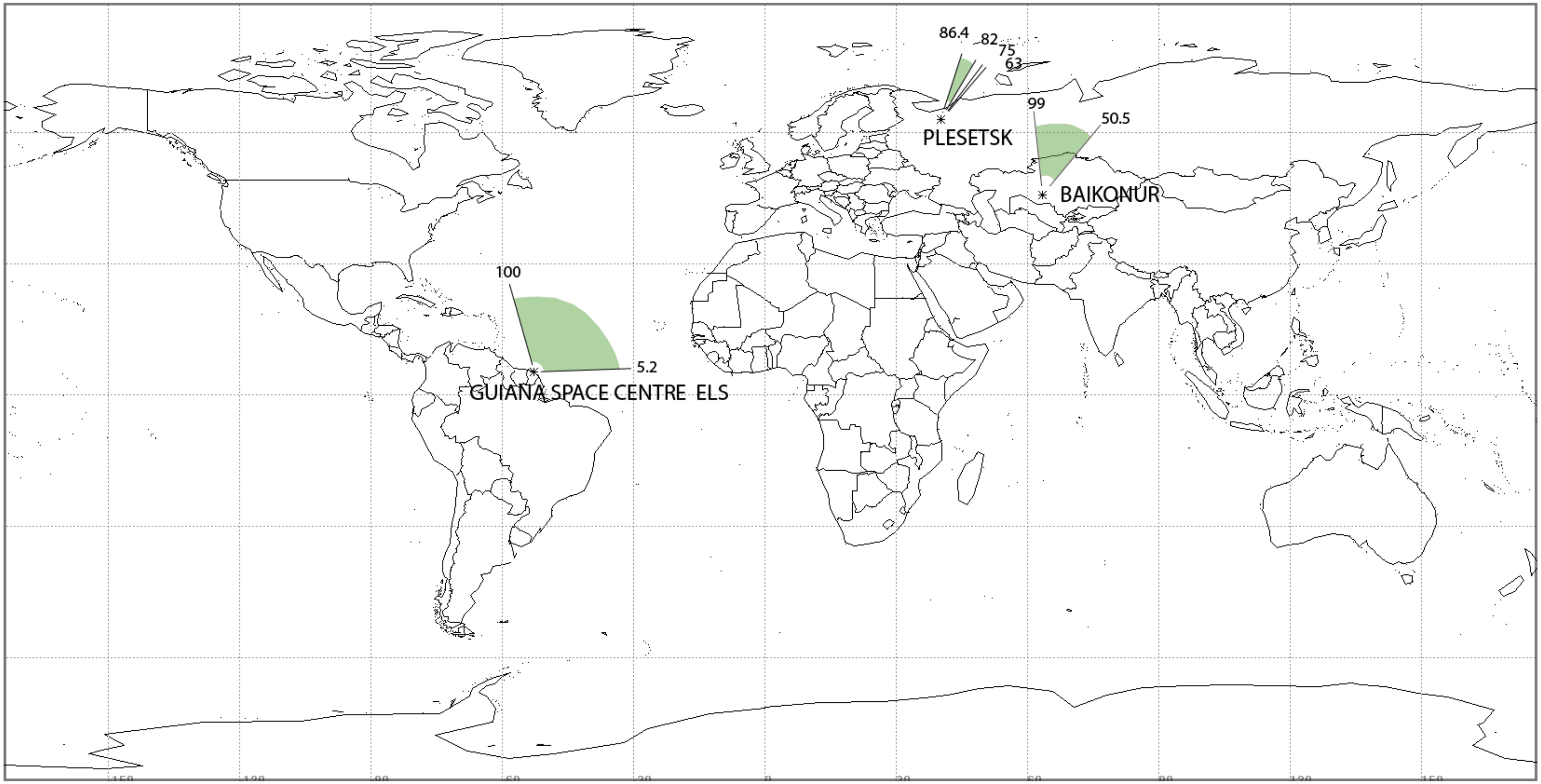
Launch Segment

Launch site

- Availability of inclination
- Compatibility with the LV
- Accessibility and cost
- Security and political situation

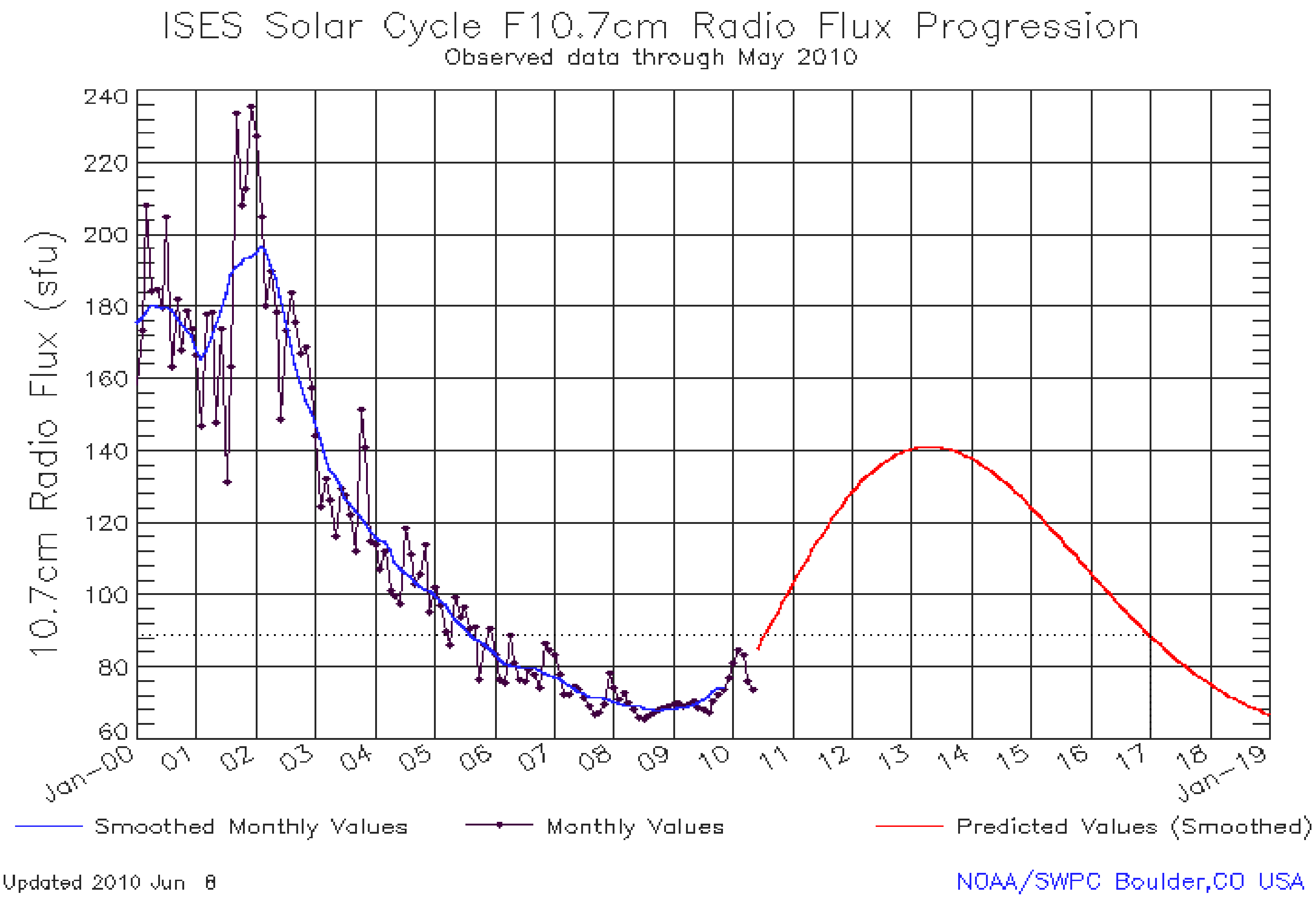
Launch Segment

Launch site



Launch Segment

Launch date



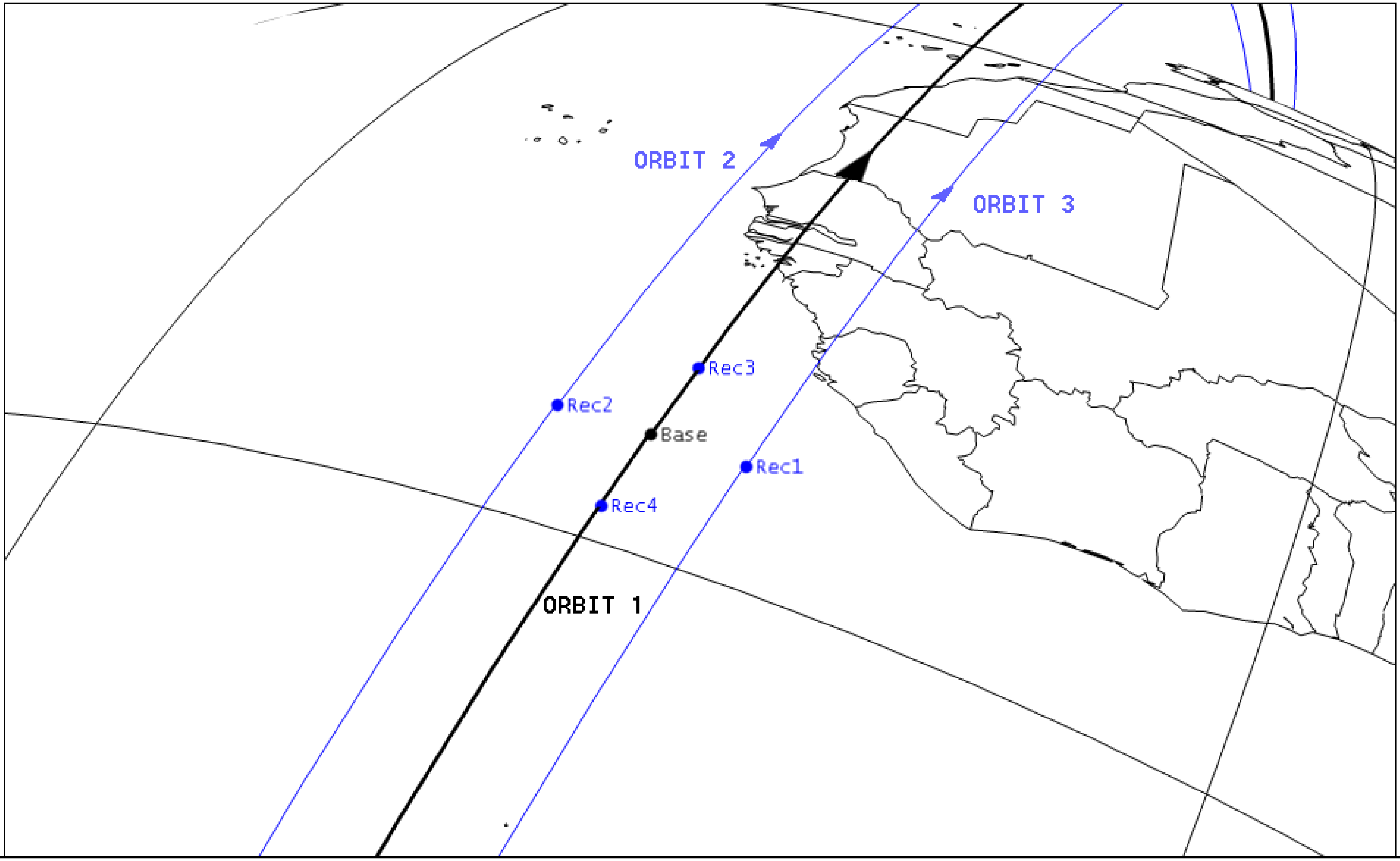
Space Segment
Orbits

Primary Orbits:
- Altitude:
  500 km
- Period:
  94.61 min
- Precession:
  -0.6667 deg/day

