JANOS

TEAM BLUE

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Tutors: Günter ***Kargl,*** *Oliver* ***Jennrich***

Organised by

Thursday 23th July 2015

Mission statement

First experimental study of quantum decoherence induced by spacetime curvature

Scientific objectives

SO1: Investigate the influence of gravitational time dilation on a single photon interference experiment.

SO2: Compare single photon interference with interference of classical light.

Scientific background

Classical physics

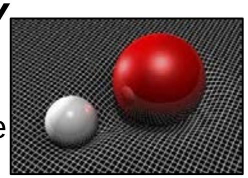
Macroscopic world

Microscopic world

SPECIAL RELATIVITY

Extension of classical physics to motion near the speed of light

GENERAL RELATIVITY



Unified description of gravity as a geometric property of space and time

QUANTUM MECHANICS

Physical phenomena at the atomic scale.

QUANTUM FIELD THEORY

Theoretical framework for subatomic and high energy physics (*CERN*).

? ?

QUANTUM MECHANICS IN A CURVED SPACETIME

Motivation

1. Curiosity

The best current theories cannot be the whole story. We lack deeper understanding about the nature of the universe (*Dark Matter/Energy?*).

2. Cosmology

QM and GR not enough to give good explanation of the first few moments of the universe (*Big Bang*), and objects where small scales and large masses are important (*Black Holes*).

3. Technology

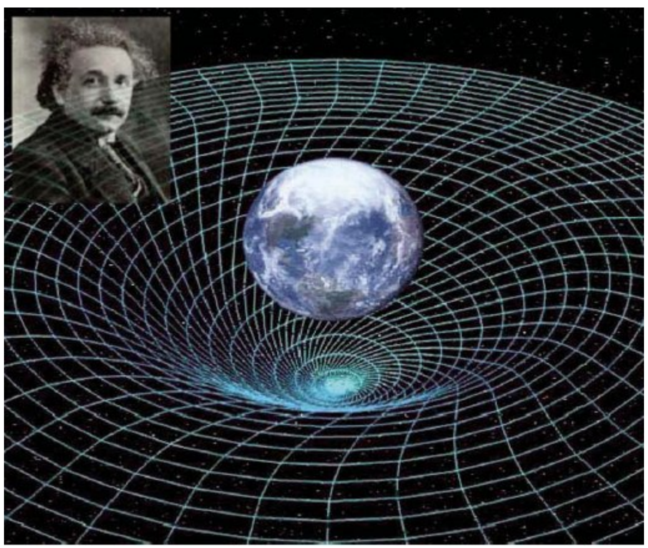
After the invention of lasers, transistors and use of nuclear energy, further research in quantum mechanics could give rise to yet unknown applications.

Scientific approach

Combine the fundamental effects of **GR** and **QM** in a single experiment.

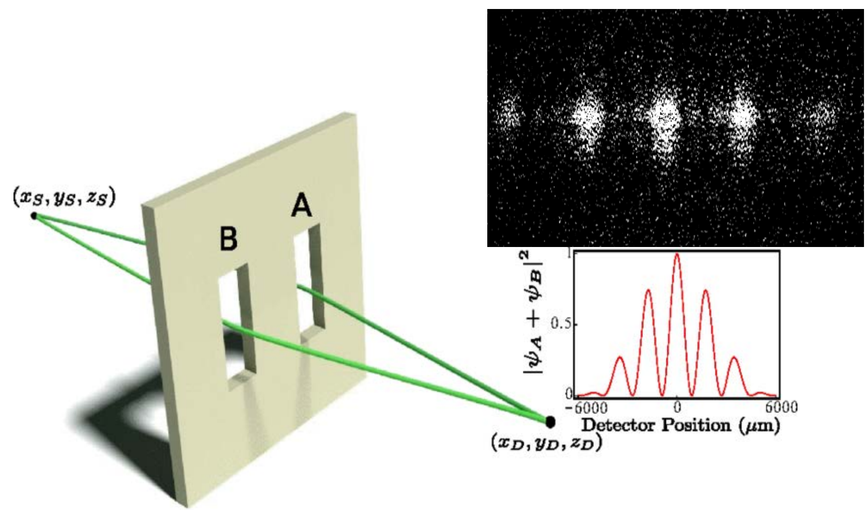
GENERAL RELATIVITY

Massive objects curve space and time



QUANTUM MECHANICS

Single particles show interference behavior

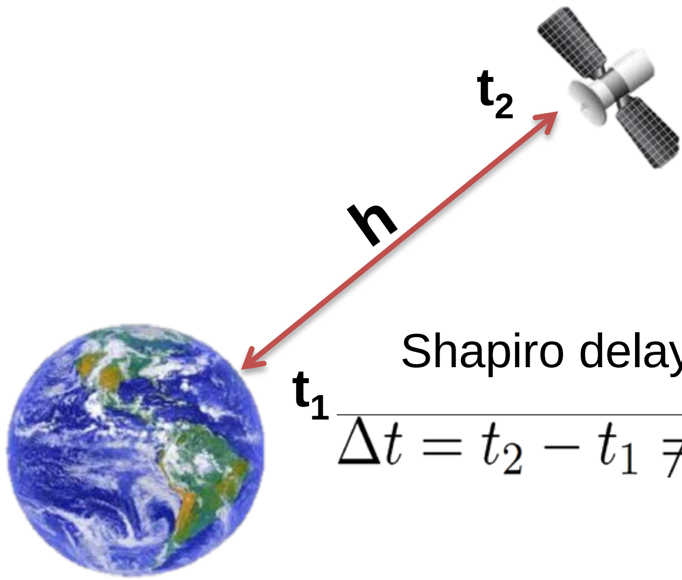


Single photon interference in presence of curved space-time

Involved effects

Shapiro delay

Gravitational time delay due to a change in the gravitational potential.



Shapiro delay

$$\Delta t = t_2 - t_1 \neq 0$$

- Pure relativistic effect
- Observed on a everyday basis
  in the global positioning system

Superposition

A quantum system can exist in a linear combination of pure states.

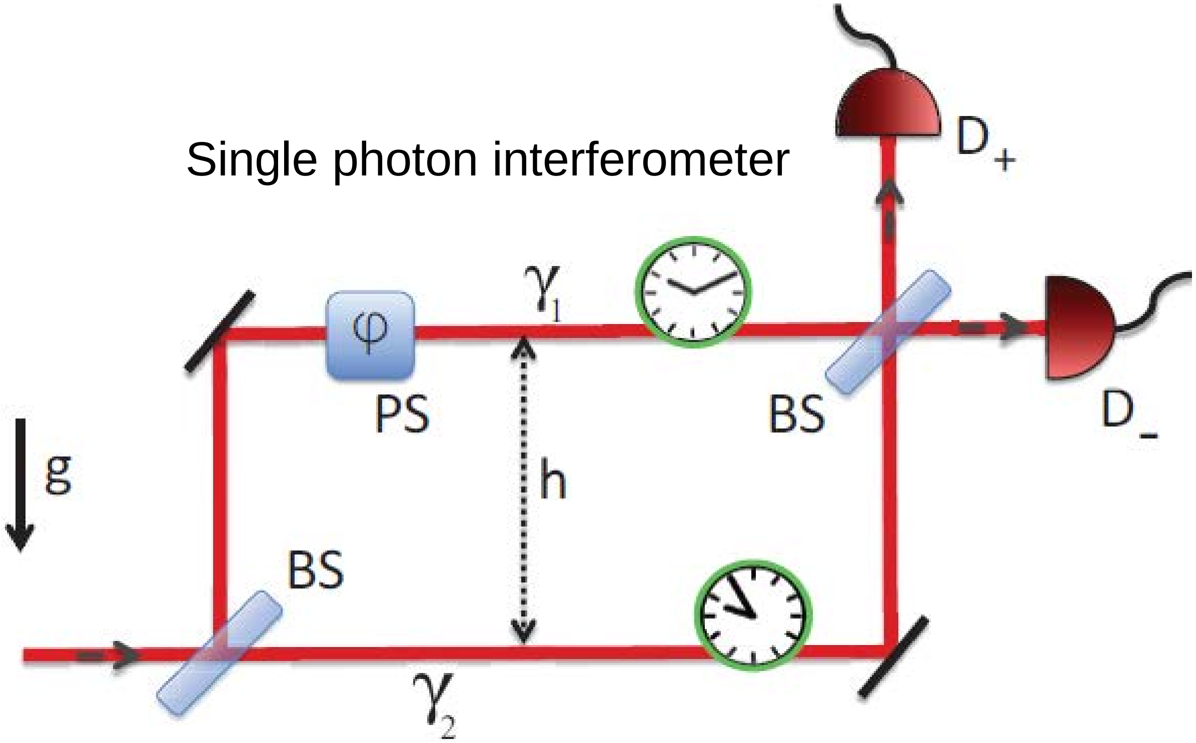
Pure states:

Superposition:

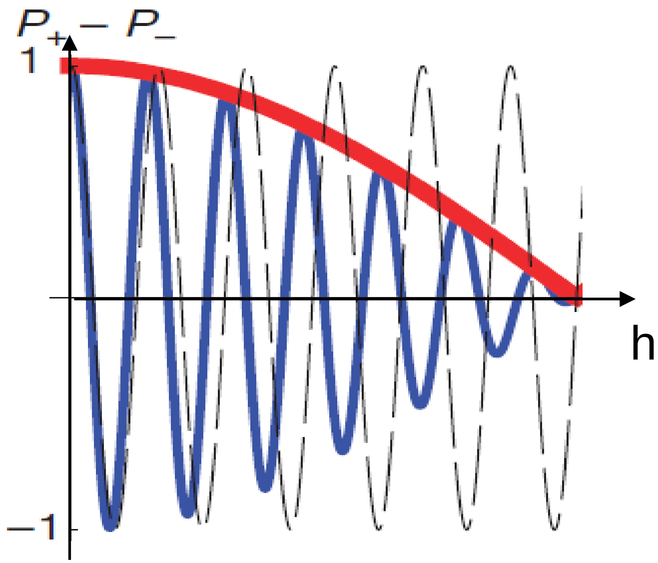
- Pure quantum mechanical effect
- Measurement results can only be
  pure states

Predicted physical effect

Single photon interferometer



Drop in fringe contrast



Magdalena Zych et al. GENERAL RELATIVISTIC EFFECTS IN QUANTUM INTERFERENCE OF PHOTONS 2012

Observe gravity induced **decoherence** (*break-down of the Schrödinger wave function*) of a single photon superposition state with increasing distance from Earth.

Experimental heritage

Gravitational red-shift in nuclear resonance
R. V. Pound and G. A. Rebka, Jr.
(Phys. Rev. Lett. **3**, 439 October 1959)

Observation of Gravitationally Induced Quantum Interference
R. Colella and A. W. Overhauser, S. A. Werner
(Phys. Rev. Lett. **34**, 23 April 1975)

Experimental Satellite Quantum Communications
Giuseppe Vallone, Davide Bacco, Daniele Dequal, Simone Gaiarin, Vincenza Luceri, Giuseppe Bianco, and Paolo Vtlloresi
(Phys. Rev. Lett. **115,** 040502, **20 July 2015**)

First experiment that will include both effects.

Scientific objectives

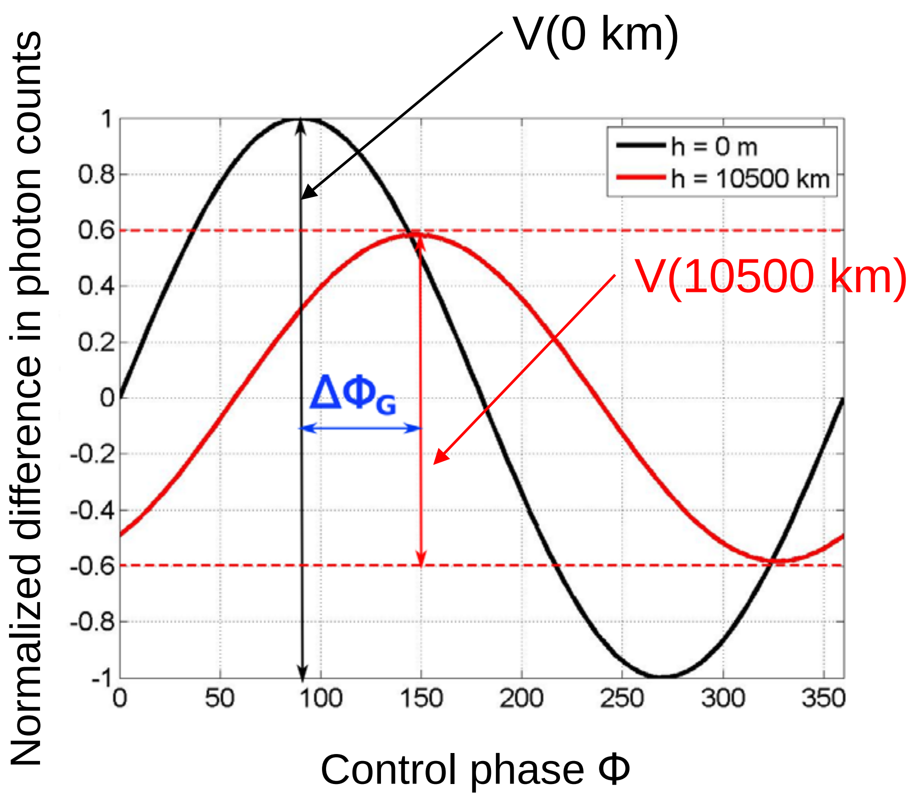
Scientific objectives

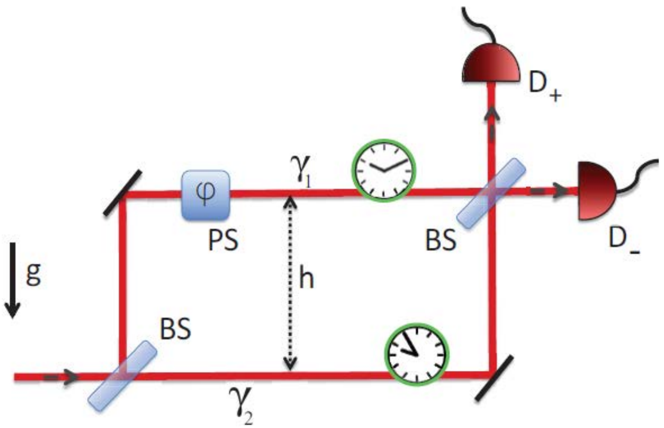
SO1: Investigate the influence of gravitational time dilation on a single photon interference experiment.

SO2: Compare single photon interference with interference of classical light.

What do we need to measure

The gravity induced **phase shift** and the **drop in fringe contrast** of single photon interference.





Phase shift:

$$\phi_G(h) = \frac{2\pi l}{\lambda}\frac{\Delta U(h)}{c^2}$$

Fringe contrast:

$$V(h) = V_0 e^{-\frac{\log 2}{2}\left(\frac{\Delta\tau}{t}\right)^2}$$

Scientific requirement

SR1: Measure the loss in coherence as a function of satellite altitude with a statistical significance of ≥5.

SR2: Measure the phase shift as a function of satellite altitude with a statistical significance of ≥5.

Traceability matrix

Scientific Theme	Scientific Objective	Scientific Requirements	Mission requirements	Instrument Requirements	System Requirements
Fundamental physics: Examination of the effect of general relativity on a single quantum state to test for connections between these two fields.	*SO1:* Investigate the influence of gravitational time dilation on a single photon interference experiment.	*SR1:* Measure the loss in coherence as a function of satellite altitude with a statistical significance of ≥5.	MR1: Need gravitational potential differences in a range between 700-32,000 km	*IR1:* Single photon source: 1550 nm, pulse width 1 ps, repetition rate 1 GHz, temperature stability ±0.5 °C	*SysR1:* Primary power supply: ≥ 350 W on average
					SysR2: Electrical storage capacity: ≥ 600 Wh
	SO2: Compare single photon interference with interference of classical light.	*SR2:* Measure the phase shift as a function of satellite altitude with a statistical significance of ≥5.	MR2: Measurements shall be carried out during local night time at ground segment	*IR2:* Reference laser: 1300 nm, output power 500 mW, frequency stabilized $\leq 10^{-11}$	*SysR3:* COMMS system: downlink capacity 50 kbit/s
		SR4: The photon flux at apogee shall be ≥ 100 photons/s	MR3: Need two ground stations to observe	*IR3:* Single photon detectors (8x): efficiency > 25% (ground), repetition rate 25 MHz	*SysR4:* Onboard memory: 20 MB
		SR3: The total number of counts shall be $\geq 7 \cdot 10^{7}$		*IR4:* Pointing accuracy: 6 µrad during 150 s, stability <1 µrad during 0.3 ms, slew rate 10 mrad/s	*SysR5:* Thermal stability <0.5°C
				IR5: Fibres: optical path difference ≤ 1 µm, dispersion 5 fs/nm/km	*SysR6:* Ionizing radiation <600rad TID
				IR6: Ground receiving telescope: FOV 10 µrad,	

Why go to space?