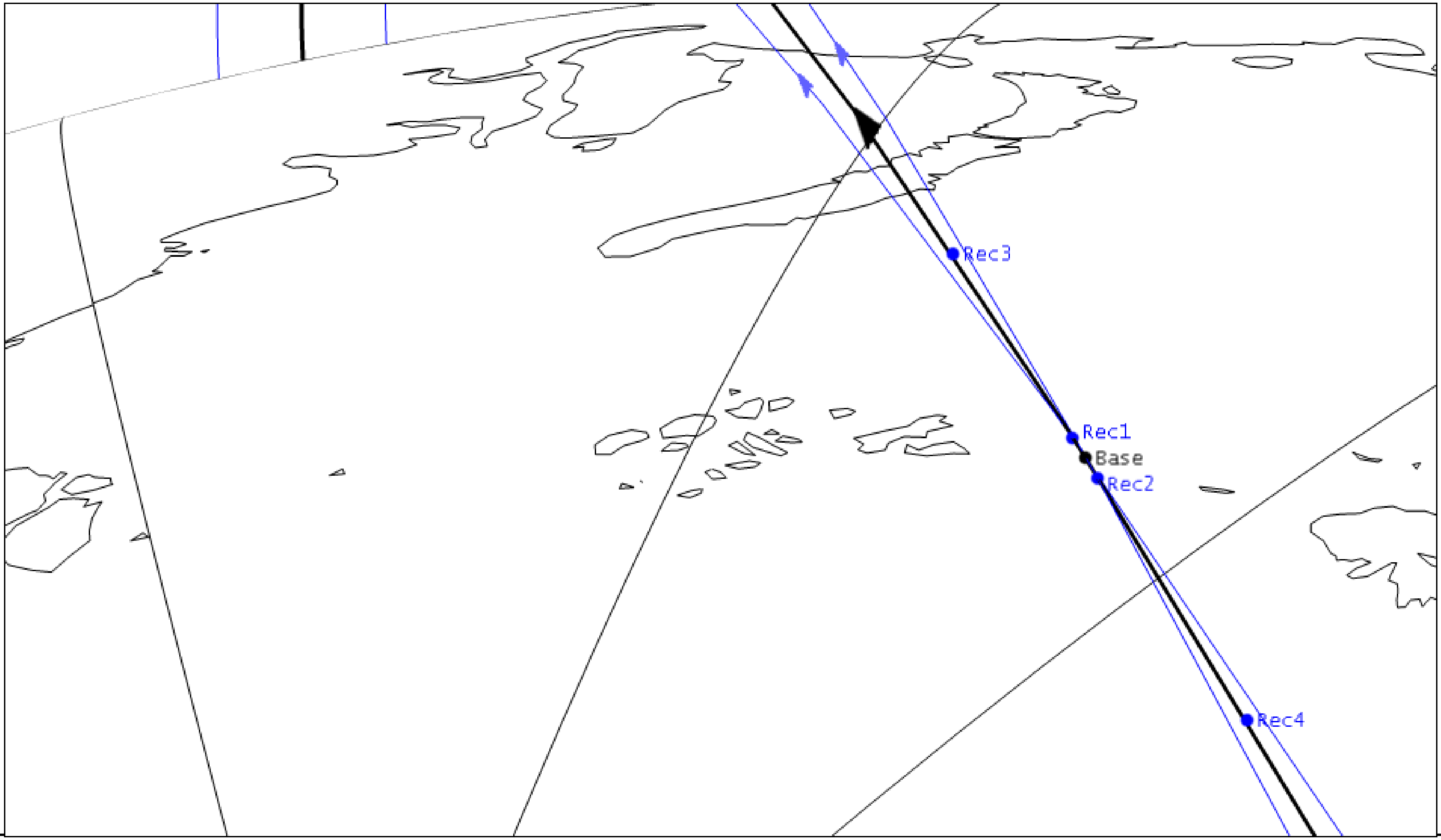
Secondary Orbits:
- Altitude:
  525 km
- Period:
  95.12 min
- Precession:
  -0.6584 deg/day

Space Segment

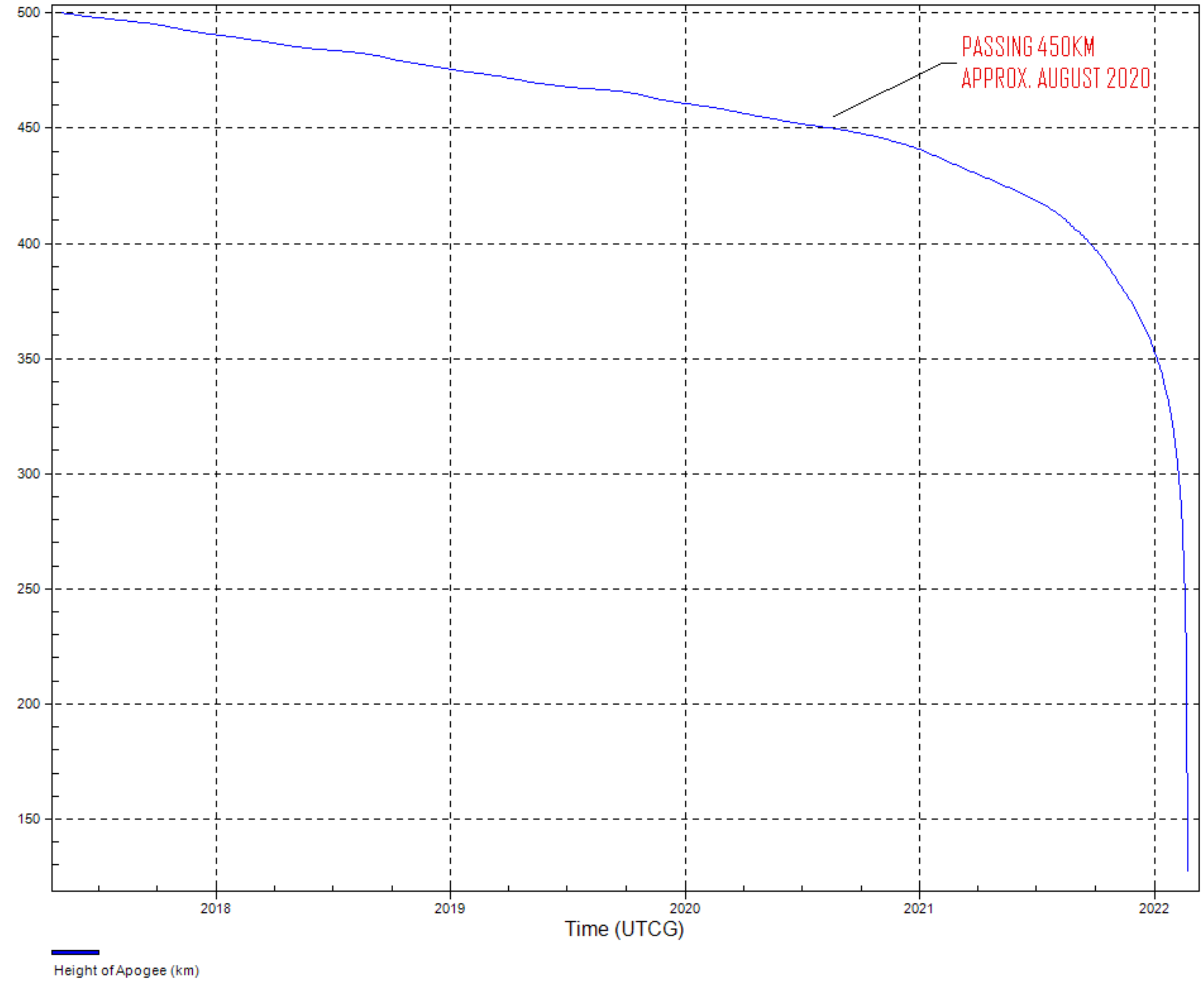
Configuration



Space Segment
Configuration



Space Segment
Configuration

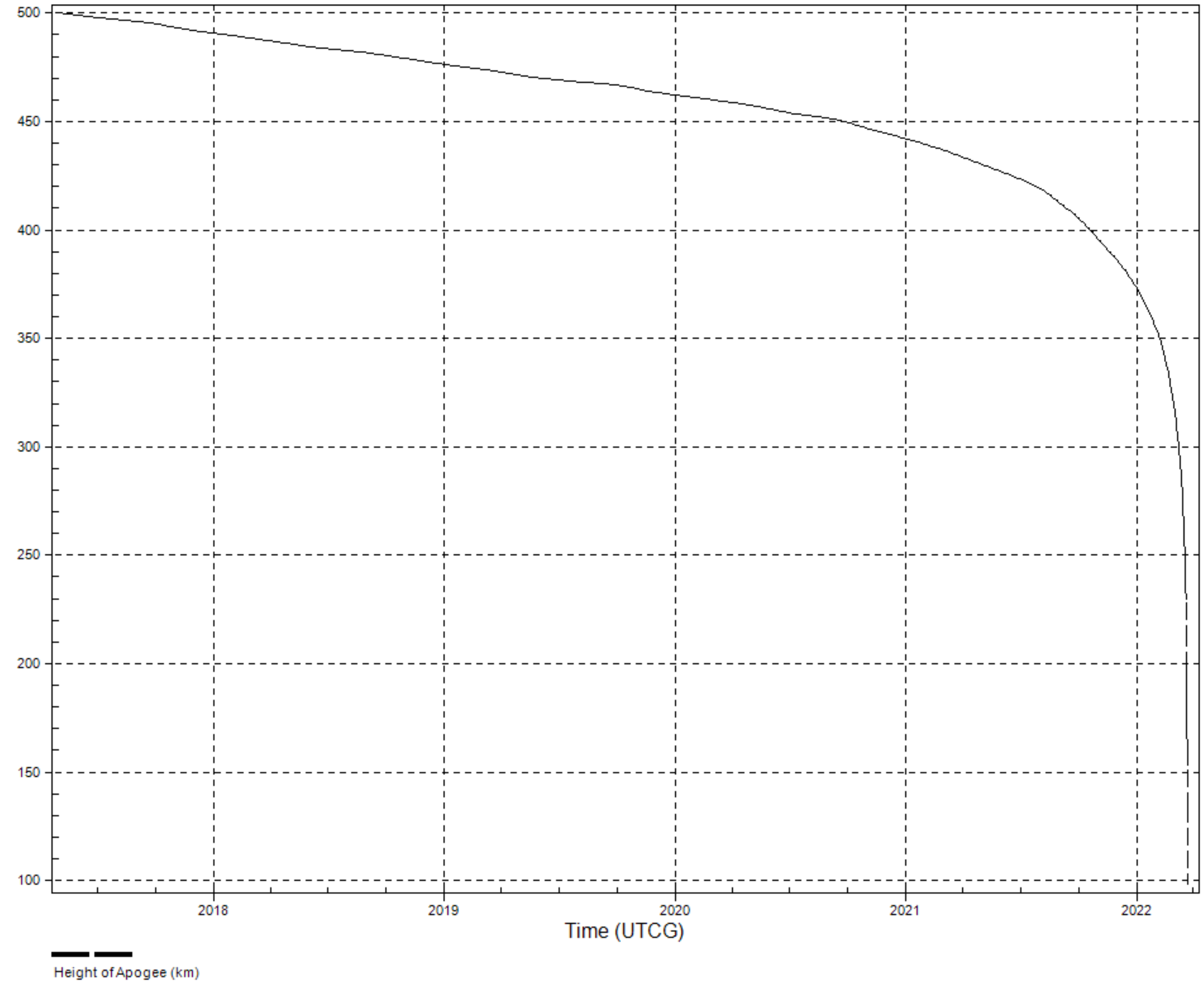


$C_d = 2.22$
$M_{orbit} = 53.1$ kg
$A = 1.05\ m^2$

B.C. = 22.87 kg/m^2

Space Segment

Configuration

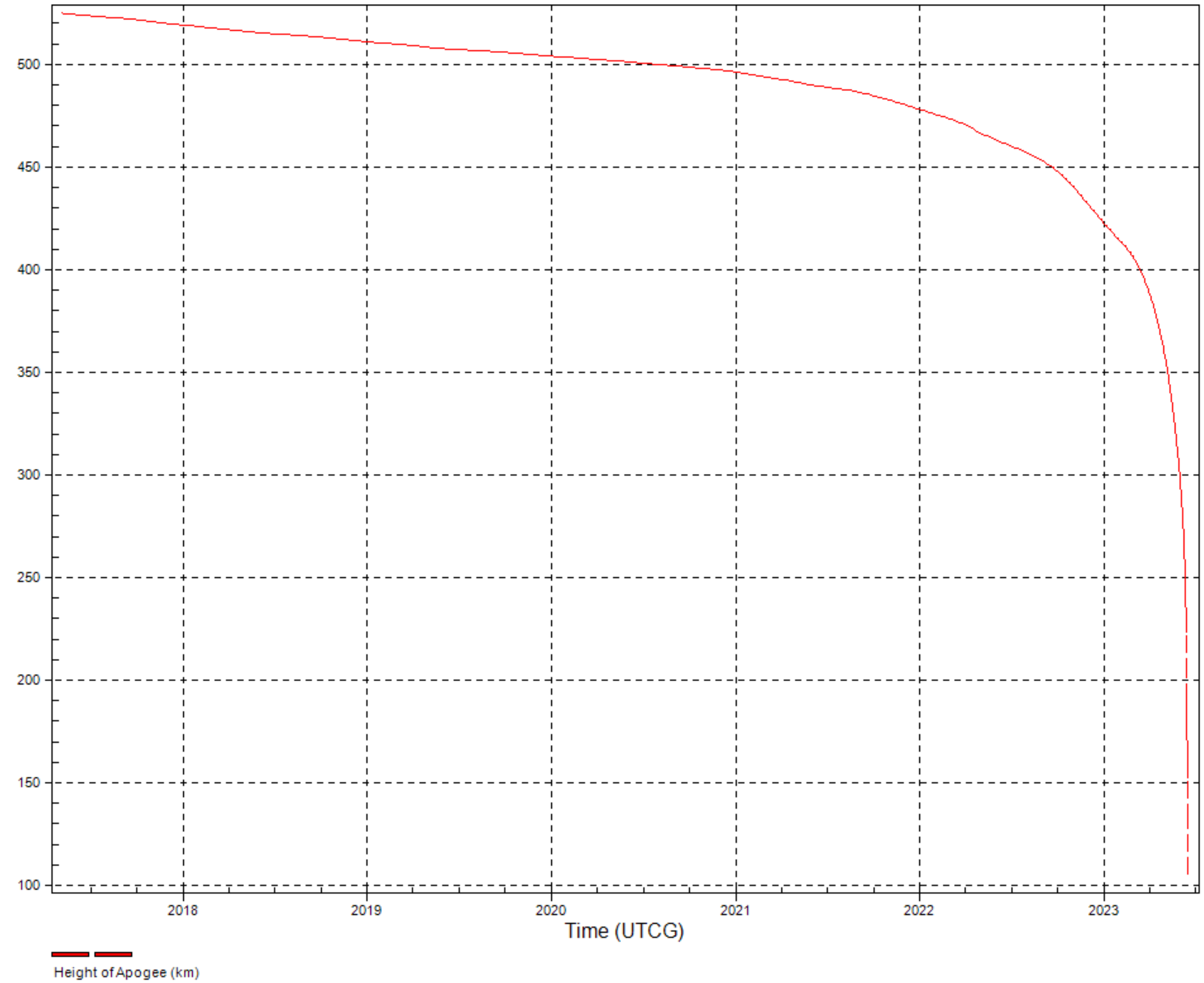


$C_d = 2.22$
$M_{orbit} = 14.92$ kg
$A = 0.3$ m^2

B.C. = 22.4 kg/m^2

Space Segment

Configuration



C_d = 2.22
M_{orbit} = 14.82 kg
A = 0.3 m^2

B.C. = 22.3 kg/m^2

Space Segment
dV

- Emitter - 225.4 m/s

- Receiver

  Primary: from 133.6 – 165.14 m/s

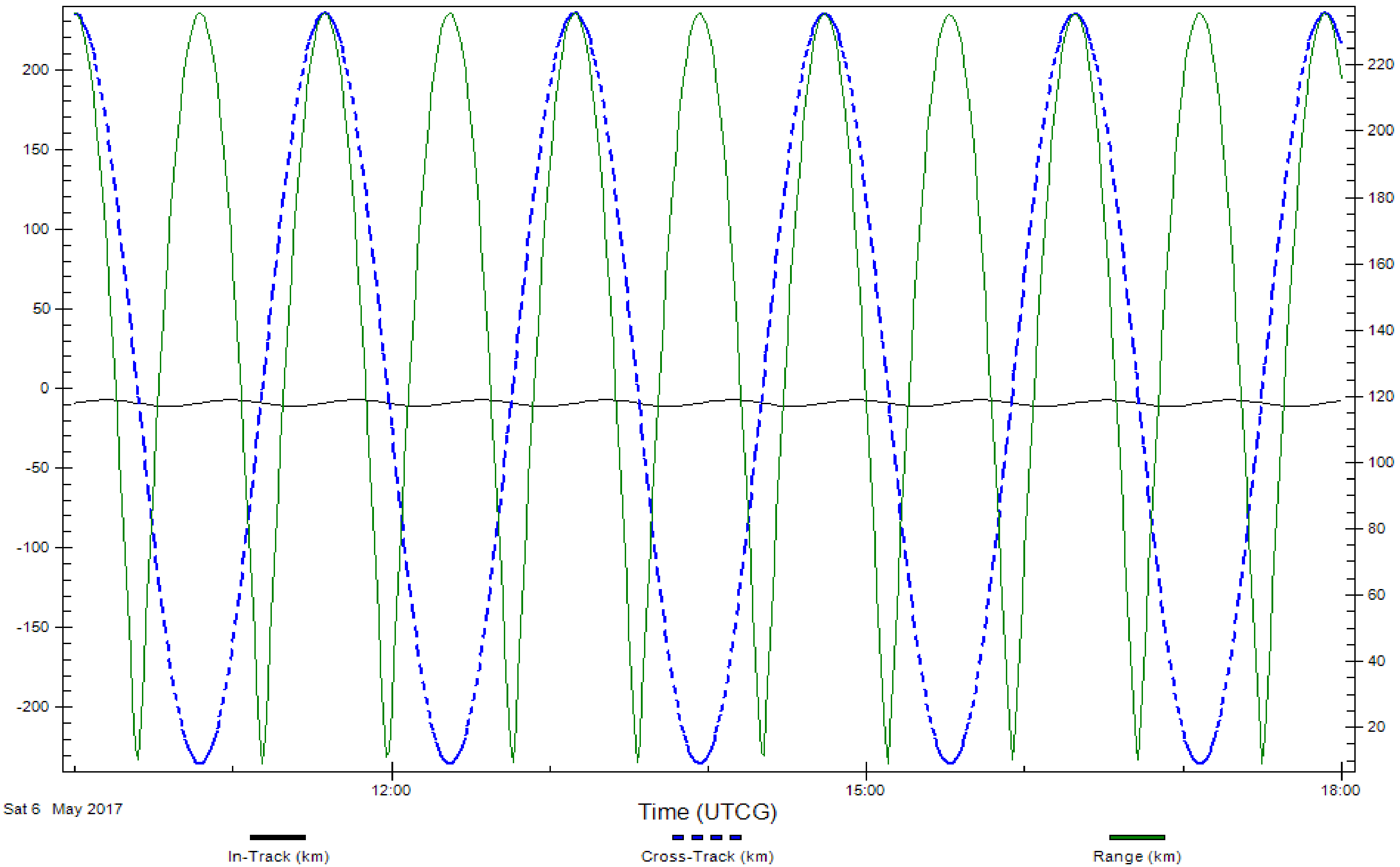
  In Orbit: 128.73 ± 4 m/s

  Secondary: from 105.75 – 137.28 m/s

  In Orbit: 100.93 ± 4 m/s