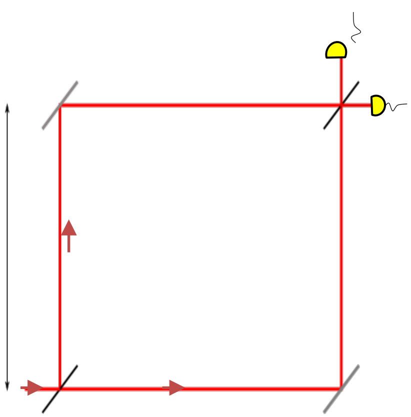
EARTH

Interferometer between Mount Everest and the Mariana Trench:

$\Delta\tau = 0.7$ fs

out of measurement precision with current technology

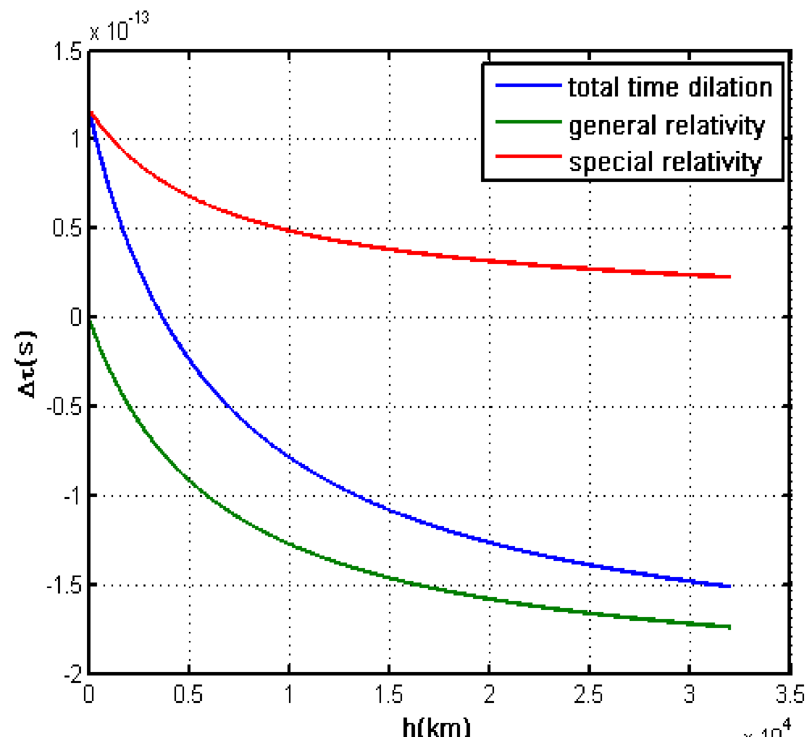
h = 19.8 km



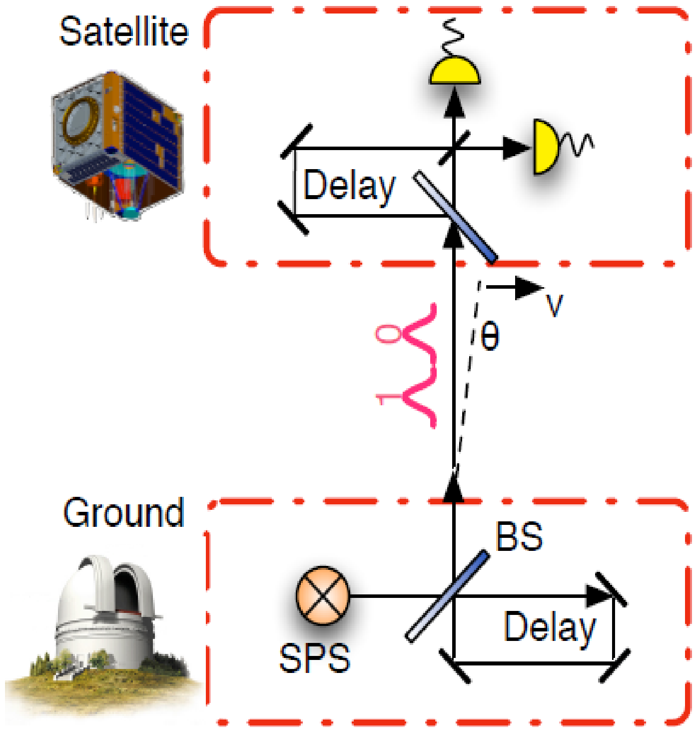
SPACE

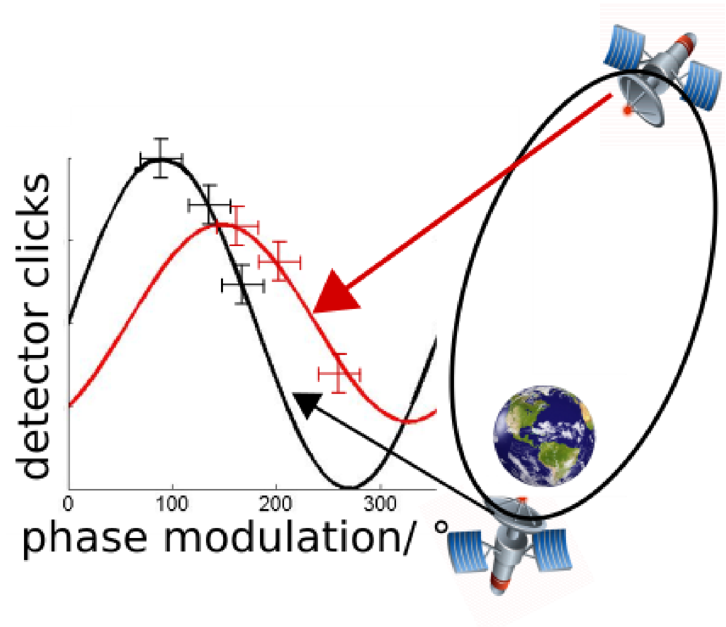
At an altitude of h = 32000 km:

$\Delta\tau = 150$ fs



Experimental realization





D.Rideout et al. – Fundamental quantum optics experiments conceivable with satellites, ArXiv 1206.4949v2

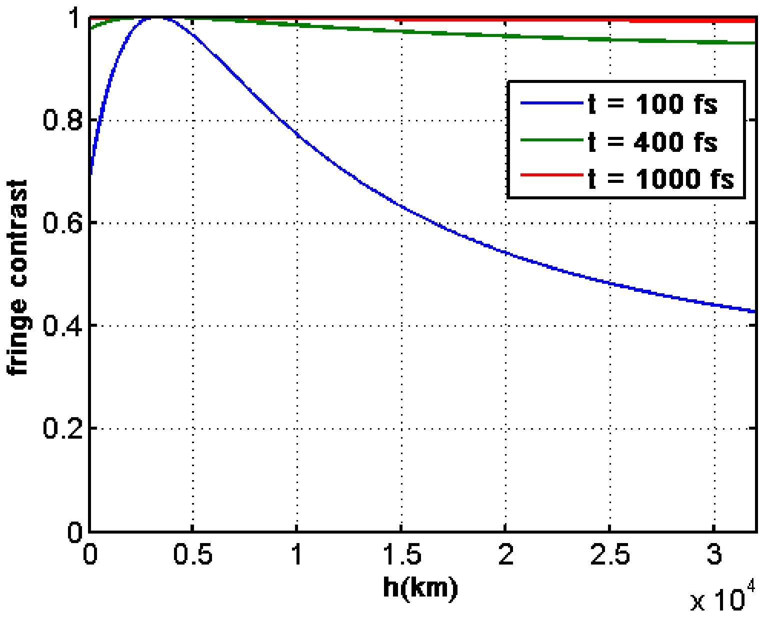
1) Realize a single photon interferometer between Earth and a satellite on a highly elliptical orbit.

2) Observe drop in fringe contrast with two ground stations at the apogee and the perigee of the orbit.

Measurement strategy

1. Measure the drop in interference fringe contrast

2. Exponential dependence on gravitational time delay and photon coherence time



Fringe contrast:

$$V(h) = V_0 e^{-\frac{\log 2}{2}\left(\frac{\Delta\tau}{t}\right)^2}$$

Δτ : gravitational time delay
t : photon coherence time

- use ultra-short single photon laser pulses
- optimize satellite orbit for altitude difference
- use laser downlink configuration to maximize photon flux
- mitigate error sources and large coherence times by statistics

Requirements reasoning

Requirement: detect drop in fringe contrast with $\mathbf{5\sigma}$ significance.

1) Polar orbit with apogee of 32000km
2) One year of mission time
3) Single photon source with pulse width of 1ps
4) Tolerate pulse dispersion to ≤ 4ps

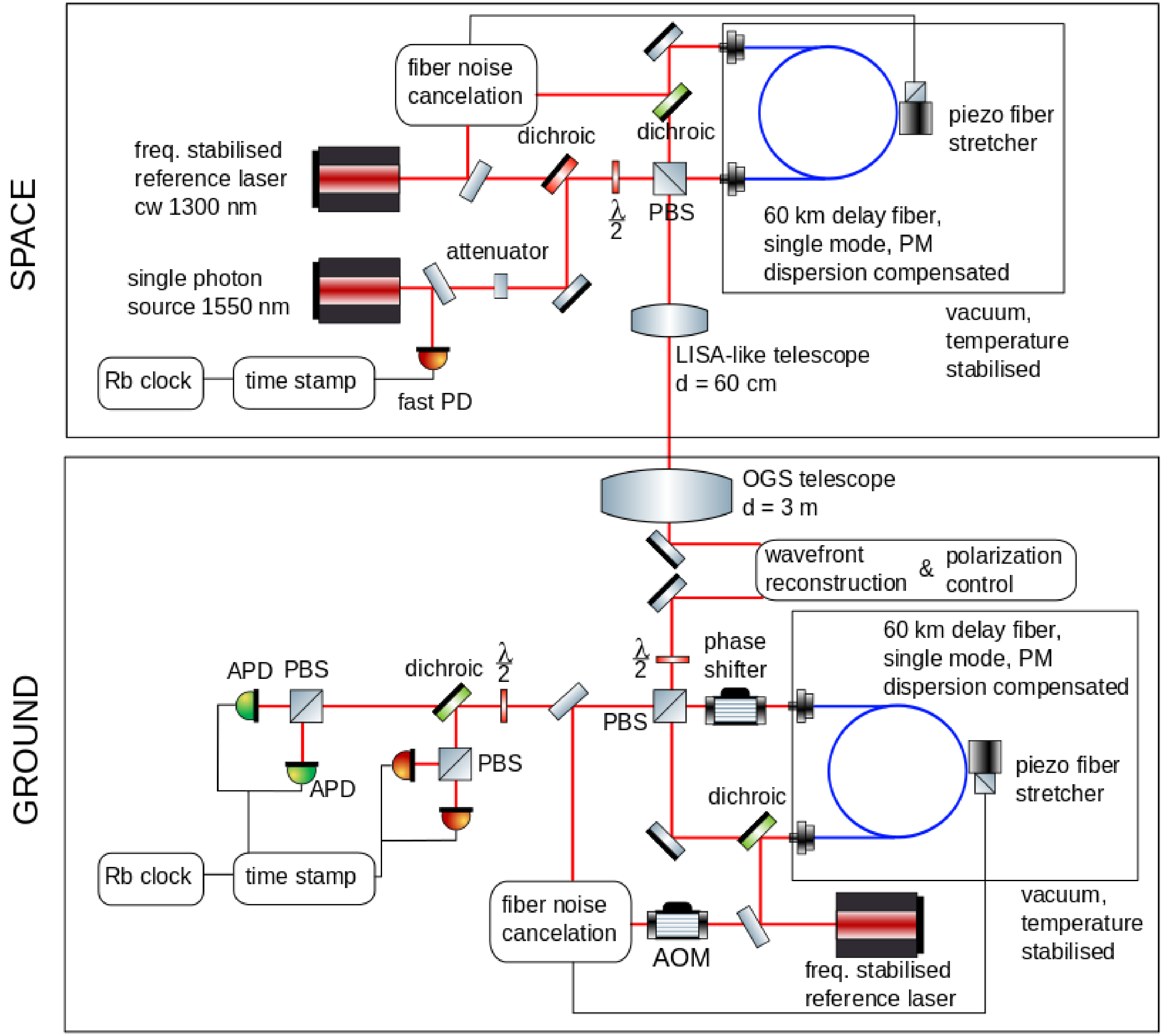
→ predicted drop in fringe contrast: 0.06%

Statistics needed:

$$\frac{S}{N} = \sqrt{n} \cdot \frac{S}{\sigma_{noise}}$$

→ single photon detection rate ≥100/s

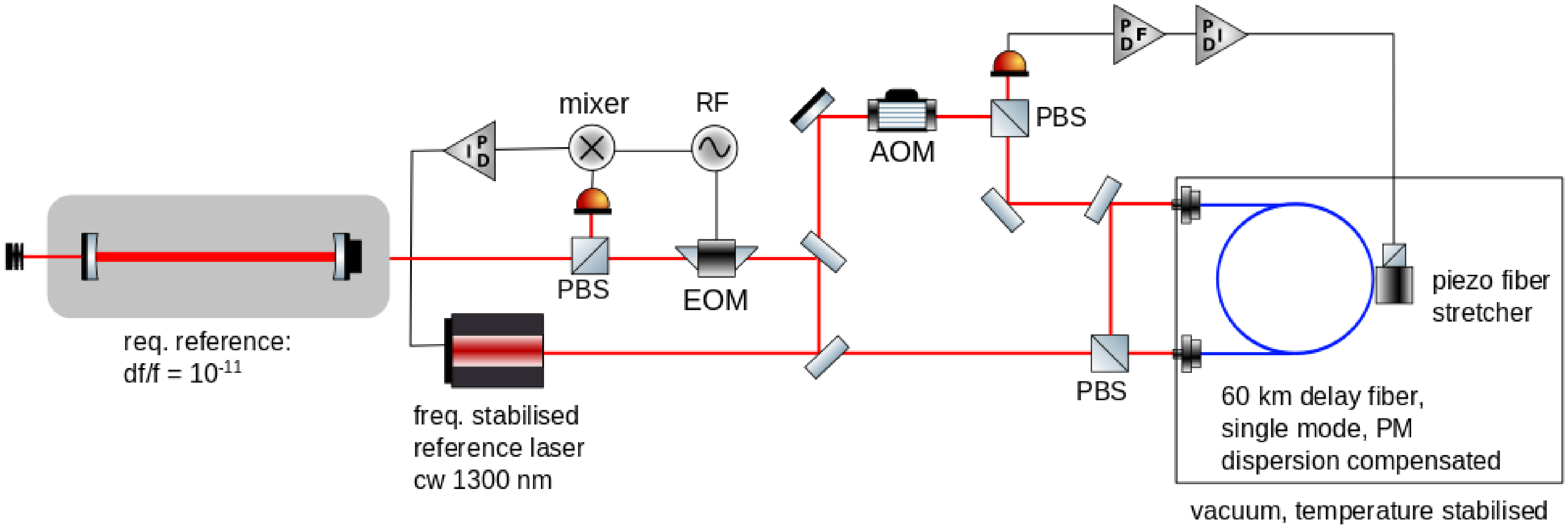
Experimental setup



Technological challenges: fiber length stabilization and noise cancelation

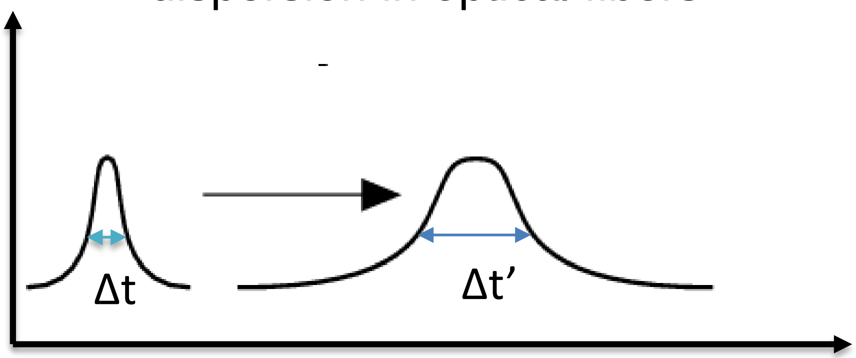
required stability of optical path length: $\pm 1 \mu m \rightarrow \frac{\Delta L}{L} = 10^{-10}$ over mission duration