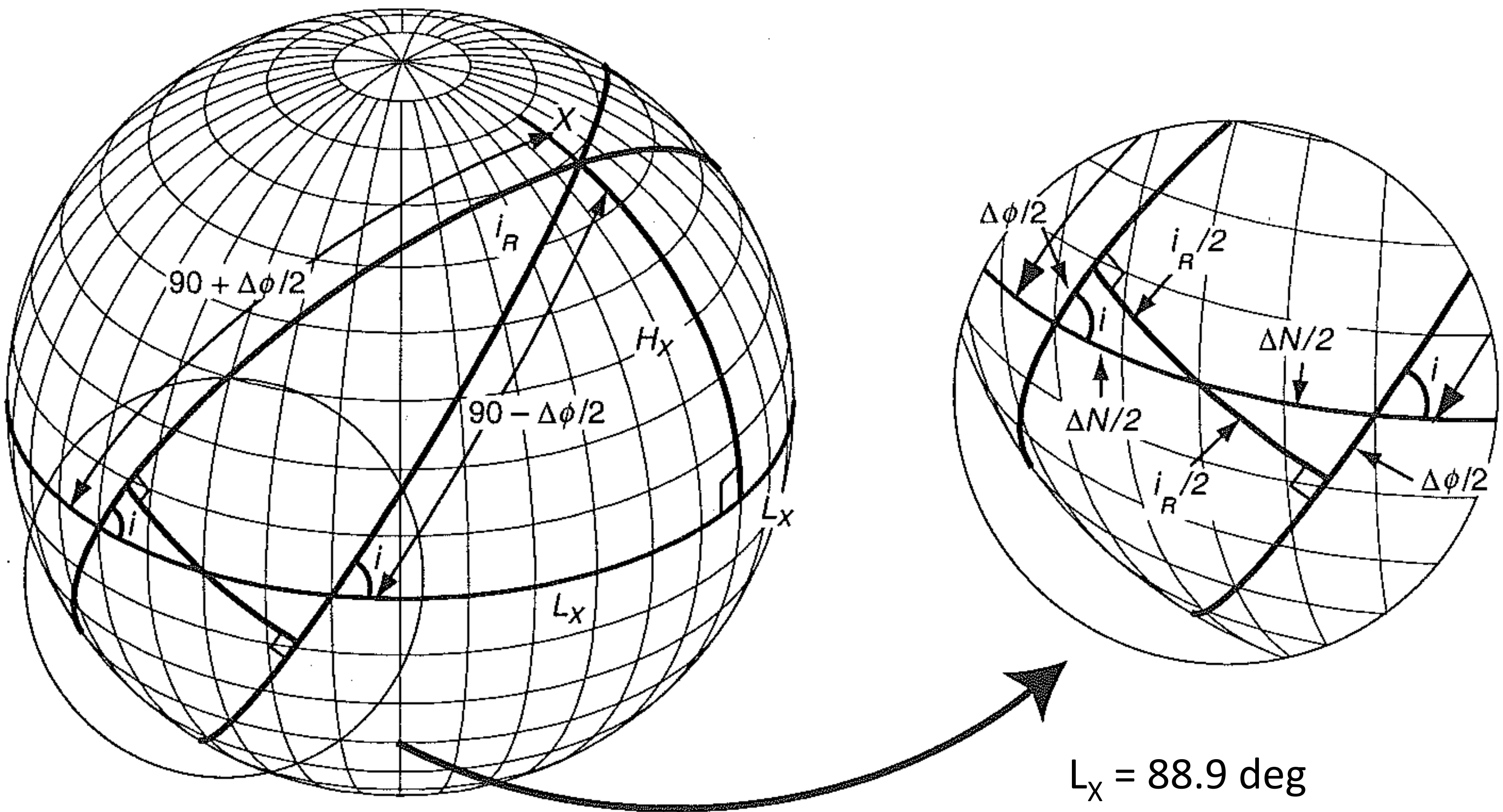
Space Segment

Orbits



Space Segment

Orbits



L_X = 88.9 deg
H_X = 85 deg

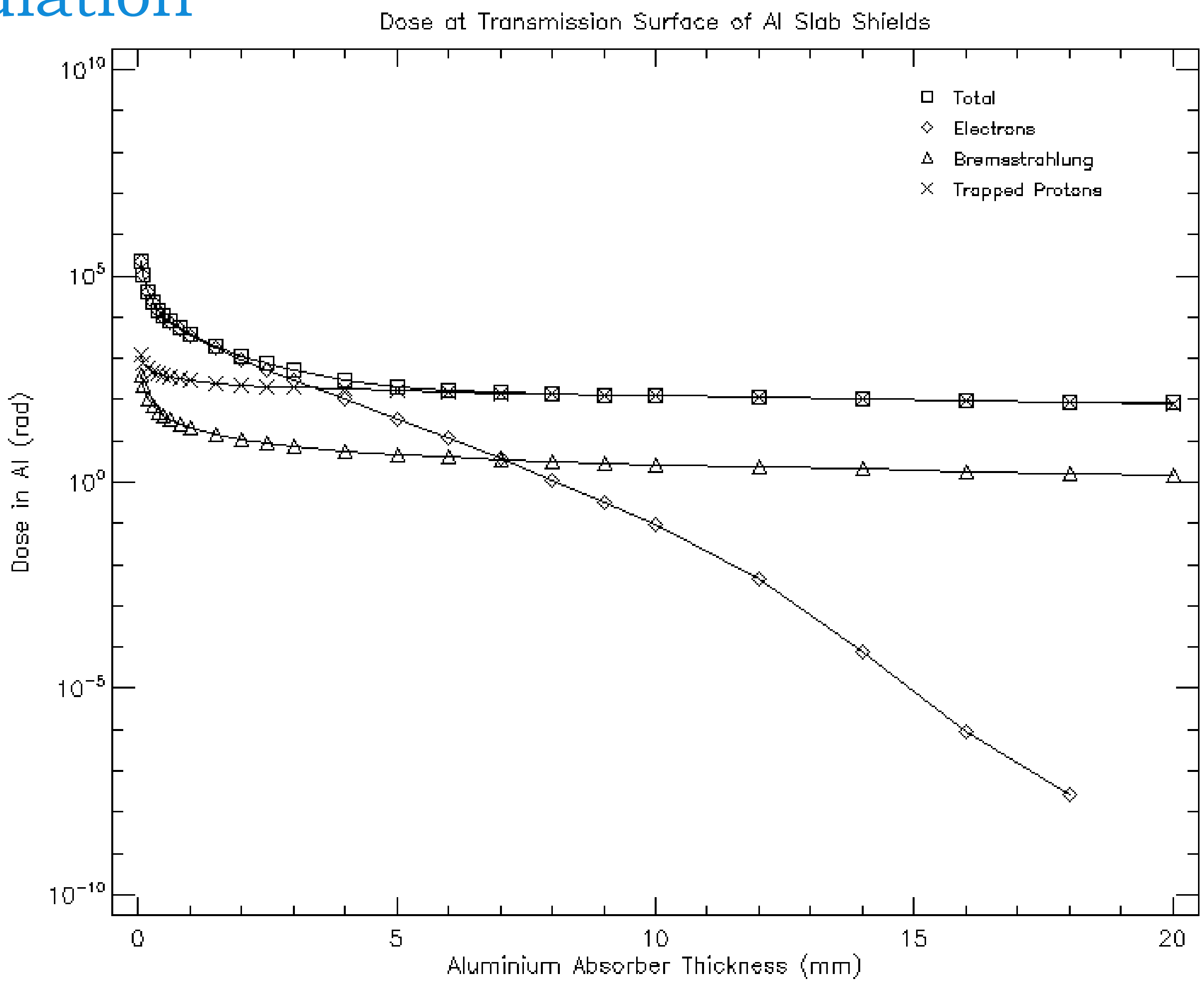
Space Segment
Stationkeeping

- Principle of differential drag.
  (Successfully demonstrated by the ORBCOMM constellation)

- Automated systems are necessary.

Environment

Radiation



3.

Software tool

Simulation results overview

- Short simulator overview
- Optimization of Aperture and Power
- Elevation and slope modeling
- BRDF reconstruction

Short simulator overview

- Basic atmospheric model

$$I = I_0 e^{-AM \cdot optTick} \text{ and } AM = \sec(z)$$

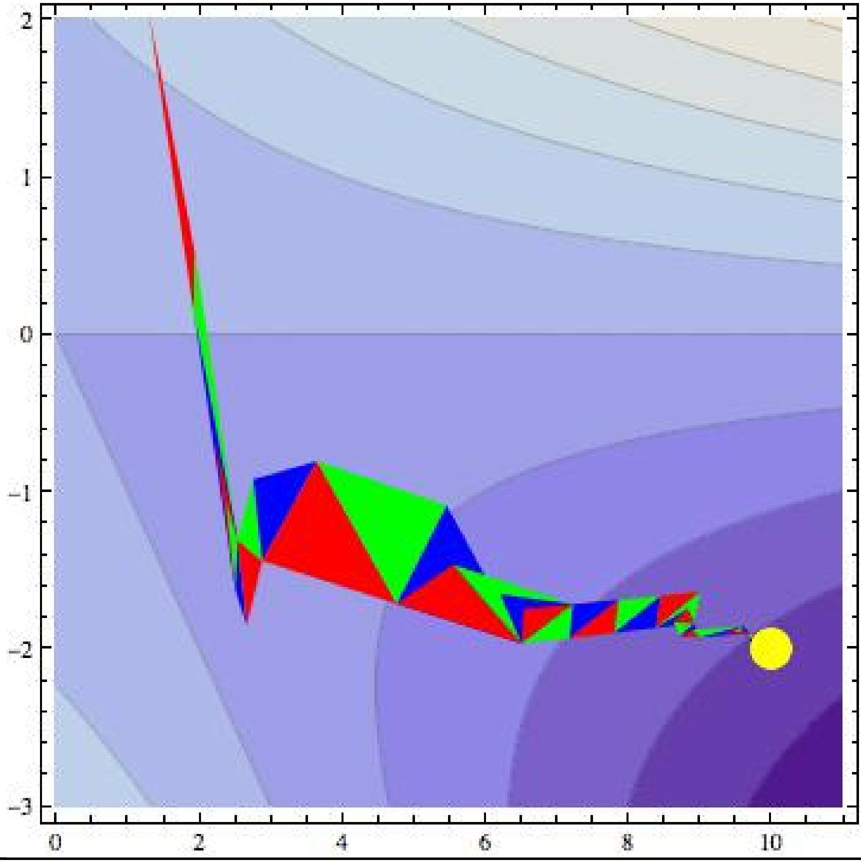
- Scattering based on
  - Lambertian
  - Minnaert parameter
  - Henyey-Greenstein

- Noise based on
  - Solar radiation
  - Sloping effects

Optimization algorithm

Nelder-Mead (Simplex) method

- Construct a simplex
  (triangle for 2 param)
- Compute functional values
- Shrink simplex
- Repeat until end conditions



Source: http://chungyuandye.wordpress.com/2009/08/09/nelder-mead-method-in-mathematica/

Power Aperture problem

- Minimize power and aperture
- Minimize aperture more than power
  (for ballistic coefficient)
- Maximize the received photons
  ⇒ target photons per satellite per pulse

Quantifying performance

- Global term
  $\Rightarrow$ global performance

- Satellite dependent term
  $\Rightarrow$ Optimize for equal reception by all satellites

$$performance = \frac{f\left(\varphi_{\text{total Rx}}, \varphi_{\text{target}} \times n_{\text{sats}}, 50\right)}{power \times aperture^{1.2}} \times \prod_{\text{sats}} f\left(\varphi_{\text{sat Rx}}, \varphi_{\text{target}}, 200\right)$$

Define f(x, mean, variance) as NormalPDF(mean, variance) evaluated at x

Optimization results

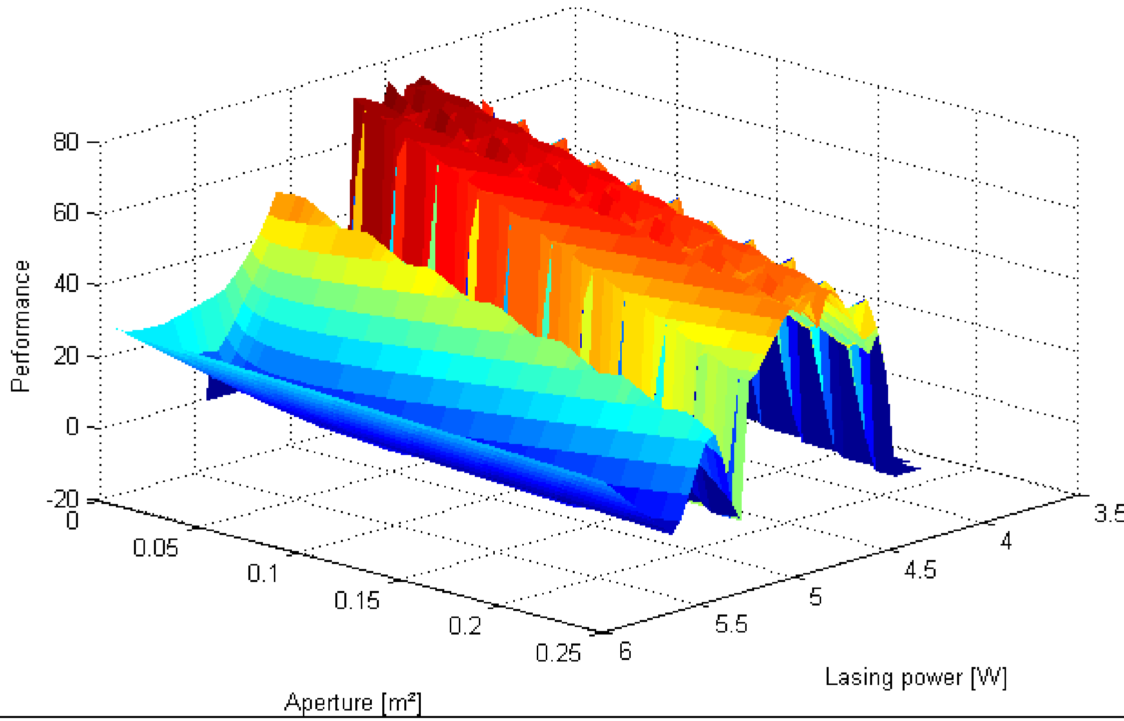
Final results:

- Power

  4.6W (5W)
- Aperture

  0.0045 m^2 (0.006m^2)

  6.7x6.7 cm (7.5x7.5cm)