Proposed setup:



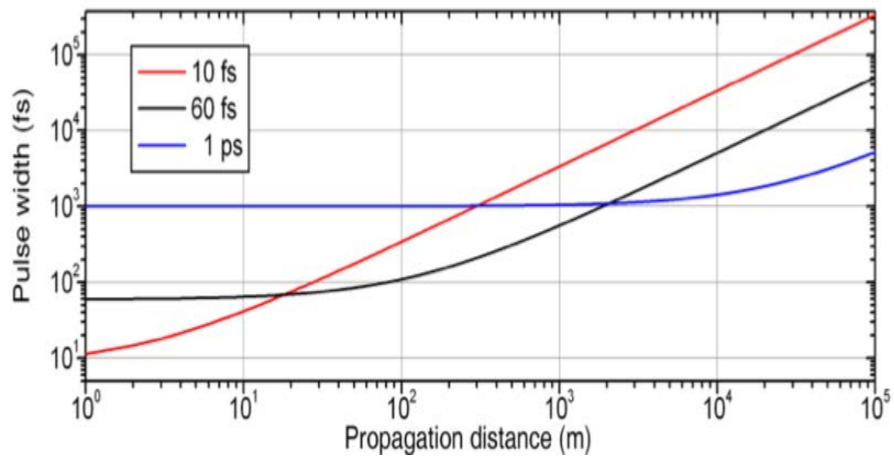
Technological challenges: pulse dispersion in dielectric media

dispersion in optical fibers



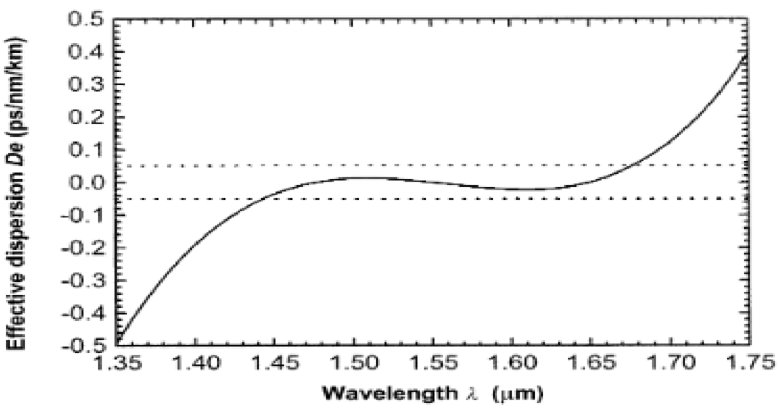
distance travelled (km)

atmospheric dispersion



Sang- Hyun Lee et al, OPTICS EXPRESS 2011

Solution: dispersion compensation



Shen, L.P. et al, Photonics Technology Letters 2003

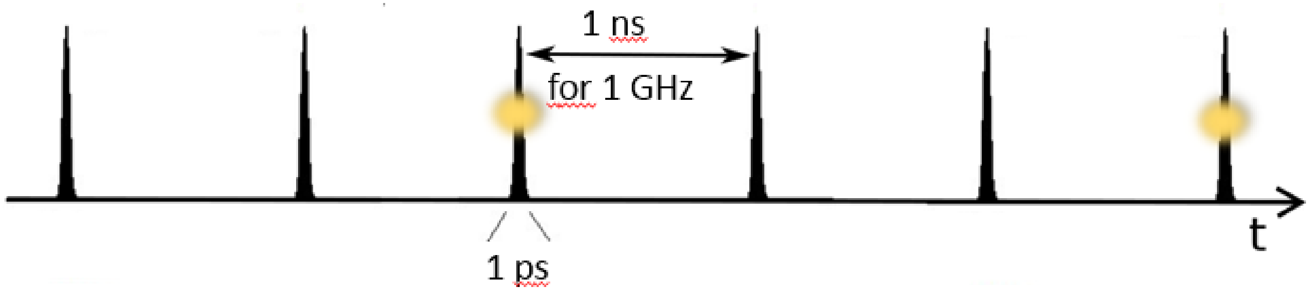
$1\ ps \longrightarrow 30\ ps$ ➡ development required

Instrument requirements

Source of single photons

- Picosecond Laser pulses:
  - Based on well-established non-linear mode locking mechanism

- Requirements:
  - Wavelength: λ = 1550 nm
  - Pulse width: 1ps
  - Repetition rate: 1GHz
  - Mean photon number per pulse: $\mu = 0.1$
  - Probability of multiphoton emission ~ 5%
  - Single photon rate: ~100 MHz



Reference Laser

- **Guided through same path as single photons**

- **Application:**
  - Comparison of classical interference to single photon interference
  - Analysis of polarization changes in down link
  - Delay measurement between satellite and ground station
  - Interferometric stabilisation of optical fibres

- **Requirements:**
  - Continuous wave
  - Power: ~ 500 mW
  - Wavelength: λ ~ 1300 nm
  - Relative frequency stability: 10^{-11}
    - *Trade off*: as close as possible to quantum channel, but clearly outside bandwidth of single photons

Instrument Link Budget

700 km - 32000 km
Altitude

-10.38 dB
Fibre Loss

3.0 m
Receiver Diameter

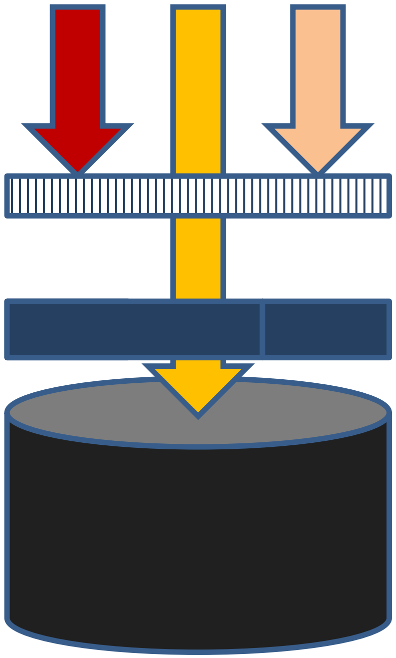
1550 nm
Wavelength

0.6 m
Transmitter Diameter

-3dB
Atmospheric /Pointing Loss

-13.51 dB
to
-46.70 dB

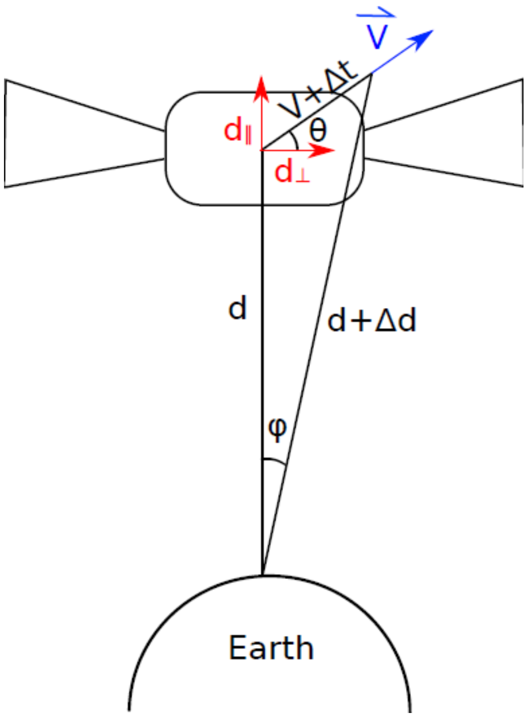
Noise (Downlink)



- 1550 nm bandpass filter
- Time gate
  - Reduces sampling by 50%
- Low optical depth
- High angle of signal incidence
- Highly precise TP system
- Doppler shift between 1.1 and 6.2 Ghz

Er-Long, M. et al (2005). *Background noise of satellite-to-ground quantum key distribution.* New Journal of Physics.

Challenge: optical path length and Doppler phase shift



Causes:

- Difference in optical path of superposition states due to moving satellite
- Doppler shift in frequency when $\theta \neq 0$
- Effects: phase shifts in our measurements, much greater effects than time dilation ($1 \text{ fs} = 0.3\ \mu\text{m}$)

Solutions:

- Measure Doppler shift via reference laser
- Calculate Δd to µm precision (requires precise measurements in *v* and *d*)
- Make posterior compensations to measured phase shift

Optical Payload Communication

Location	Requirements	Solution	Remarks
	Lifetime of two years	3 lasers on satellite for redundancy	
Apogee	Ground receiver FOV of 10 µrad	+ Beam FOV 6 µrad	Atmospheric Compensation
	SNR > 5 100 detected photons/s	Time gate filter (1 ns) and 100 ms sync, Bandwidth filter of 100 nm	4000 counts/s worst case 50% mission lifetime
	Transmission loss < -40 dB	3 m diameter telescope 0.6 m diameter laser sources	Requires building groundstations, SCIATRAN or sim. data
	Compensate for 63.0 GHz redshift	Real-time software package at ground	
Perigee	Ground receiver FOV of 10µrad		
	SNR > 5 100 detected photons/s	Time gate filter (1 ns) and 100 ms sync	90,000 counts/s worst case
	Transmission Loss < -10dB	3 m diameter telescope 0.6 m diameter laser sources	
	Compensate for 1.1 GHz redshift	Real-time software package at ground	

Telescopes

- **Onboard transmitting telescope:**
  - *60 cm* aperture to meet link budget requirements
  - *1 m* long
- **Onboard tracking telescope:**
  - *13.5 cm* aperture to meet transmission requirements
- **Groundstation receiver telescope:**
  - *3 m* aperture to meet link budget requirements
  - Shall have *10 µrad FOV* to account for atmospheric aberrations
  - Shall achieve an angular velocity of *10 mrad/s* to track the satellite

ADCS requirements

Location	Requirements	Solution	Remarks
Perigee	2 µrad pointing accuracy	Reaction wheels	
	10 mrad/s		
	65.1 µrad point ahead angle		
Apogee	0.05 µrad pointing accuracy	Reaction wheels	Design Driver Comparable to Hubble
	0.1 mrad/s		
	8.9 µrad point ahead angle		
Orbit	1 cm distance accuracy	PRS based laser ranging	GNSS principle

Instrument model development and test plan

Model	Purpose

Instrument breadboard models	• Validate technologies for instrument elements in lab environment:
	  • Fibre stabilization
	  • Dispersion compensation
	  • Single photon source

Electrical and optical interface model	• Validate electrical and optical interfaces
Structural and Thermal Model	• Validate instrument structure for launch and space environment: • Validate instrument thermal control interfaces and stability for space environment
Engineering Model	• Validate instrument interfaces and operation with the spacecraft platform
Proto-Flight Model	• Validate for flight with qualification level tests • Used also for actual mission