Finding Elevation and Slope

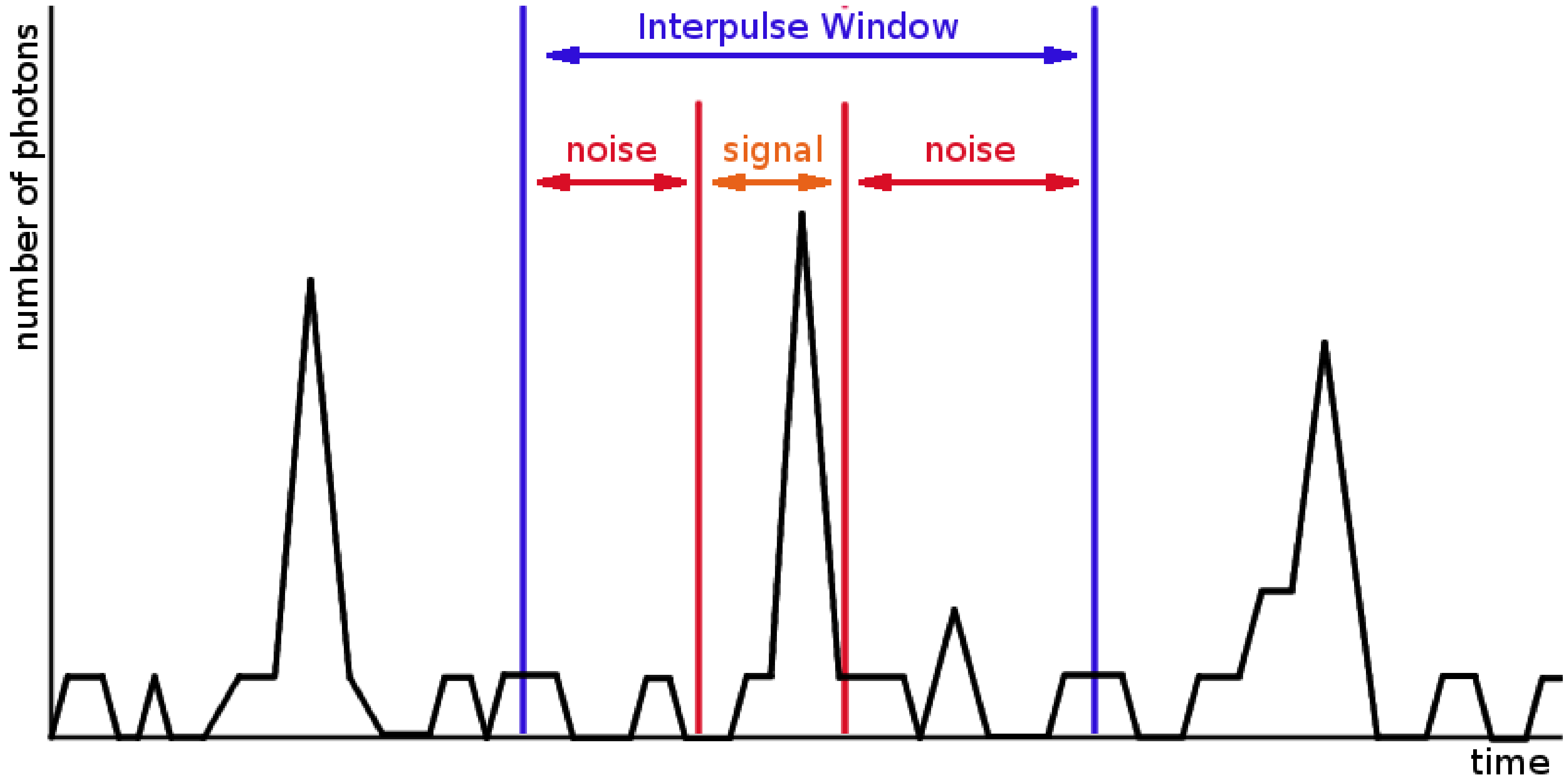
Elevation

- Windows
- Algorithms
- Tuning

Slope

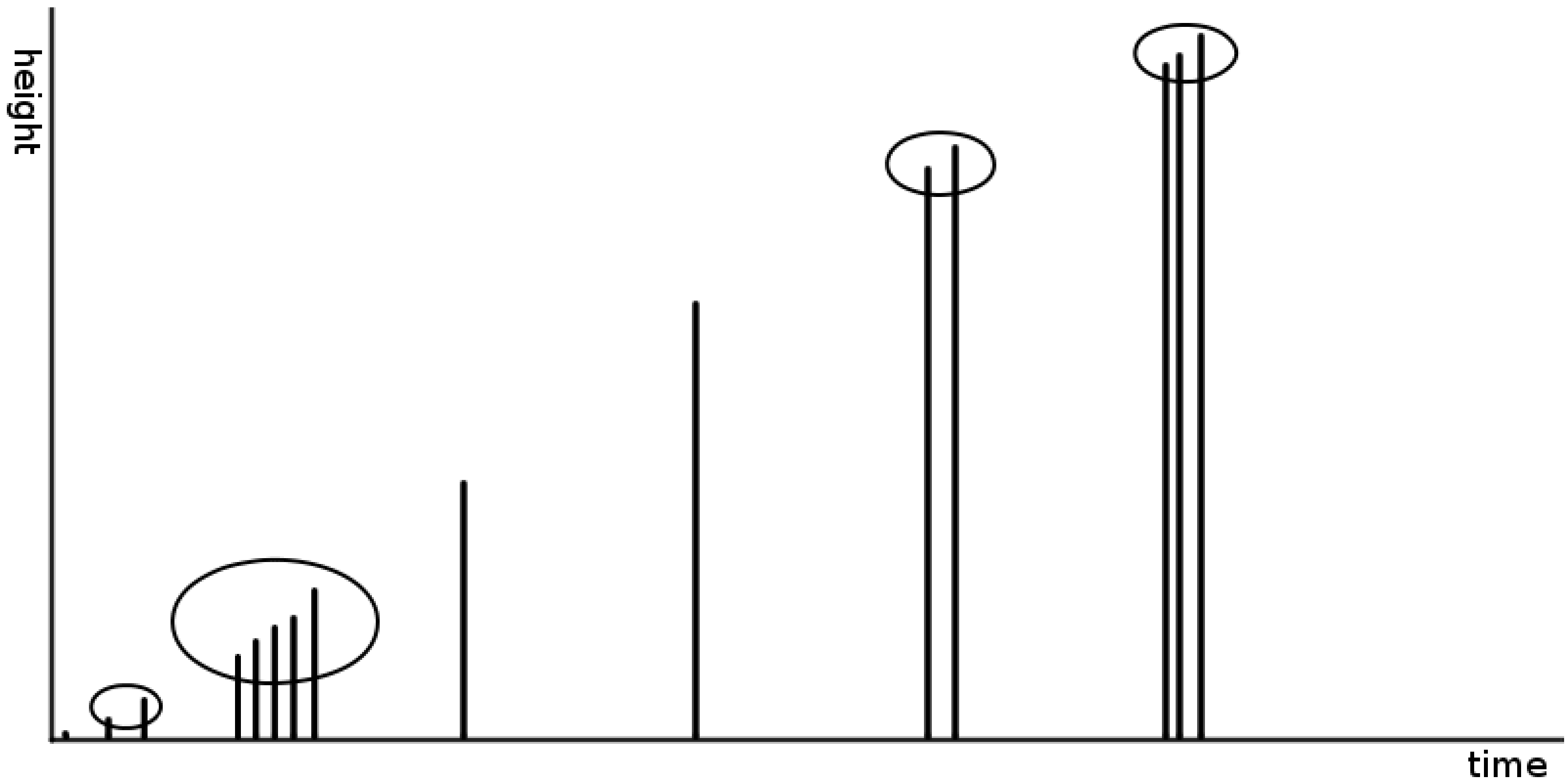
- Algorithm
- Results

Elevation
Windows



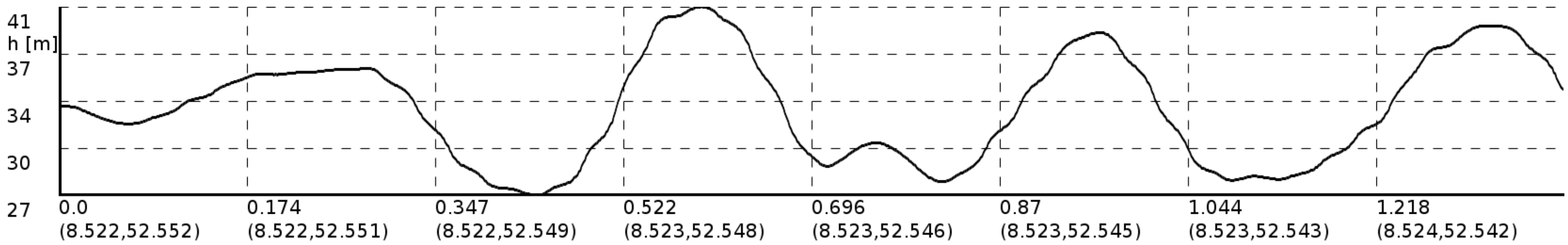
Elevation

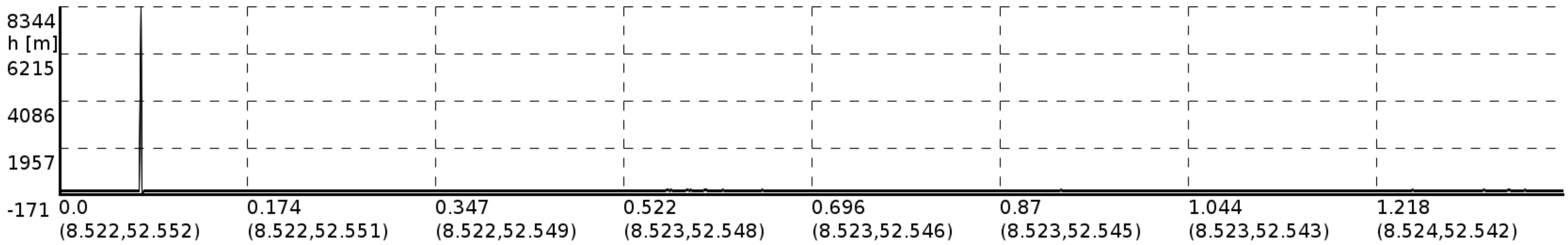
Algorithm



Elevation

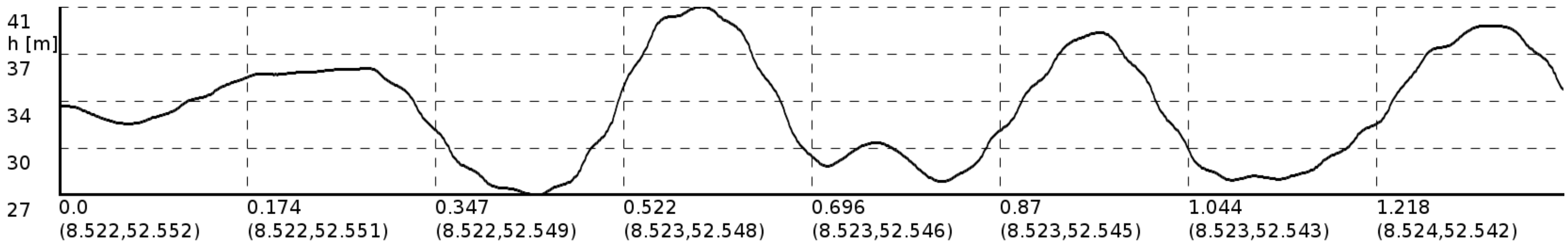
Tuning

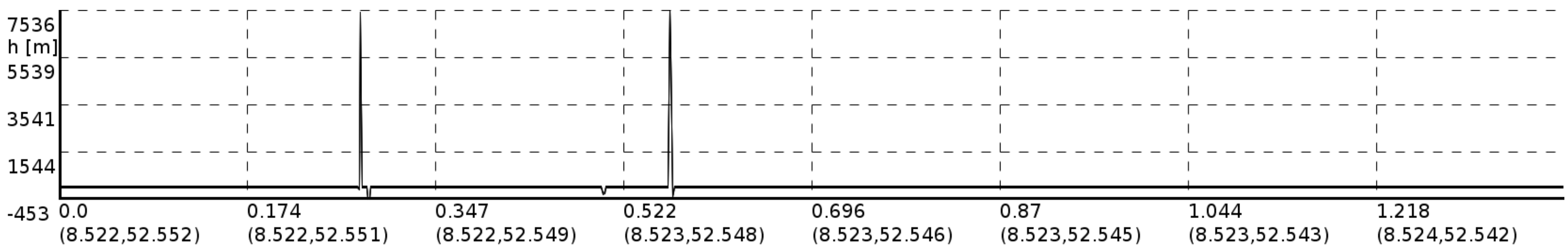




Elevation

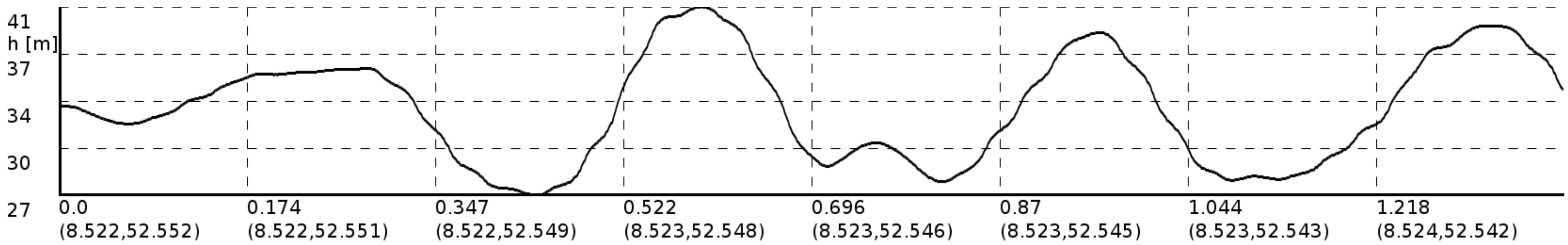
Tuning

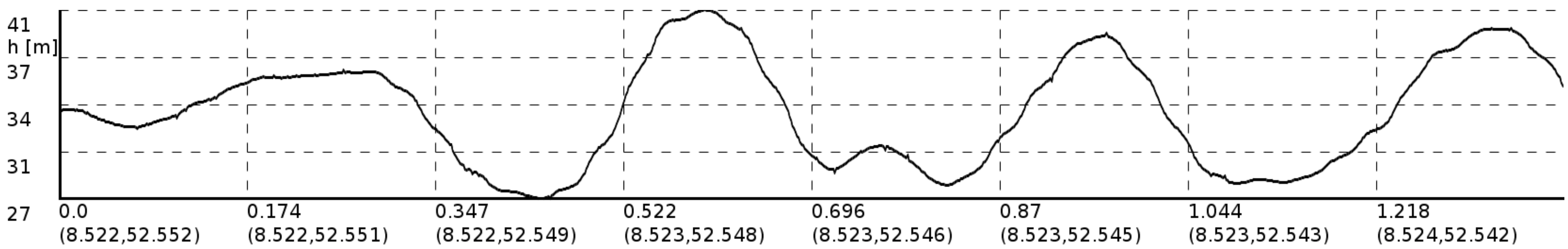




Elevation

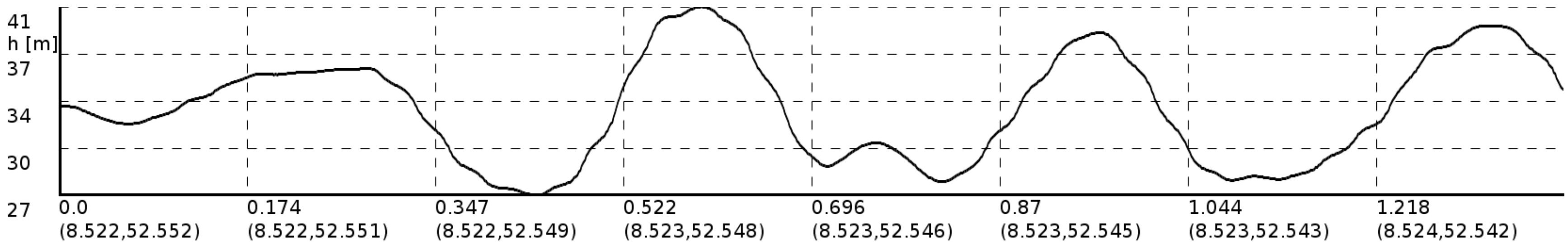