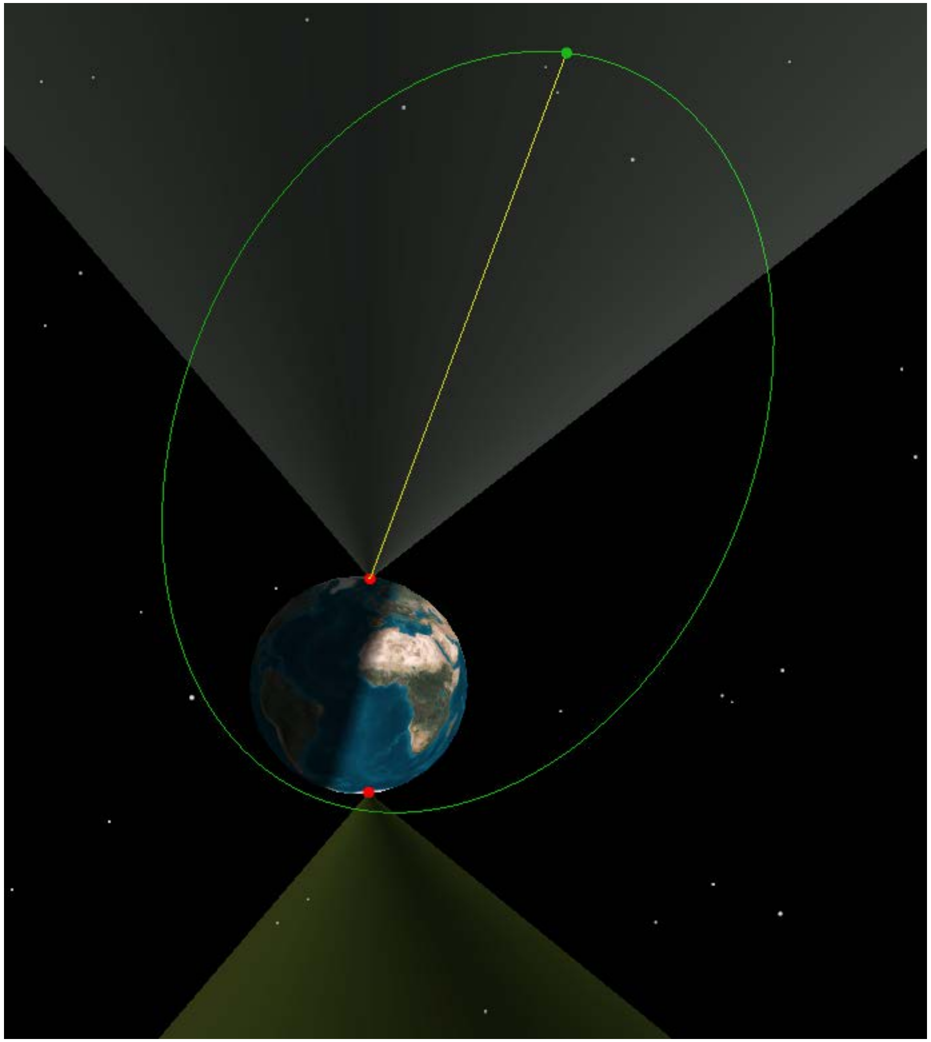
Mission requirements

Orbit

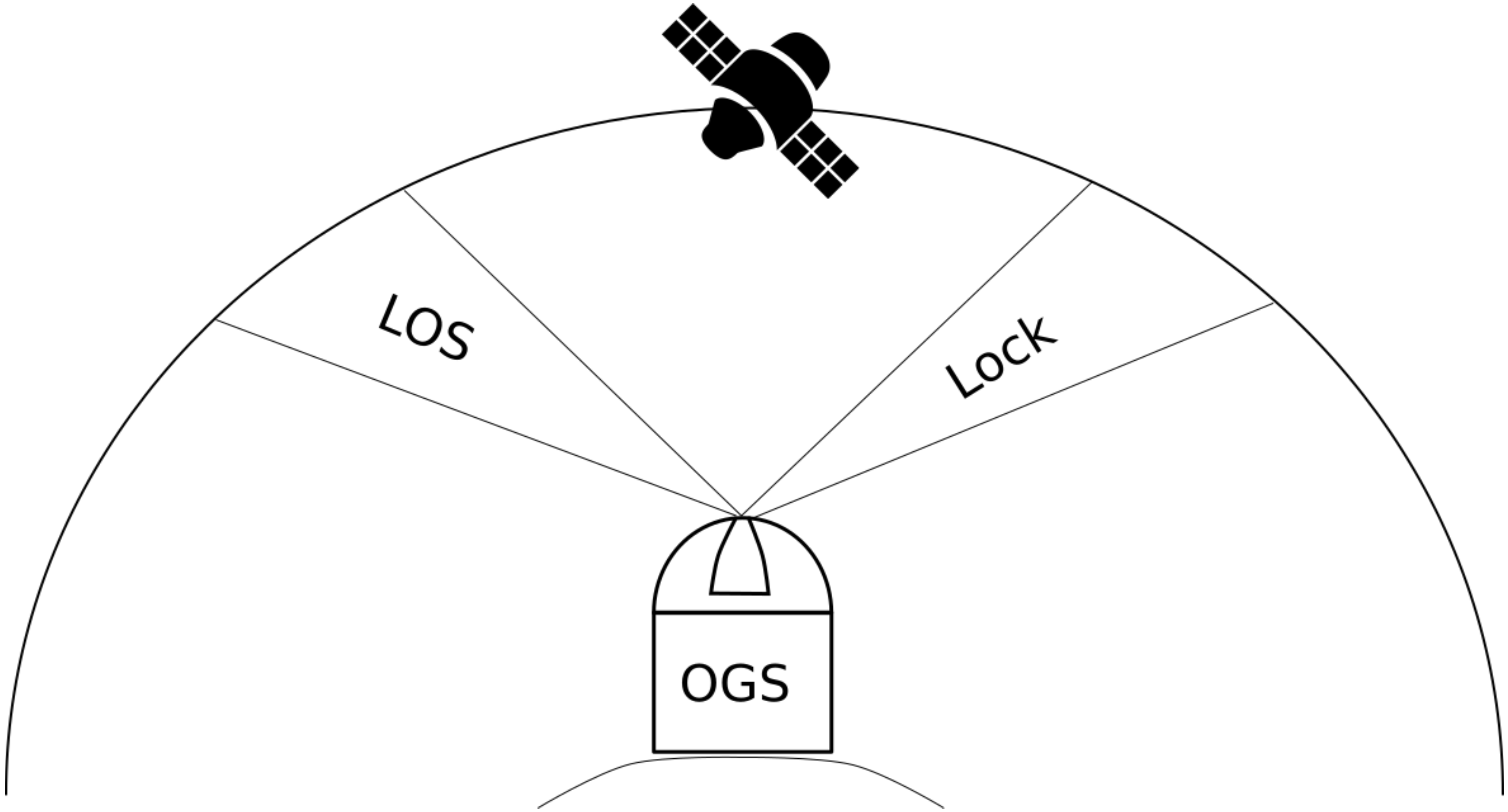
Requirements
GS in shadow
Maximized difference in gravitational potential
Pointing away from sun during measurement

Parameters
Polar Orbit: P:700km A:32000km
AoP:270°

Environment
One year total radiation dose: 1.47×10^6 rad



Experiment connection

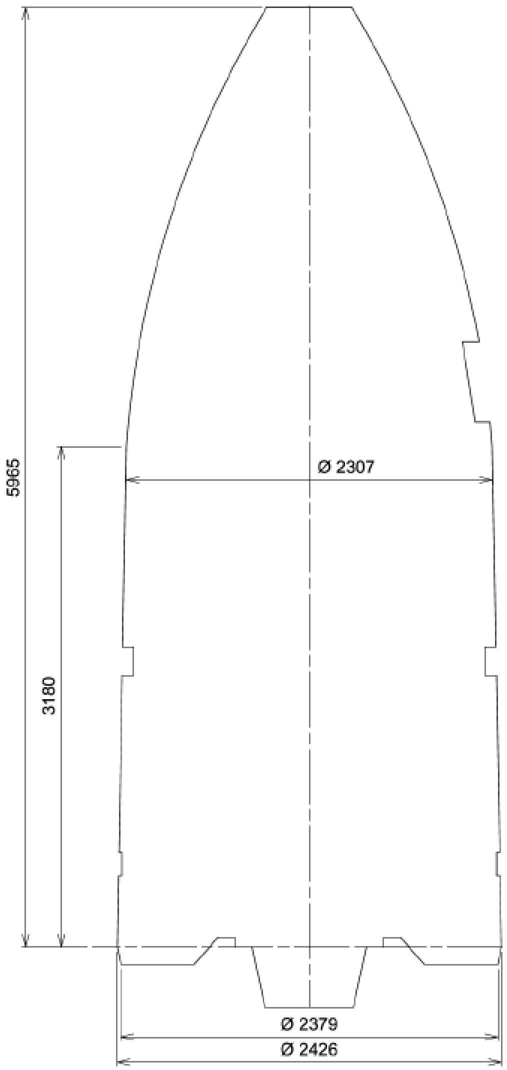


Launcher – VEGA

- Orbit insertion at 90° inclination
- Elliptic orbit
- 700 km Perigee
- 20 000 km Apogee

Mission Performance:

Launch Vehicle:	Vega
Launch Site:	Guiana Space Center (Kourou)
Destination Orbit:	700 x 20000 km, 90 deg
Estimated Payload:	419 kg
95% Confidence Interval:	336 - 511 kg

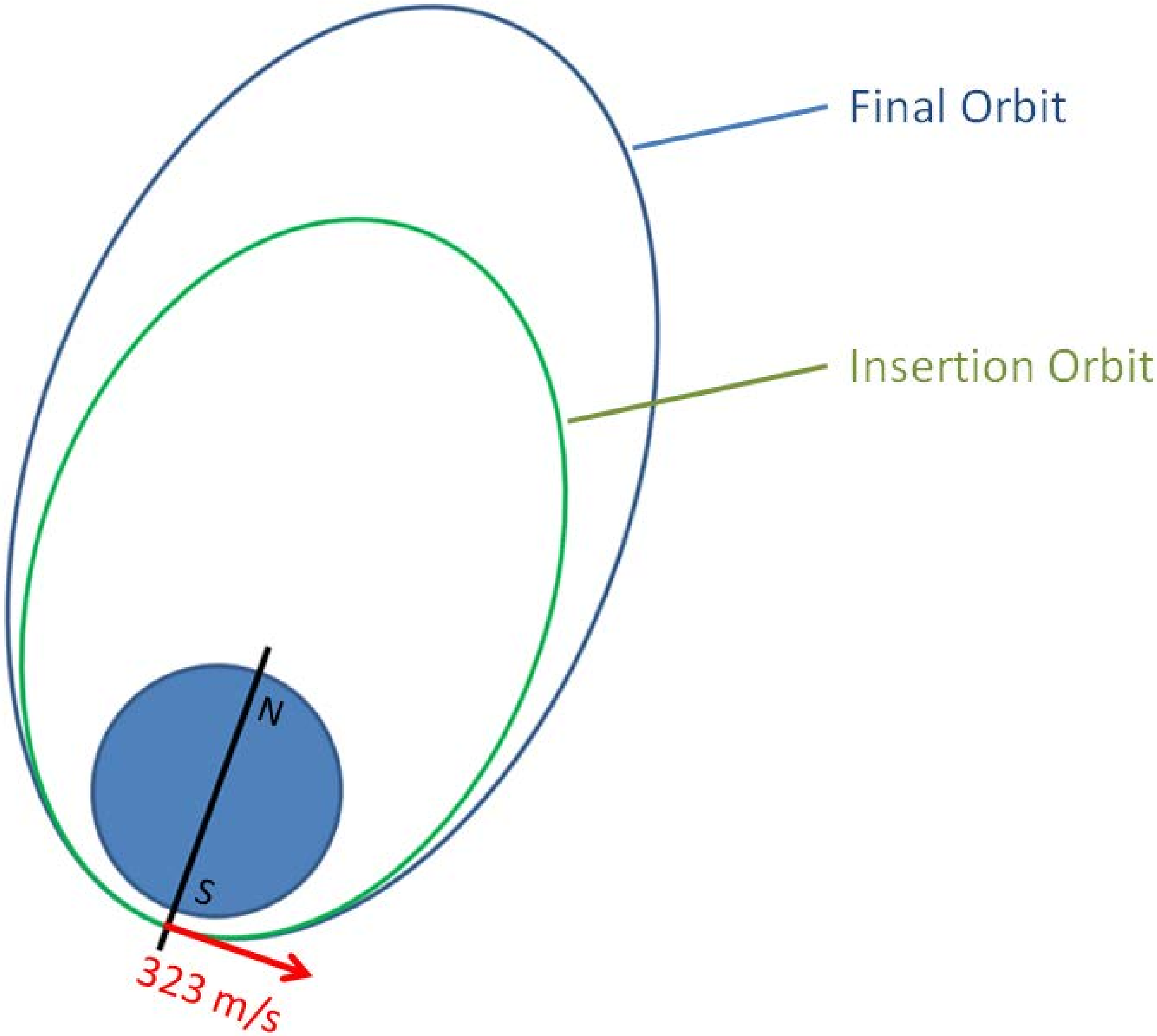


Propulsion

400N Apogee Motor
Isp=321s
Apogee change Δv=323 m/s
Controlled deorbit manoeuvre Δv=61 m/s

Orbital Control System
12 x 10N thruster
Station keeping Δv: 40m/s

Orbital Manoeuvre



Satellite bus

Specifications

Core Bus Features	
Bus Dry Mass:	800-1,500 kg
Max. Launch Mass:	3,325 kg
Payload Mass Capability:	500 kg
Orbit:	Geosynchronous
Typical Mission Lifetime:	>15 years
Delivery:	24 months (typical) after receipt of order
Launch Vehicle Compatibility:	Ariane, Soyuz, Land Launch, Proton, H2A, Falcon-9, Sea Launch

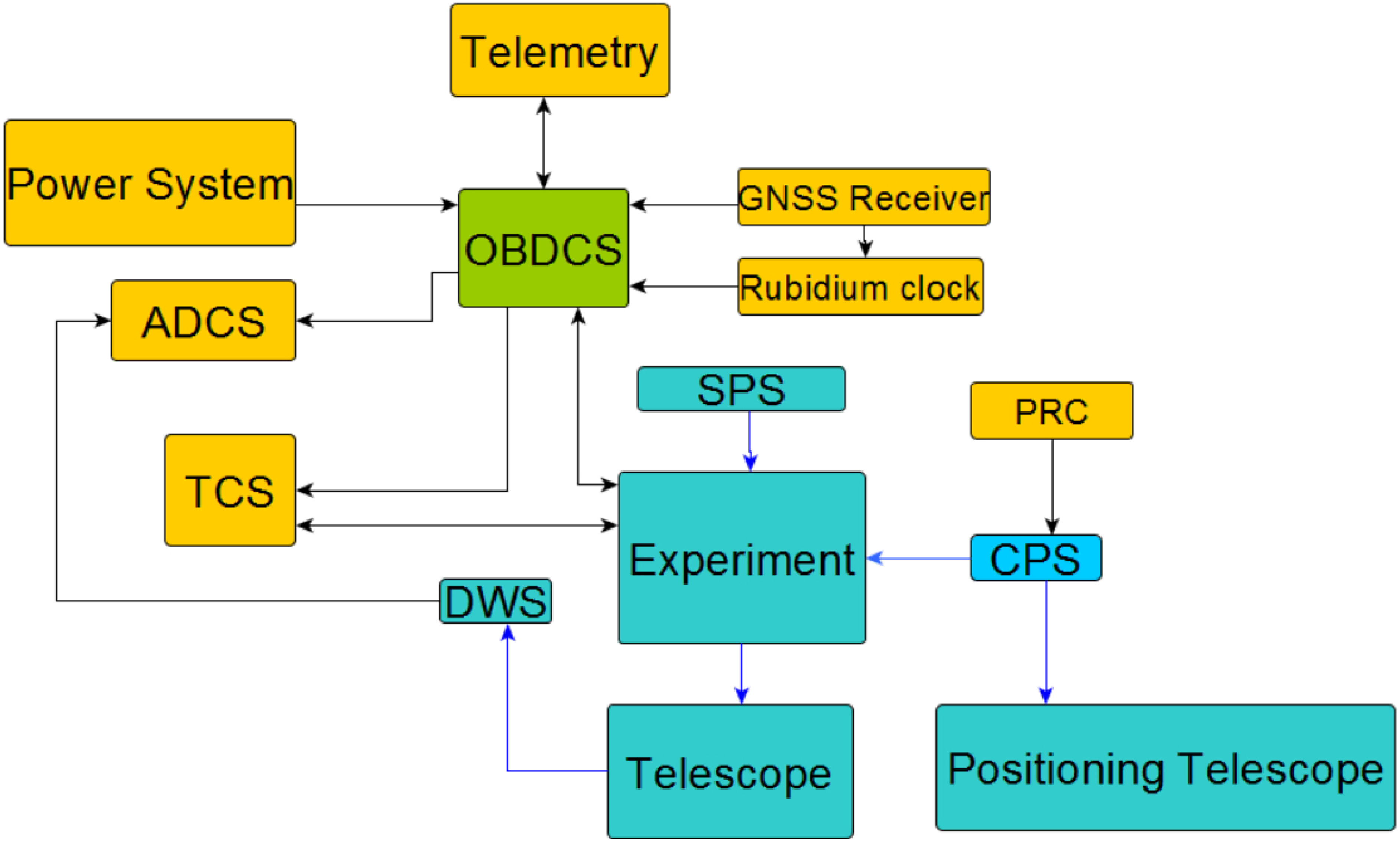
Structure	
Bus Dimensions (HxWxL):	1.75 m x 1.7 m x 1.8 m
Construction:	Composite/Al

Power Subsystem	
Payload Power:	Up to 5,550 W orbit average @ 15 years
Bus Voltage:	24-36 VDC (nominal)
Solar Arrays:	Multi-junction GaAs cells
Batteries:	Li-Ion

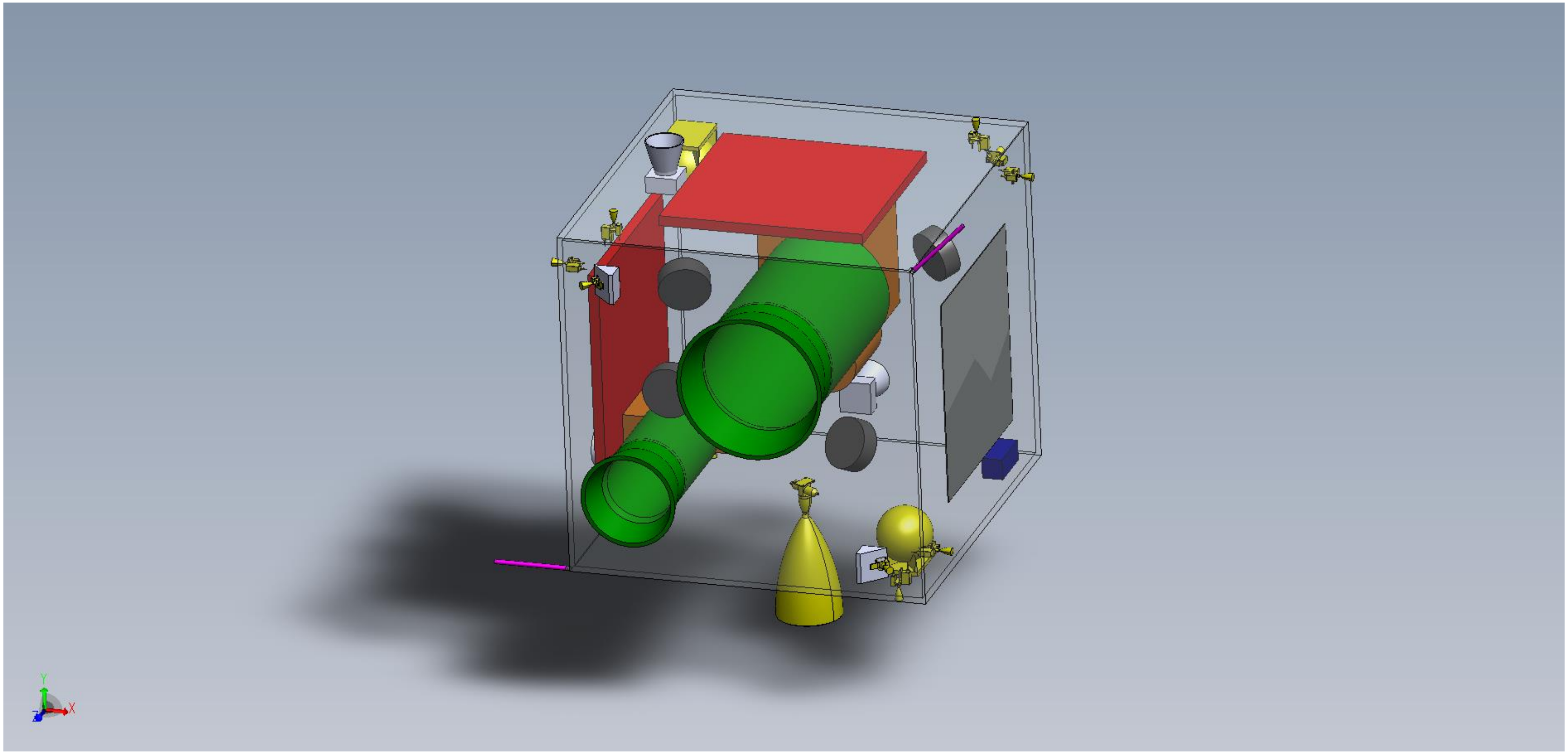
Attitude Control Subsystem	
Stability Mode:	3-axis; zero momentum
Propulsion Subsystem	
Transfer Orbit System:	Liquid bi-propellant
On Orbit:	Monopropellant (hydrazine)