Tuning

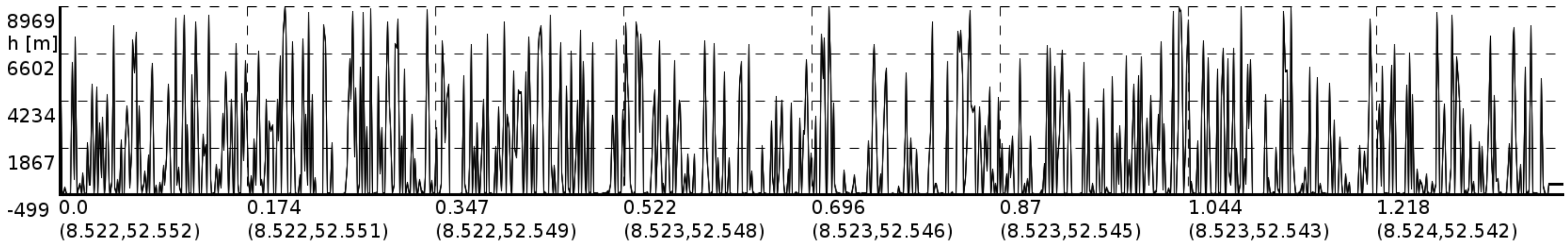




Elevation

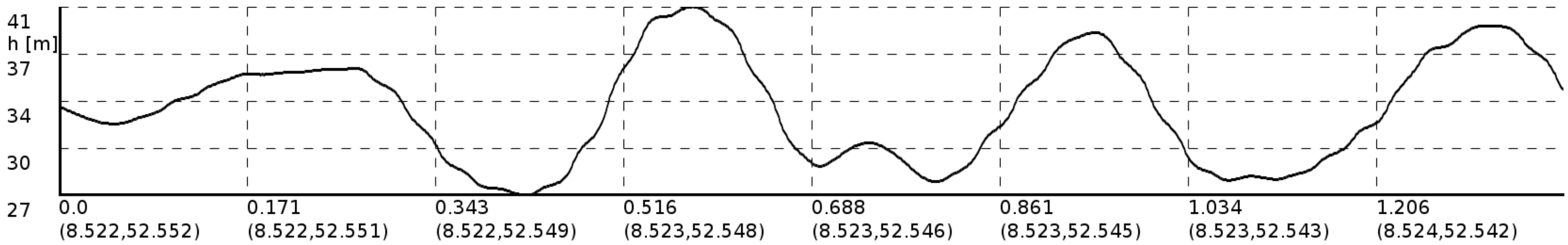
Tuning

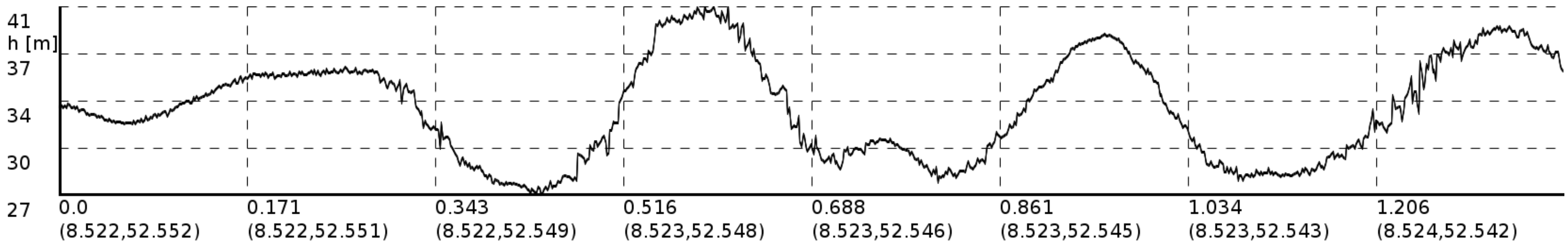




Elevation

Tuning – now with sloping



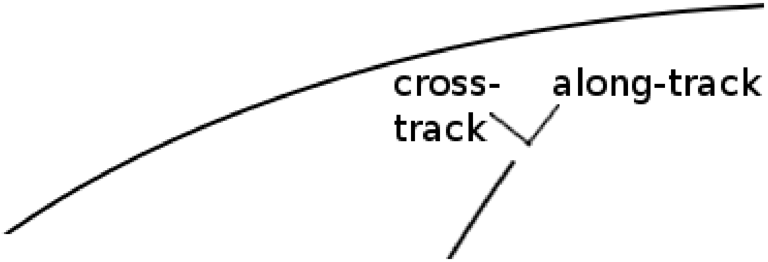


Slope

Algorithm

Along-track slope: determined by time derivative of elevation.

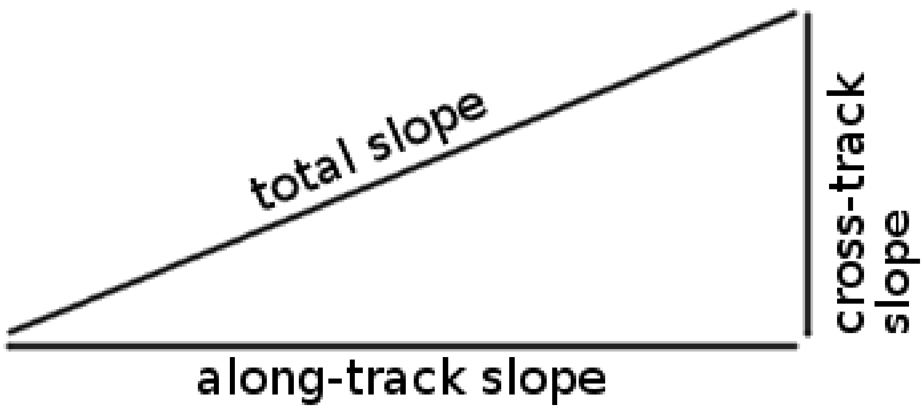
Total slope slope: determined from sub-footprint heights.



Slope

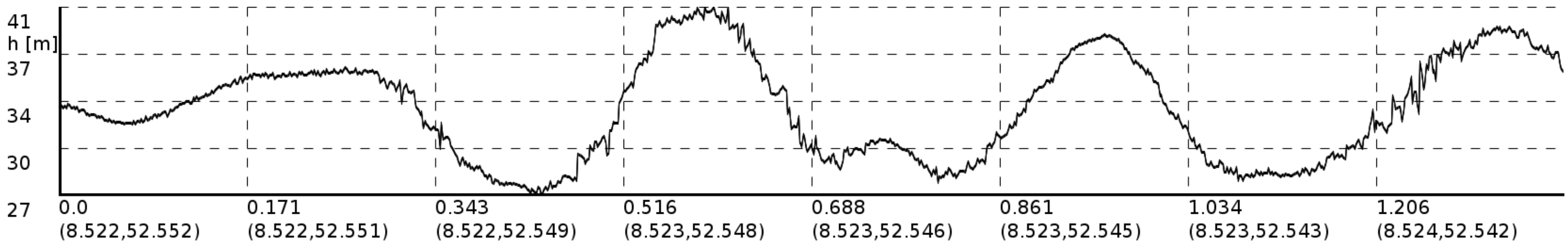
Algorithm

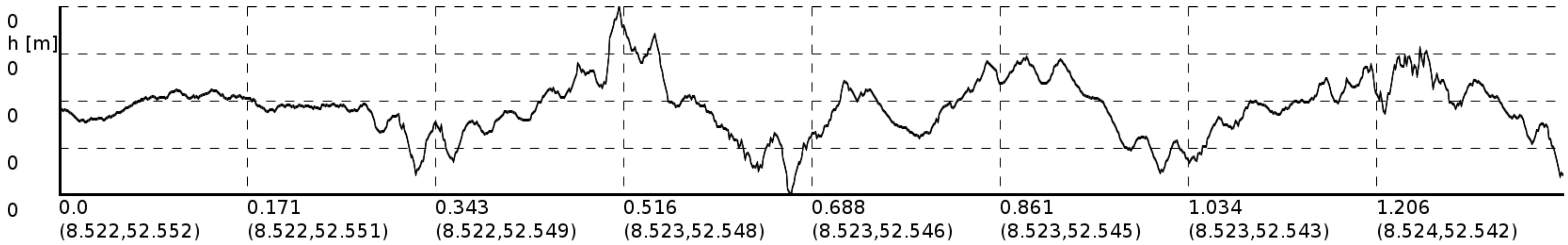
Cross-track slope: determined by Pythagoras.