Command & Data Handling Subsystem	
Flight Processor:	MIL-STD-1750A
Interface Architecture:	MIL-STD 1553B, CCSDS

Spacecraft architecture



Satellite assembly



Communication subsystem

- 430 MHz (UHF) half-duplex
- Downlink
  - 16 W RF power
  - Bitrate 50 kbit/s: 25 kbit/s data + 25 kbit/s error correction
  - Half wave dipole antenna
  - Link closes with 1.0 dB margin
- Uplink
  - 10 W RF power
  - Bitrate 5 kbit/s: 2.5 kbit/s data + 2.5 kbit/s error correction
  - 3 m diameter parabolic antenna
  - Link closes with 5.6 dB margin

Mass Budget

Subsystem	Mass [kg]	Margin [%]	Mass with margin [kg]
Instrument	89,6	20	107,52
Communication system (RF)	10	10	11
On-board Command and Data Handling System	1,5	10	1,65
Electrical Power System	32,79	10	36,07
Structure	28	20	33,6
Attitude Determination and Control System	11,7	10	12,87
Thermal Control System	14	10	15,4
Radiation shielding	50	10	55
Total dry mass	**237,59**		**273,11**
20 % Total margin	47,52		54,62
Total dry mass with margin	**285,11**		**327,74**
Propulsion system:	78,10	20	93,72
Total	**363,21**		**421,46**

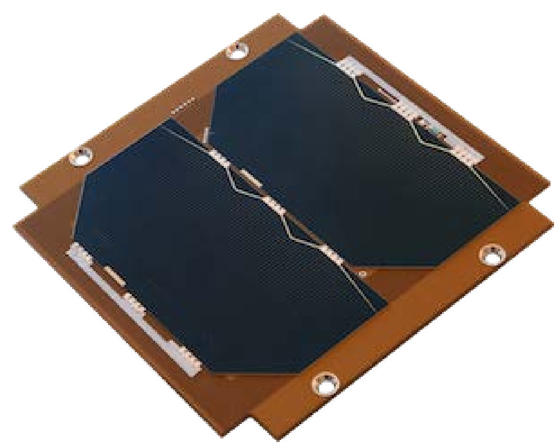
Power Budget

Subsystem	Peak power [W]	Average power [W]	Margin [%]	Average power with margin [W]
Instrument	137,3	102,3	20	122,76
Attitude Determination and Control System	382	150	5	157,5
Electrical Power System	30	30	5	31,5
Thermal Control System			5	0
On-board Command and Data Handling System	7,3	4	10	4,4
Communication system	27	25	10	27,5
Total	**583,6**	**311,3**		**343,66**
System margin (20 %)	116,72	62,26		
Total with margin	**700,32**	**373,56**		

→ Power consumption averaged over a typical orbit taking subsystem duty cycles into account: **299 W**

Electrical Power System

- Solar panel
  - Area: 1 m²
  - Efficiency 28 % (triple junction cells)
  - BOL power: 383 W, EOL power: 380 W (power consumption averaged over a typical orbit: 299 W)
- Batteries
  - Technology: Li-Ion
  - Usable capacity: 1500 Wh



On-Board Command and Data Handling System

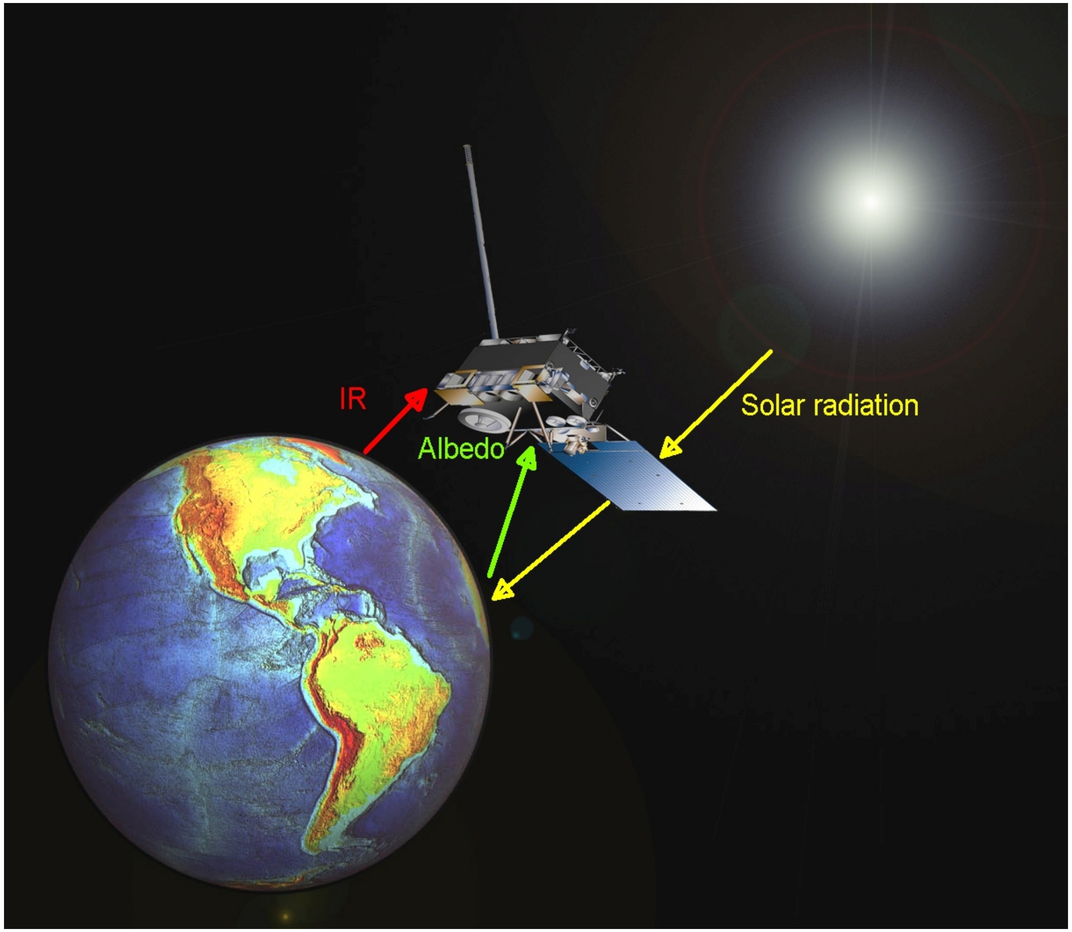
GEN 6 LEON 3FT Single Board Computer from Cobham Semiconductor Solutions

- Radiation tolerance: TID > 100 krad(Si)
- Max. Power consumption 7.3 W
- Memory
  - 64 MB of EDAC SRAM Memory
  - 32 MB of EDAC Non-Volatile MRAM
- Utilised also for the instrument controller

Thermal Control System

Orbital thermal environment:

1. Solar radiation
2. Earth albedo
3. Earth radiation
4. Satellite heat emission



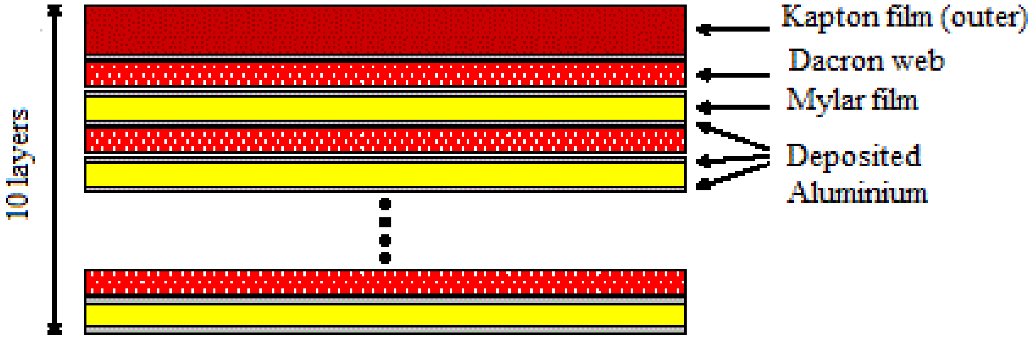
Worst hot case scenario

Solar Radiation,
$J_S = 1374$ W/m²
Albedo radiation,
$J_a = 320{,}54$ W/m²
Planetary radiation,
$J_p = 212{,}22$ W/m²
Internal dissipation, Q = 300 W/m²

Thermal Control System

Thermal Analysis

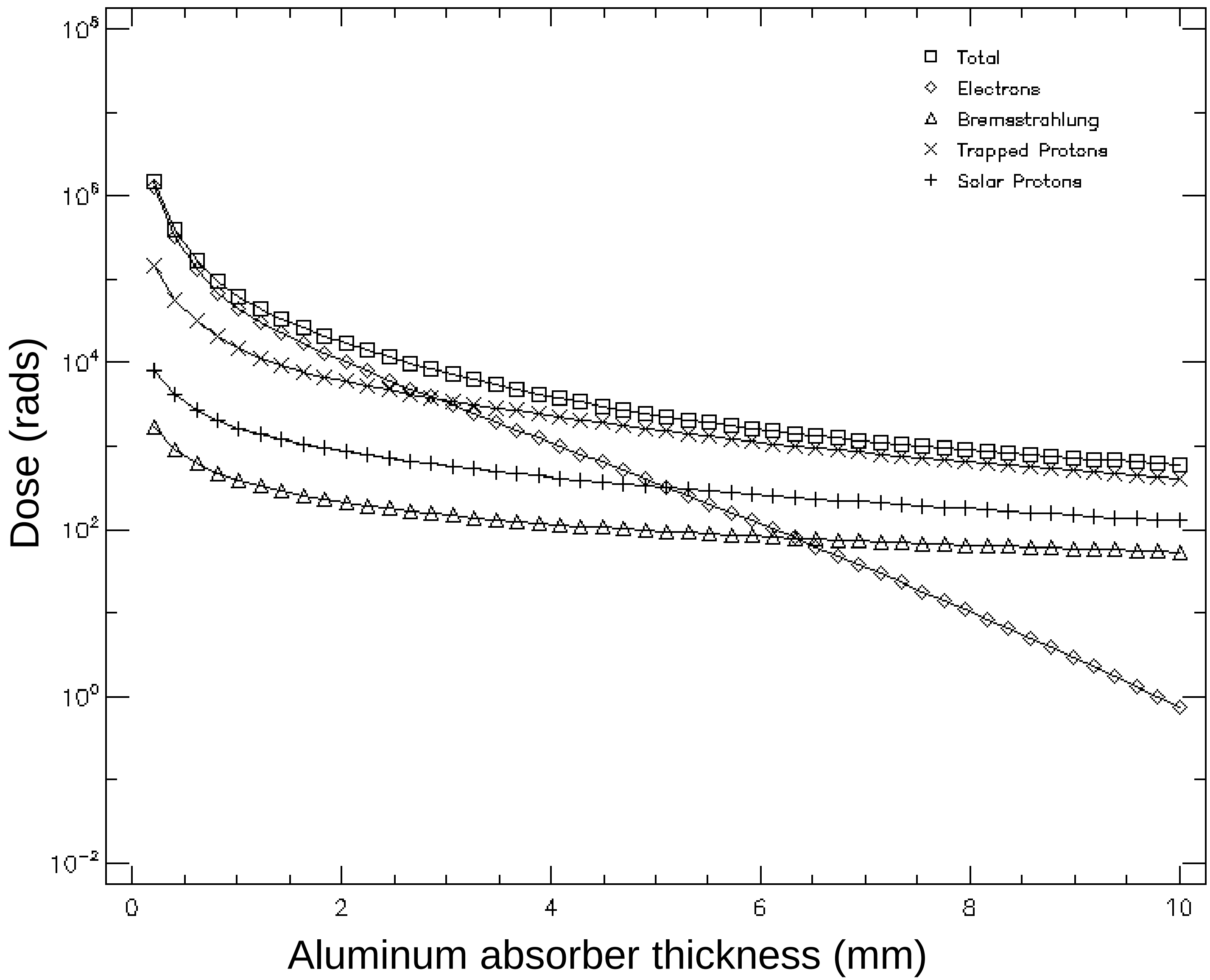
Maximum power dissipation	300	W
Minimum power dissipation	100	W
Maximum Temperature	24,41	°C
Minimum Temperature	-35	°C
Upper temperature limit	35	°C
Lower temperature limit	5	°C



Thermal Control System Configuration

1. MultiLayer Insulation (MLI): *10 double-sided aluminized layers, separated by Dacron net spacers, with an outer layer of Kapton*
2. External surface paint: *silver*
3. Radiator (Teflon): *active surface of 1,92 m^2*
4. Heat pipes
5. Special requirement for optical bench and optical fibre container: *MLI*

Radiation Doses (1 year)



Radiation Shielding Design

Ionising radiation increases attenuation in optical fiber:

0.5 dB/km for TID of 9000 rad

Uffelen, M. et al. *Feasibility Study for Distributed Dose Monitoring in Ionizing Radiation Environments with Standard and Custom-made Optical Fibers*, SP IE Photonics for Space Environments VIII, Proceedings of SPIE, Vol. 4823 (2002)

The radiation dose for 1 year with a shielding of 1 cm of Aluminum is: 593 rad

Therefore for a 60 km fibre the resulting loss is:

$$0.5 \times 60 \times \frac{593}{9000} = -1.98\ dB$$

Radiation Shielding Design

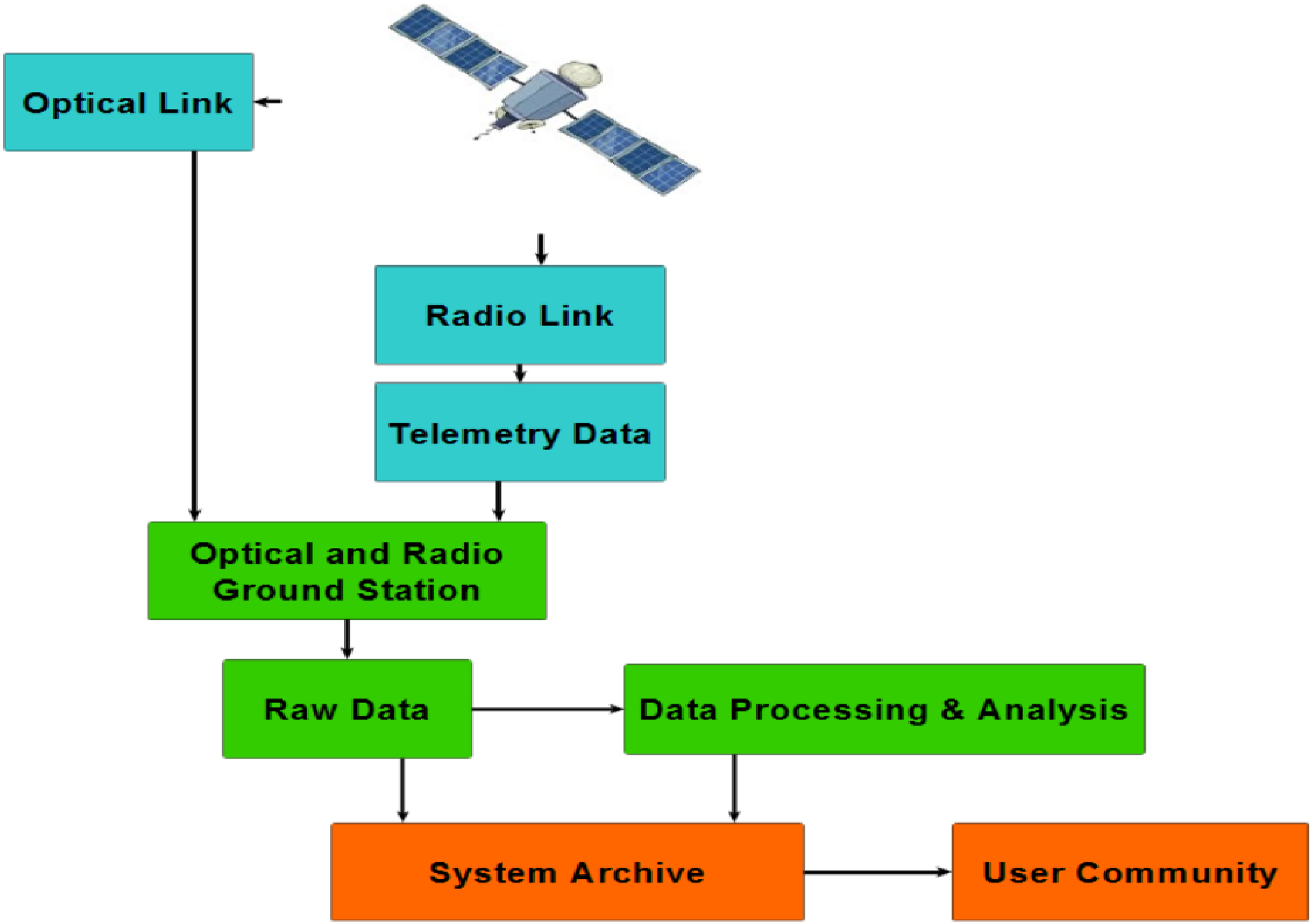
2mm shielding for optical bench and laser.

1 cm Al layer protects detectors from radiation.

1mm shielding for onboard computer - can resist up to 100 krad, enough for our mission.

Programme management

Mission architecture



Project timeline

6 months	2 years	2 years	4 years	4 years
Phase 0	**Phase A**	**Phase B**	**Phase C/D**	**Phase E/F**
• Early concept studies	• Preliminary mission analysis • System trade studies	• Definition studies	• (DDT&E)	• Operations & disposal

Technology development

TRR

Every required technology development have to be finished at that point.

Risk analysis

Risks	Severity	Likeliness	Risk level	Mitigation
Development risks				
Delay of availability of optical fibres in specification range	Extreme	Likely	Very high	Extended technology development and test program, technology has to be ready before Phase B.
Delay of availability of the frequency stabilisation	Very high	Moderate	Medium	Extended technology development and test program, technology has to be ready before Phase B.
Operational risks				
Blackening of fibres due to radiation damage	Very high	Moderate	Medium	Radiation shielding, short mission duration
Single laser failure	Medium	Unlikely	Low	Redundancy concept, short mission time
One reaction wheel fails	Negligible	Moderate	Very low	Redundancy: continue operation with 3 reaction wheels.

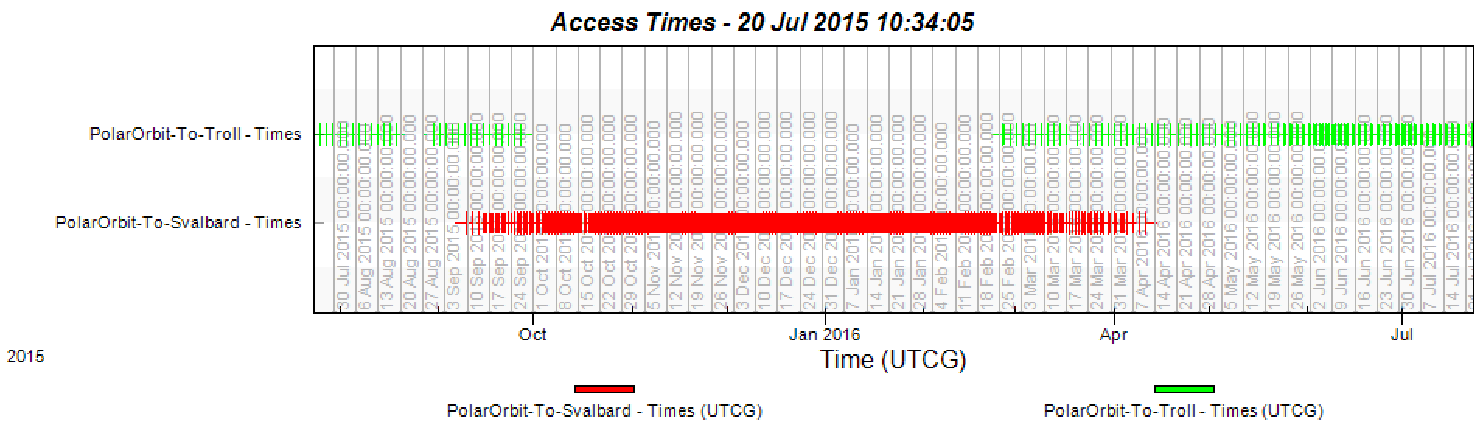
Finances – M Class Mission

Item	Cost (M€)
Project Team (PT)	30
Spacecraft (S/C)	150
Mission Operation Cost (MOC)	40
Science Operation Cost (SOC)	40
Payload (P/L)	200
Launcher	45
Contingency	28
Technology development	50
TOTAL COST	***583***

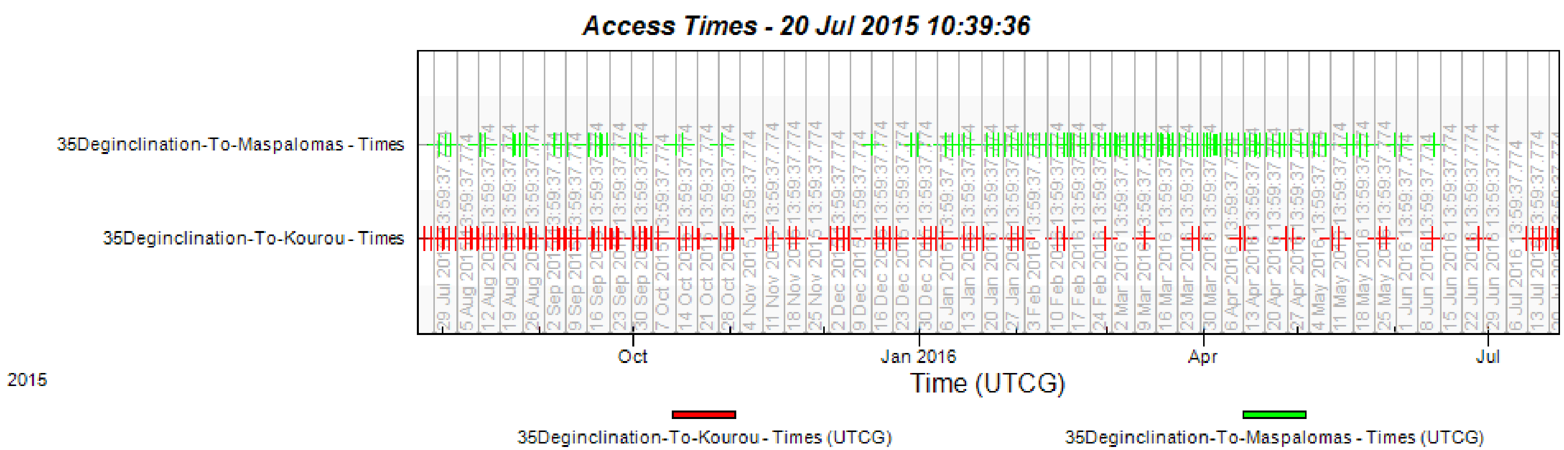
Item	Budget (M€)
ESA	333
Member states	250

Descoping option

90° inclination: 708 connections with a total of 1816 h



35° inclination: 188 connections with a total of 173 h



Outreach and public benefit

Outreach

Educational browser games (e.g. Quantum optic experiments) accessible via QR codes hidden in mission related publications

Public data archive, real time measurement visualization

Public benefit

Optical fiber technology – dispersion less communication networks, high speed system control for large science facilities (e.g. linear accelerators)

Janos will advance the foundations for satellite based quantum communication

Conclusion

- Janos will be the first mission to test the interaction between quantum mechanics

  and Einstein’s theory of general relativity in a **controlled experiment**.

- Experiment realization is within reach of current laser and detector technology.

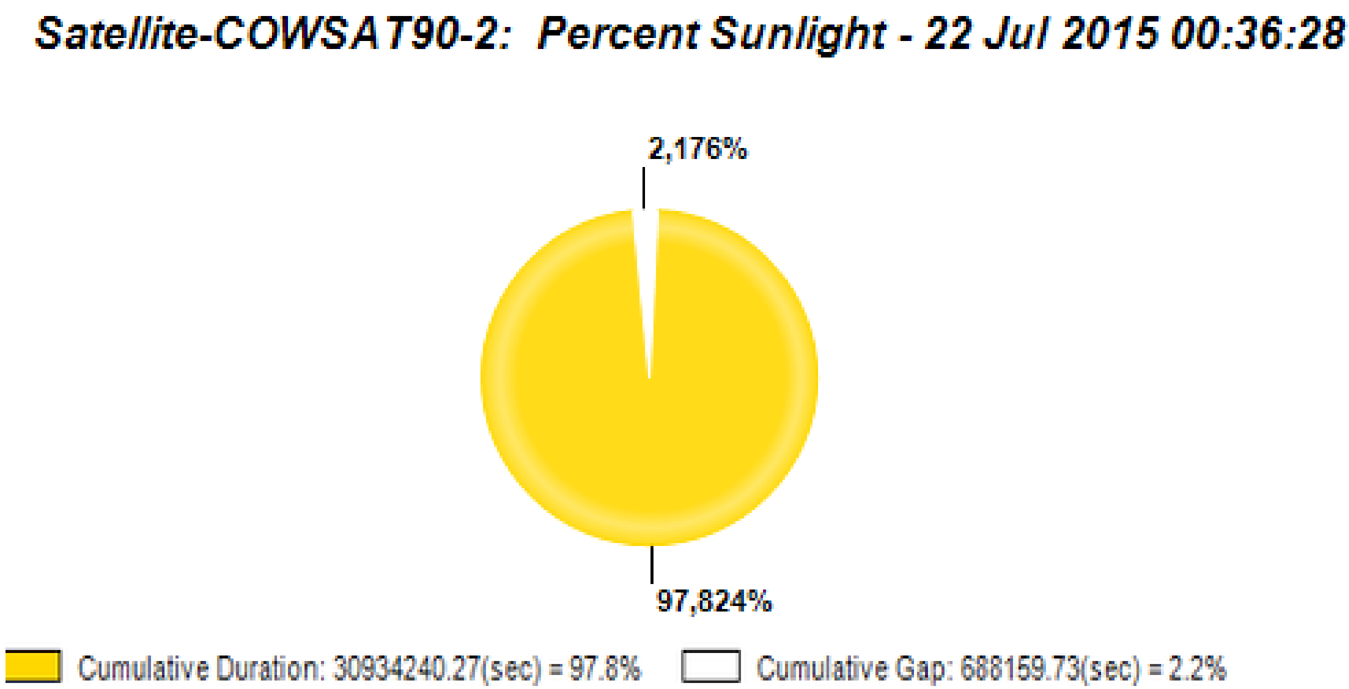
- Technology development is relevant for quantum science
  and the high tech industry.