Slope

Result – along-track slope





BRDF Determination

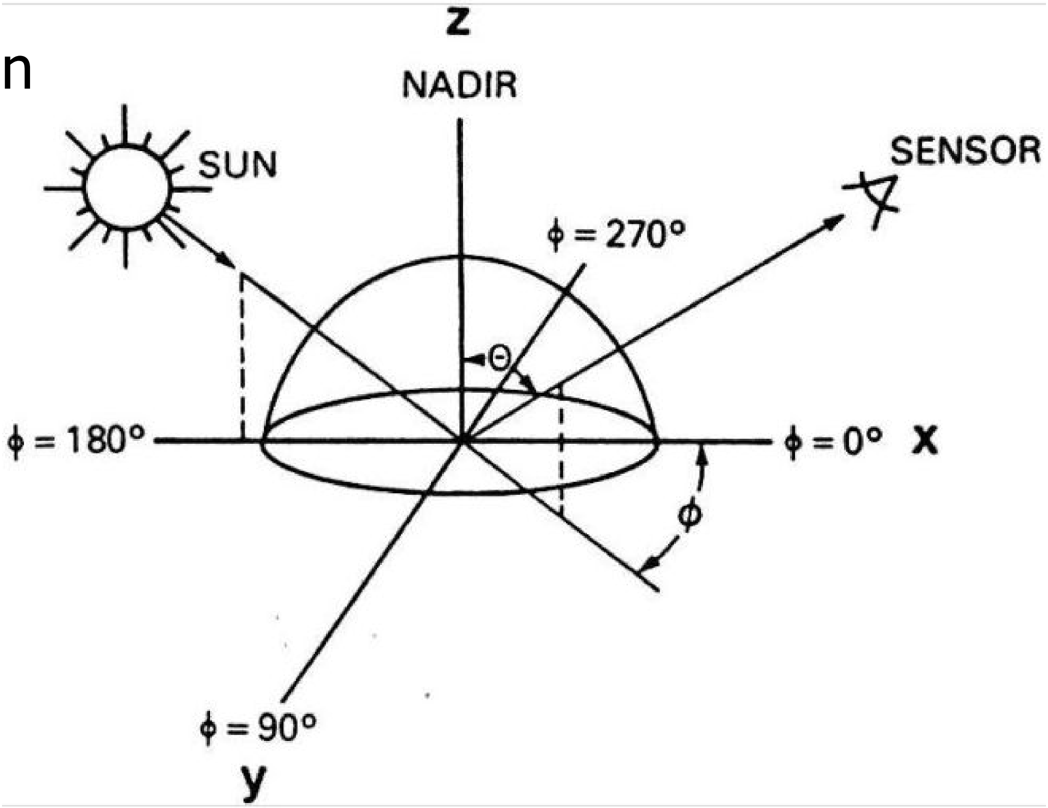
About BRDF

Estimation

Determination in the Simulator

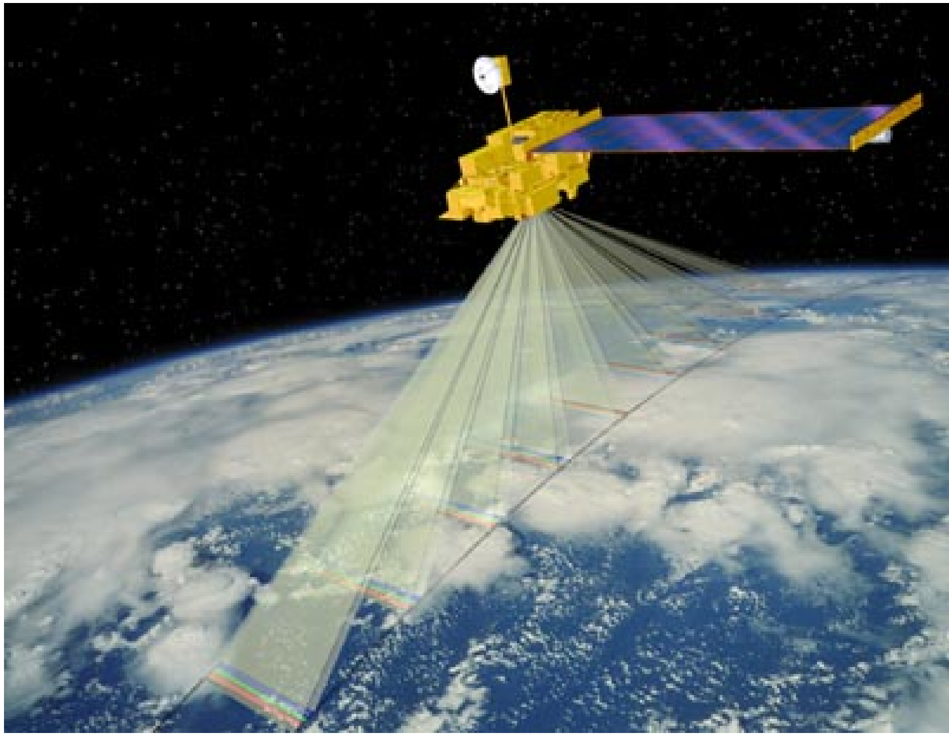
About BRDF

- Bidirectional Reflection Distribution Function
- Measure of reflectance of surface



Practicality

- Correction for anisotropy
- Normalization
- Aids in identification of VI



Estimation

- Three general categories of BRDF models:
  - Physical,
  - Empirical,
  - Semi-Empirical

- Easier to inverse linear models
- Semi-Empirical:

$$R(\theta,\vartheta,\varphi) = f_{iso} + f_{geo}K_{geo}(\theta,\vartheta,\varphi) + f_{vol}K_{vol}(\theta,\vartheta,\varphi)$$

- Empirical:

$$R(\theta,\vartheta,\varphi) = p_0(\theta^2 + \vartheta^2) + p_1\vartheta^2\theta^2 + p_2\vartheta\theta\cos(\phi) + p_3$$

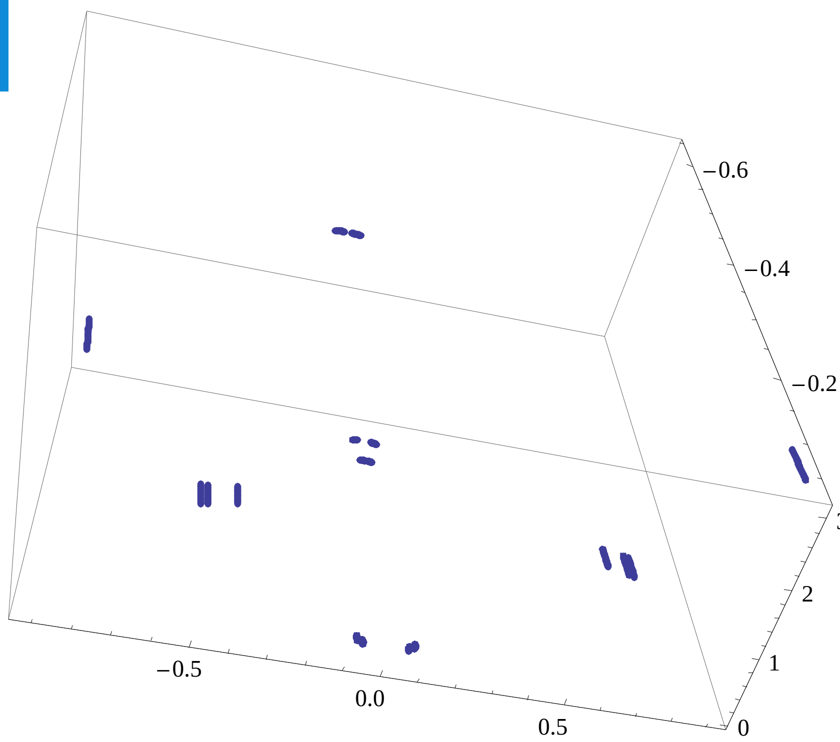
Determination of the BRDF

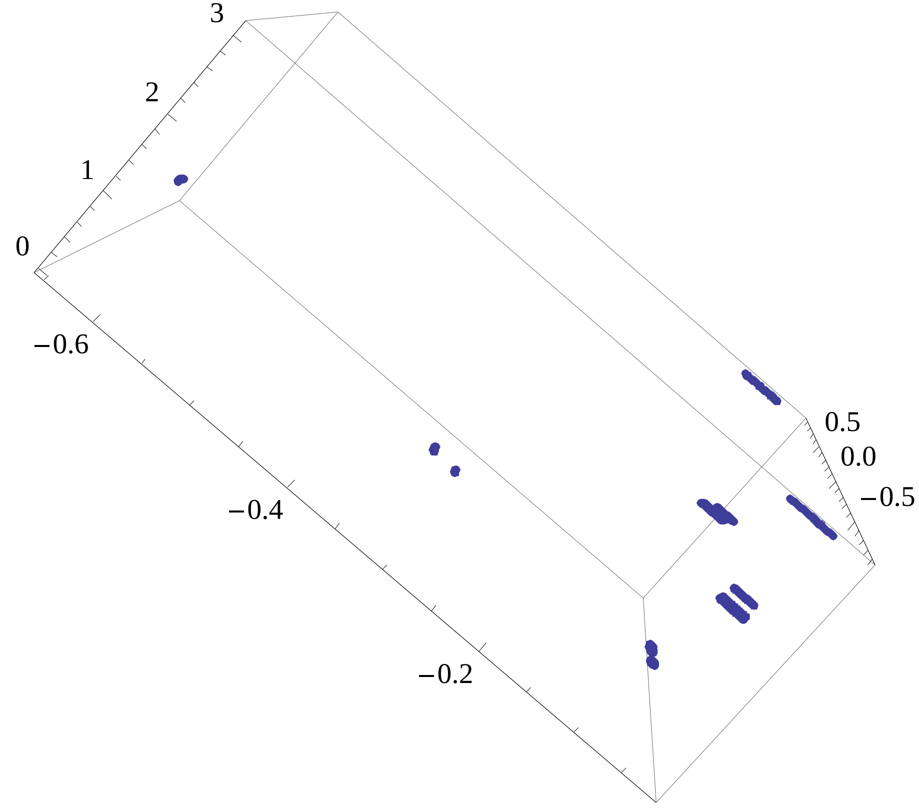
- Goal: Find BRDF from limited number of measurements
- Photons equal irradiance
- Least squares estimation

$$\sum_{j=1}^{N} \frac{\left(R_{obs_j}(\theta, \vartheta, \varphi) - R_{model_j}(\theta, \vartheta, \varphi)\right)^2}{W_j}$$

$$R_{model}(\theta, \vartheta, \varphi) = p_0(\theta^2 + \vartheta^2) + p_1 \vartheta^2 \theta^2 + p_2 \vartheta \theta \cos(\phi) + p_3$$

Calculated points





4.

Concluding remarks

Cost Overview

	Unit Cost				Swarm (9 satellites)	
	Emitter satellite		receiver satellite			
Subsystem	Cost [k$]	%Subtotal	Cost [k$]	%Subtotal	Cost [k$]	%Subtotal
Payload	8215.96	41.5	4048.74	46.58	8660	25.3
Bus Total						
Structure	1920.38	9.7	843.2	9.7	3322.33	9.7
Thermal	217.776	1.1	95.62	1.1	376.76	1.1
EPS	541	2.7	266	3.06	1193.694	3.49
Navigation	25	0.13	25	0.29	191.235	0.558
Communication	2940	14.9	612.5	7.05	7141.14	20.85
ADCS	199.093	1	175.914	2.02	1405.687	4.1
Tank	0.713	0.0036	0.428	0.0049	3.649	0.011
Thruster	570.64	2.88	356.65	4.1	3016.9	8.8
Wraps						
IAT	1445.24	7.3	634.58	7.3	2500.34	7.3
Program Level	2395.53	12.1	1051.84	12.1	4144.36	12.1
GSE	692.92	3.5	304.25	3.5	1198.78	3.5
LOOS	633.53	3.2	278.17	3.2	1096.03	3.2
Subtotal	19797.79	100	8692.92	100	34250.88	100
Launch	-	-	-	-	18534.25	-
Total	-	-	-	-	52785.13	-
Total (FY00)	-	-	-	-	43089.90	-

Mass Overview

	Emitter		Receiver	
Subsystem	$M[kg]$	$\%M_{dry}$	$M[kg]$	$\%M_{dry}$
Communication	10.66	21	3	22.2
Navigation	0.25	0.5	0.25	1.85
OEP	15	29.8	-	-
ORP	0.22	0.4	0.22	1.63
EPS	5.8	11.5	3.6	26.6
ADCS	2	4	2	14.8
Thermal	1.48	3	0.3	2.22
Structure	12.35	24.5	2.45	18.12
Propulsion(tank)	1	2	0.75	5.55
Thruster	0.65	1.3	0.15	1.11
Shielding	1	2	0.8	5.92
M_{dry}	50.41	100	13.52	100
$M_{propellant}$	4	-	1.5	-
M_{Loaded}	54.41	-	15.02	-
M_{Orbit}	53.1	-	14.92	-

Conclusion

This shows that the Laser SWARM concept demonstrated is feasible.