Thank you for your attention

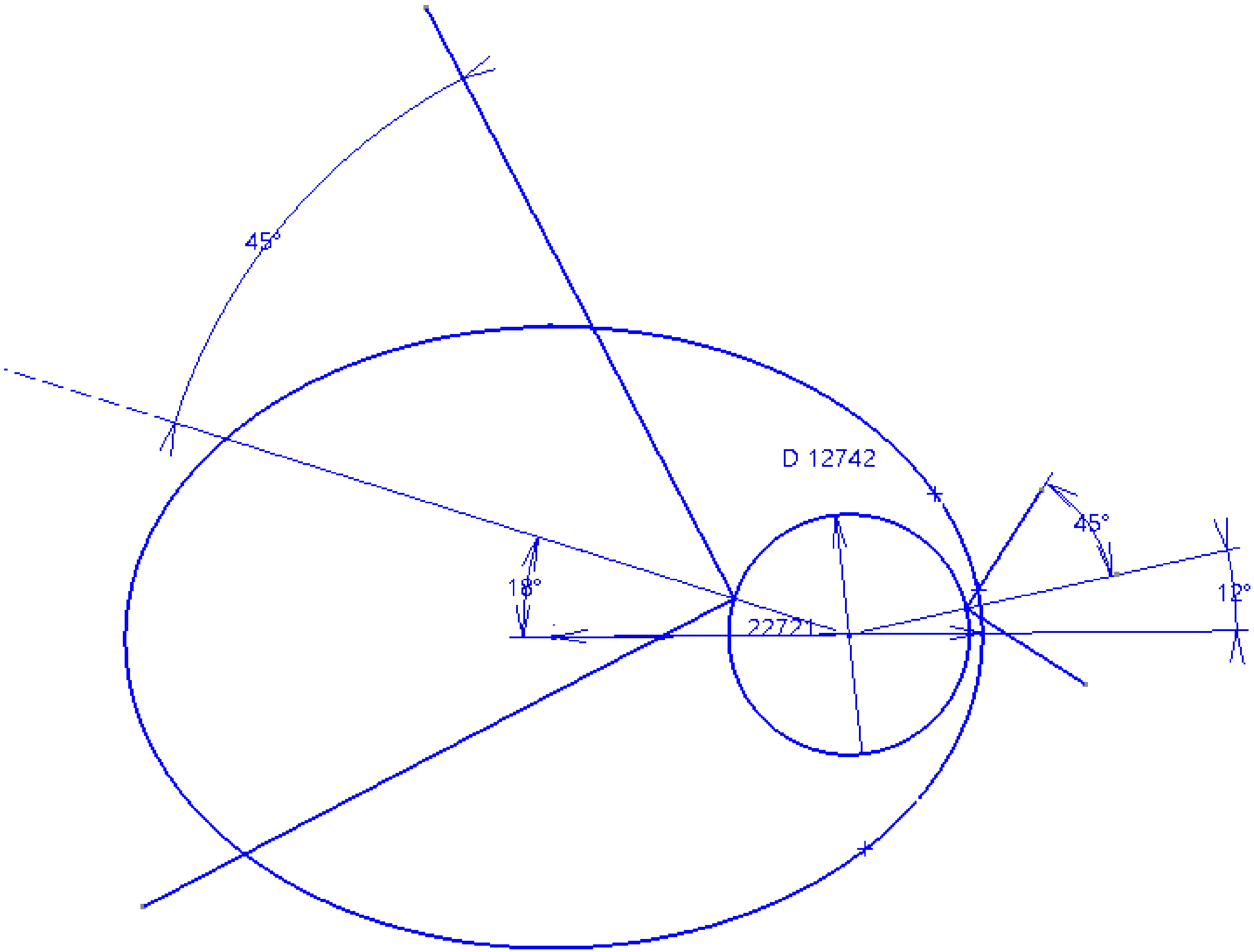

Hard Rock
CAFE

Backup slides

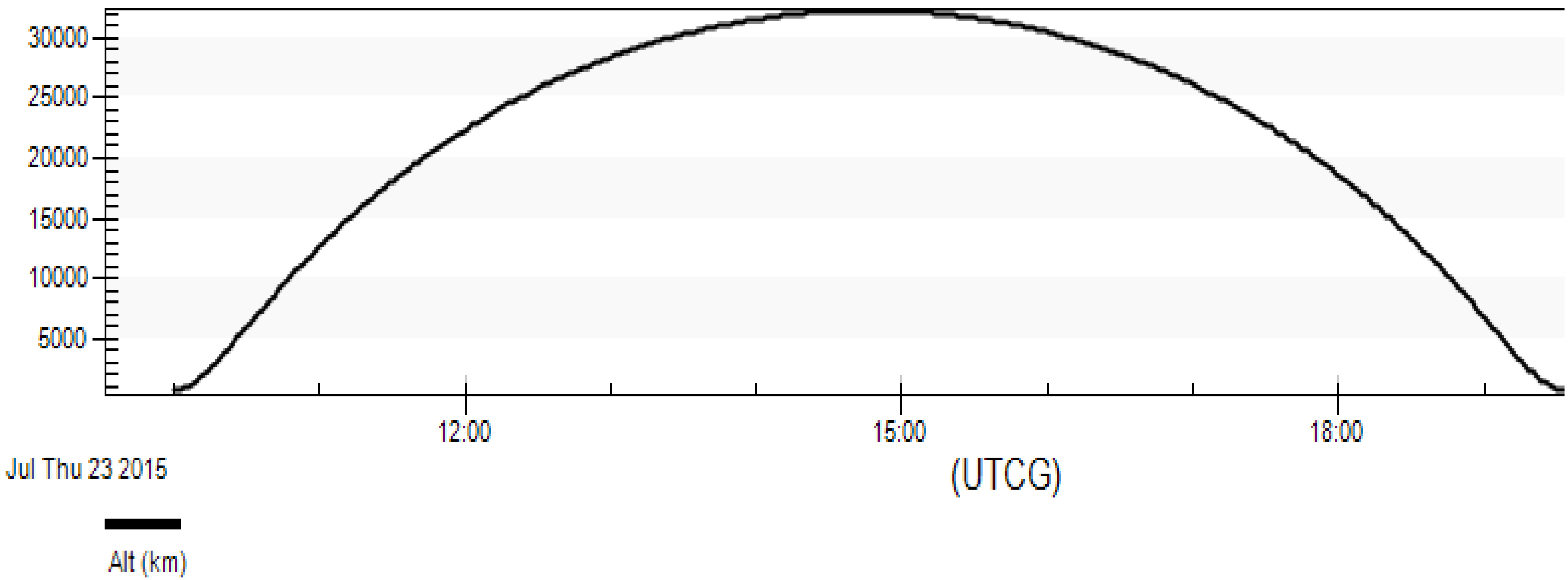
Orbits 1-Sunlight



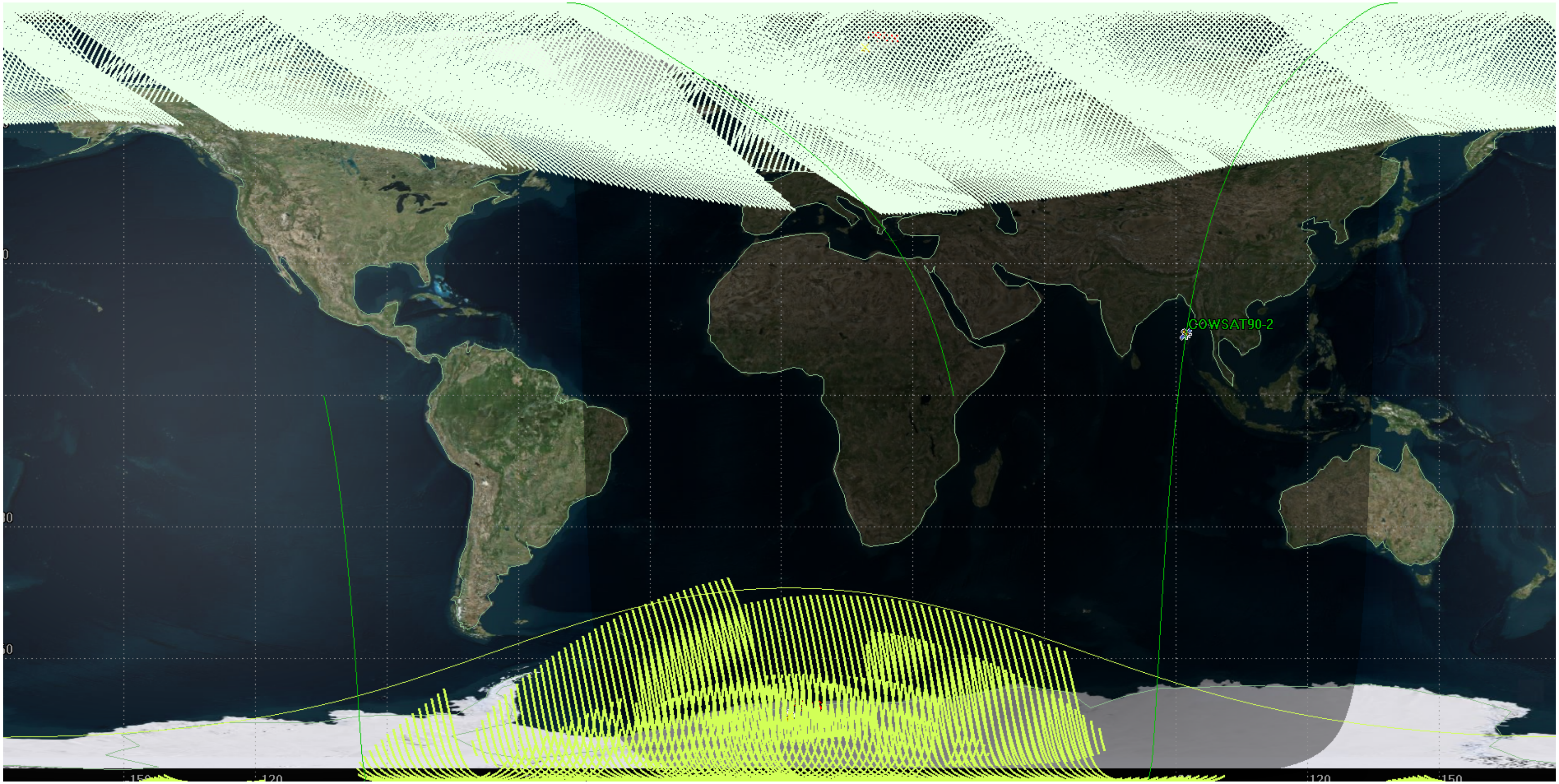
Orbit 4 - Geometry



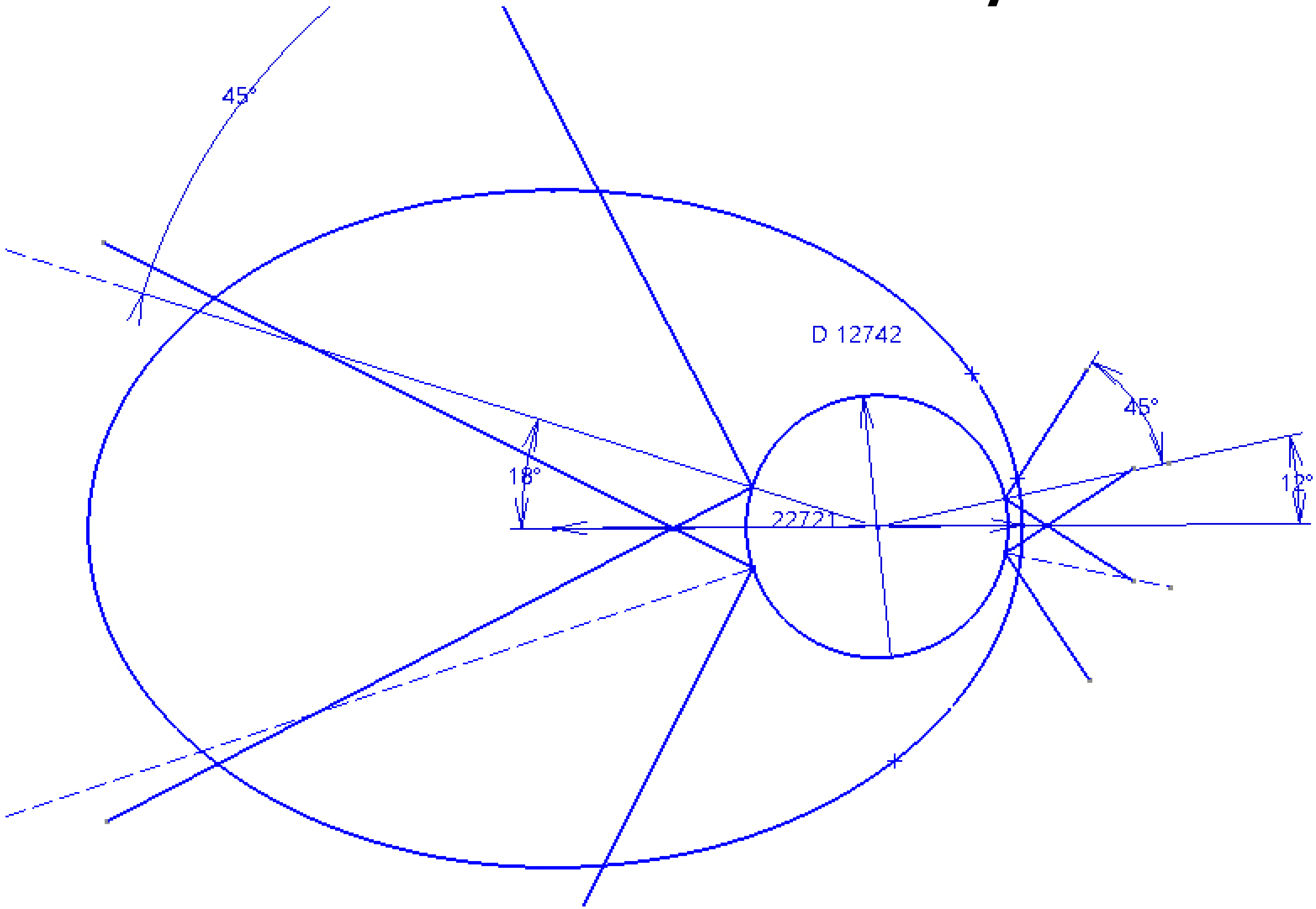
Orbits 2 – Altitude change



Orbital Coverage



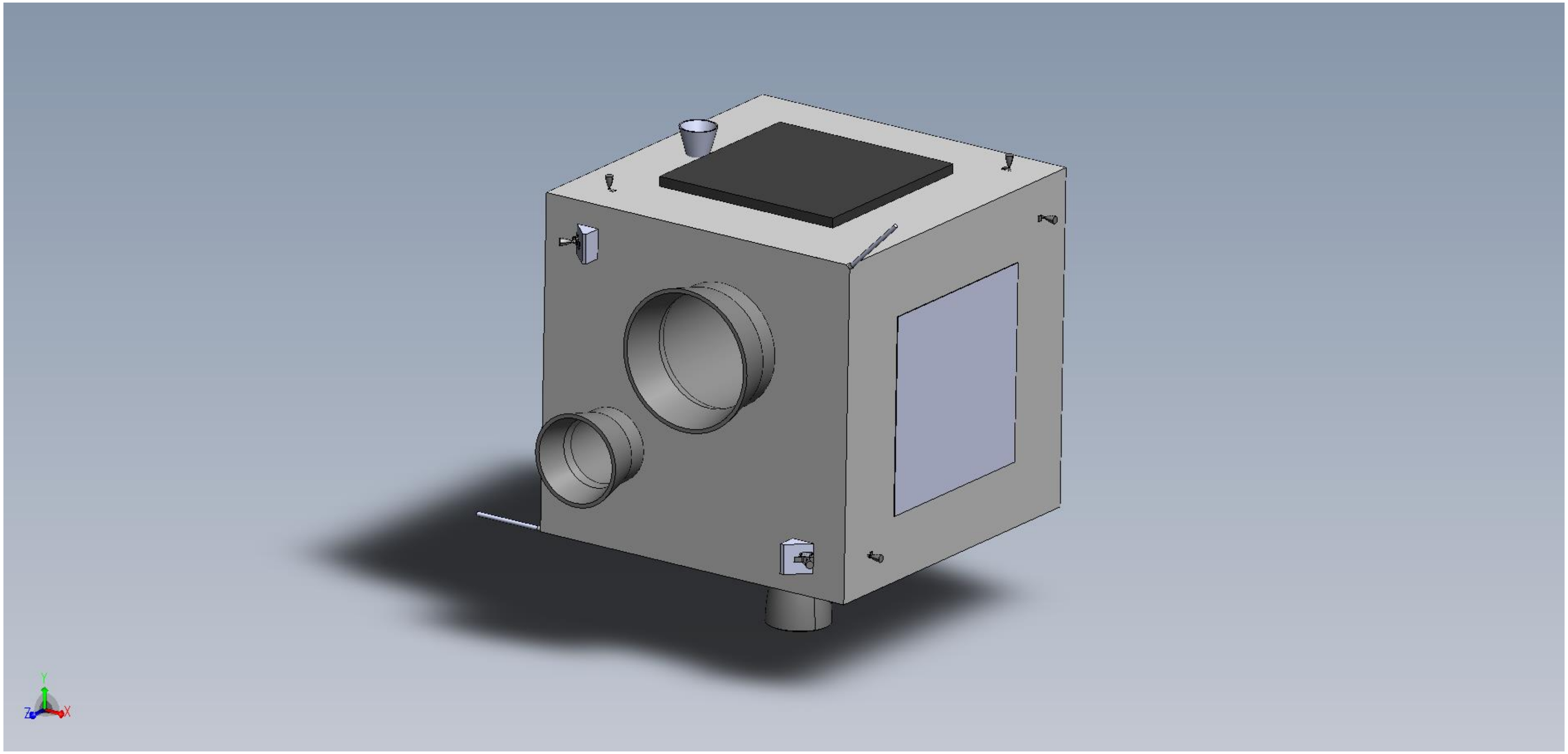
Orbit 5 – Geometry 2



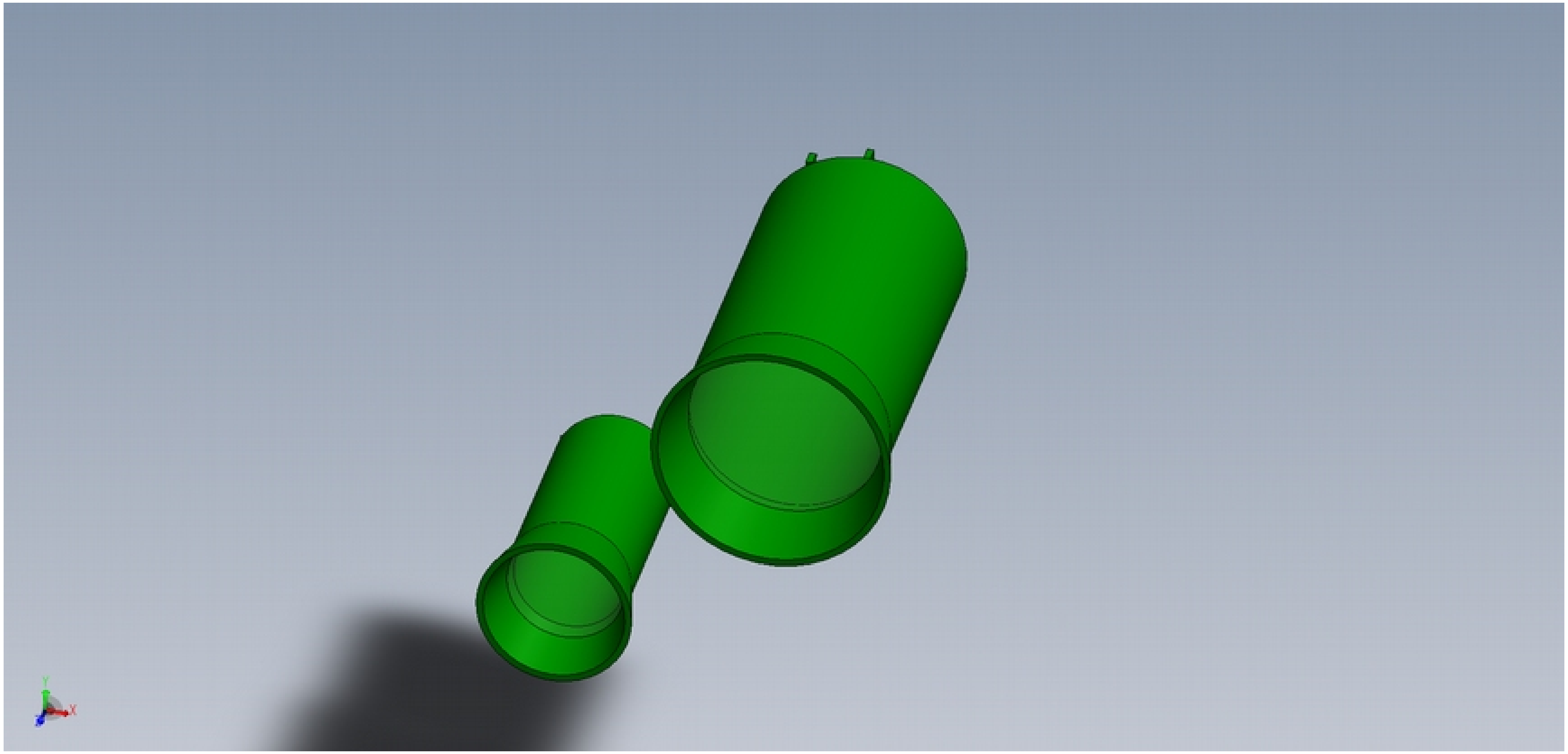
Propulsion

- MMH: 11.22kg
- N2O4: 18.52kg
- Pressurize gas: Helium
- Tank mass: 4.72kg (Titanium)

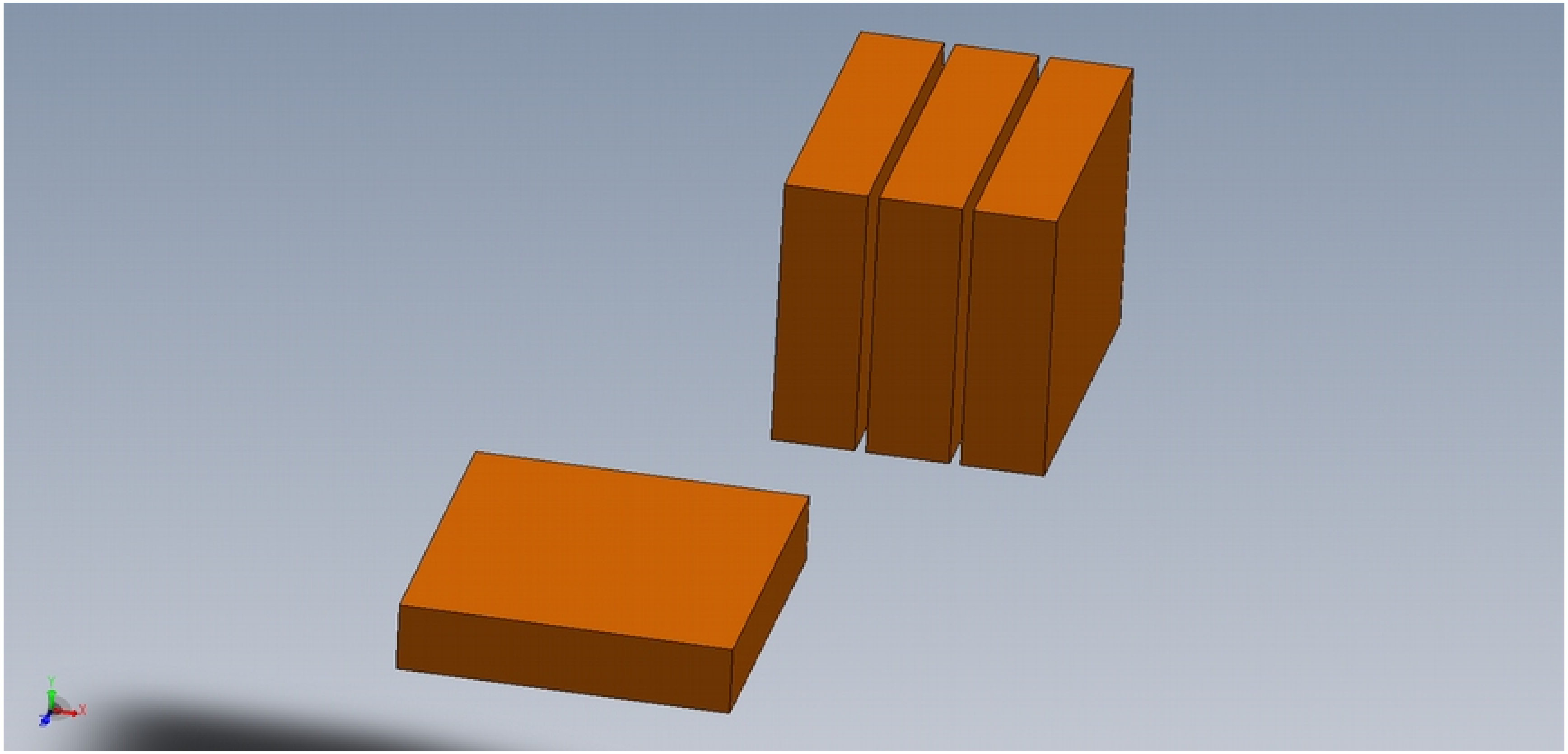
Satellite assembly



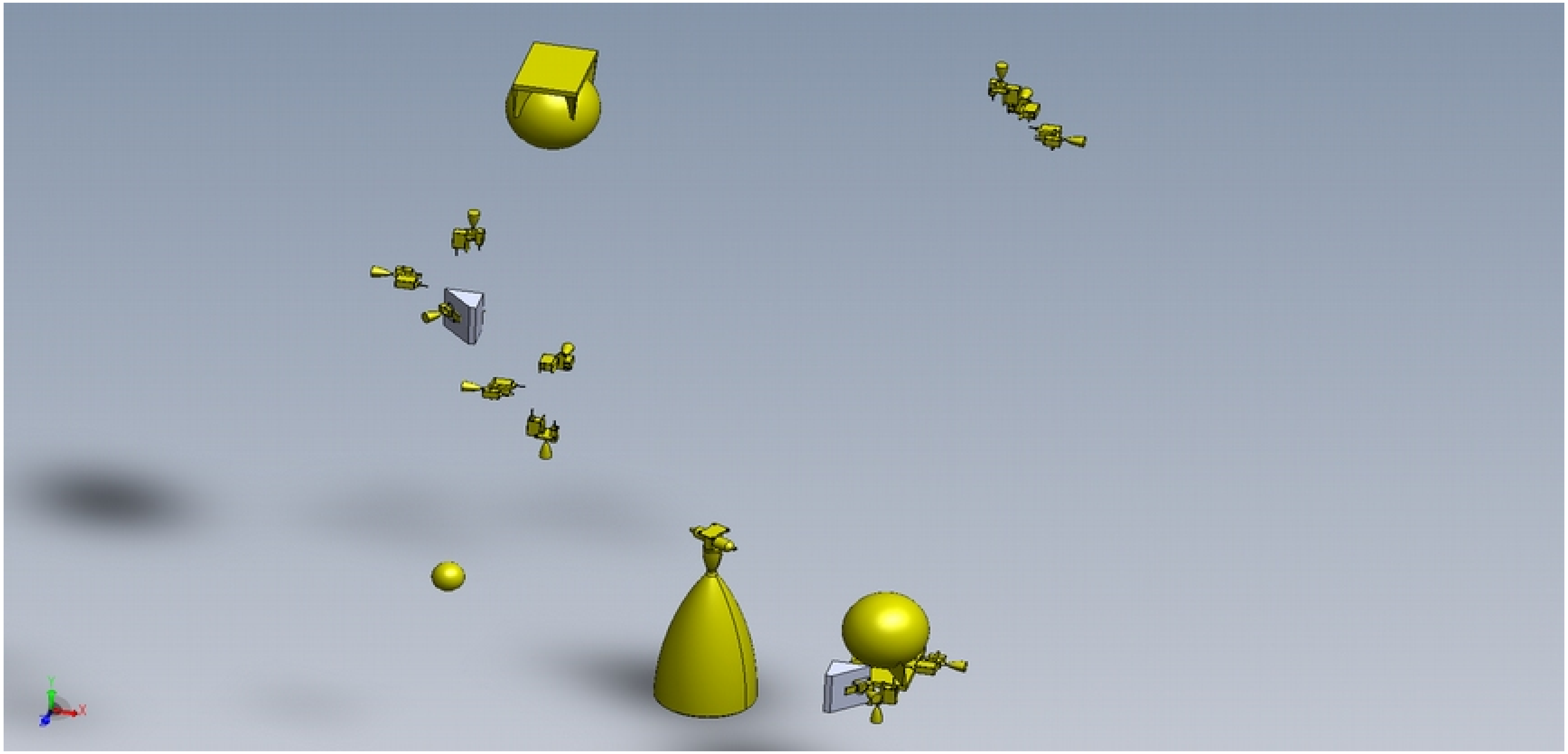
Optical assembly



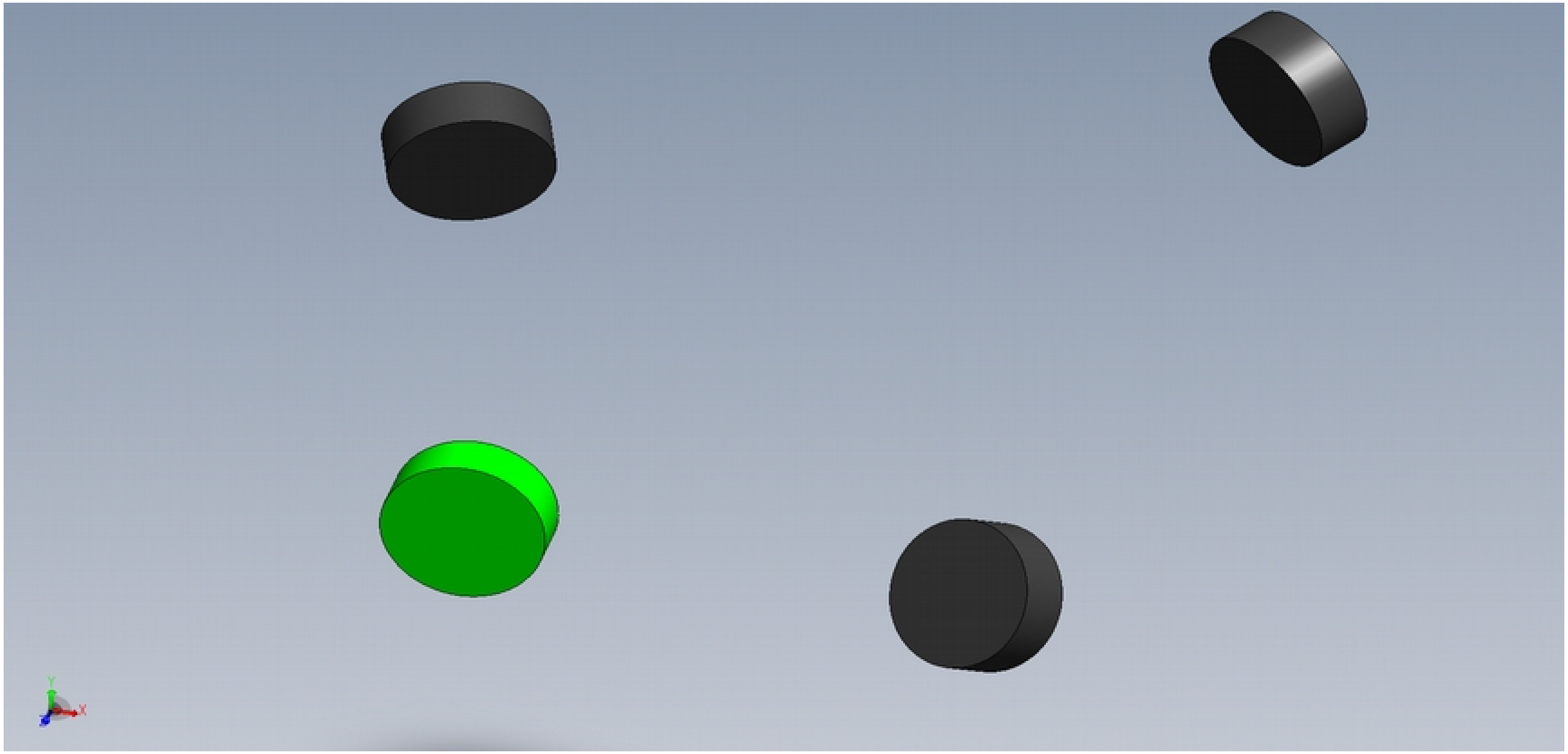
Laser



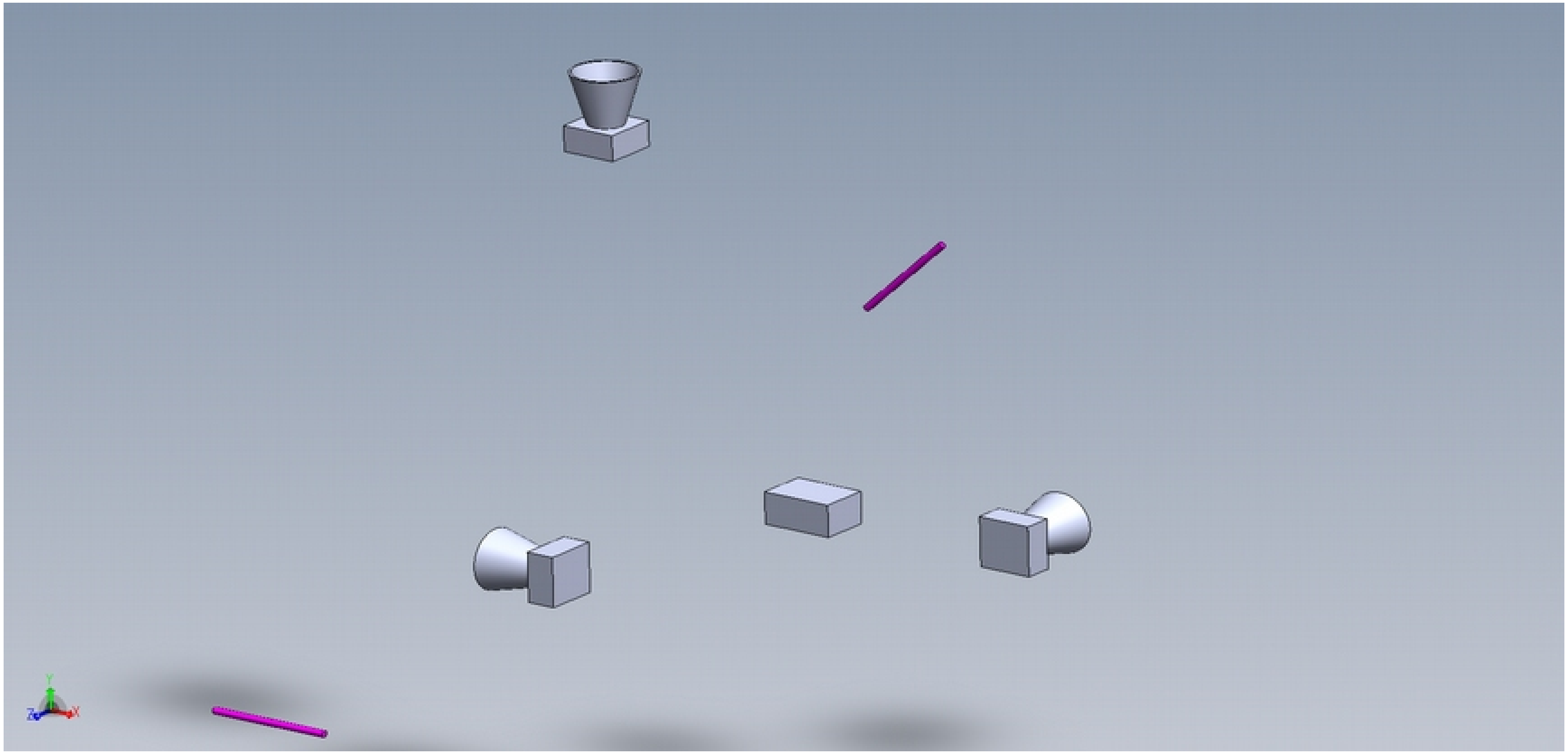
Thruster propulsion



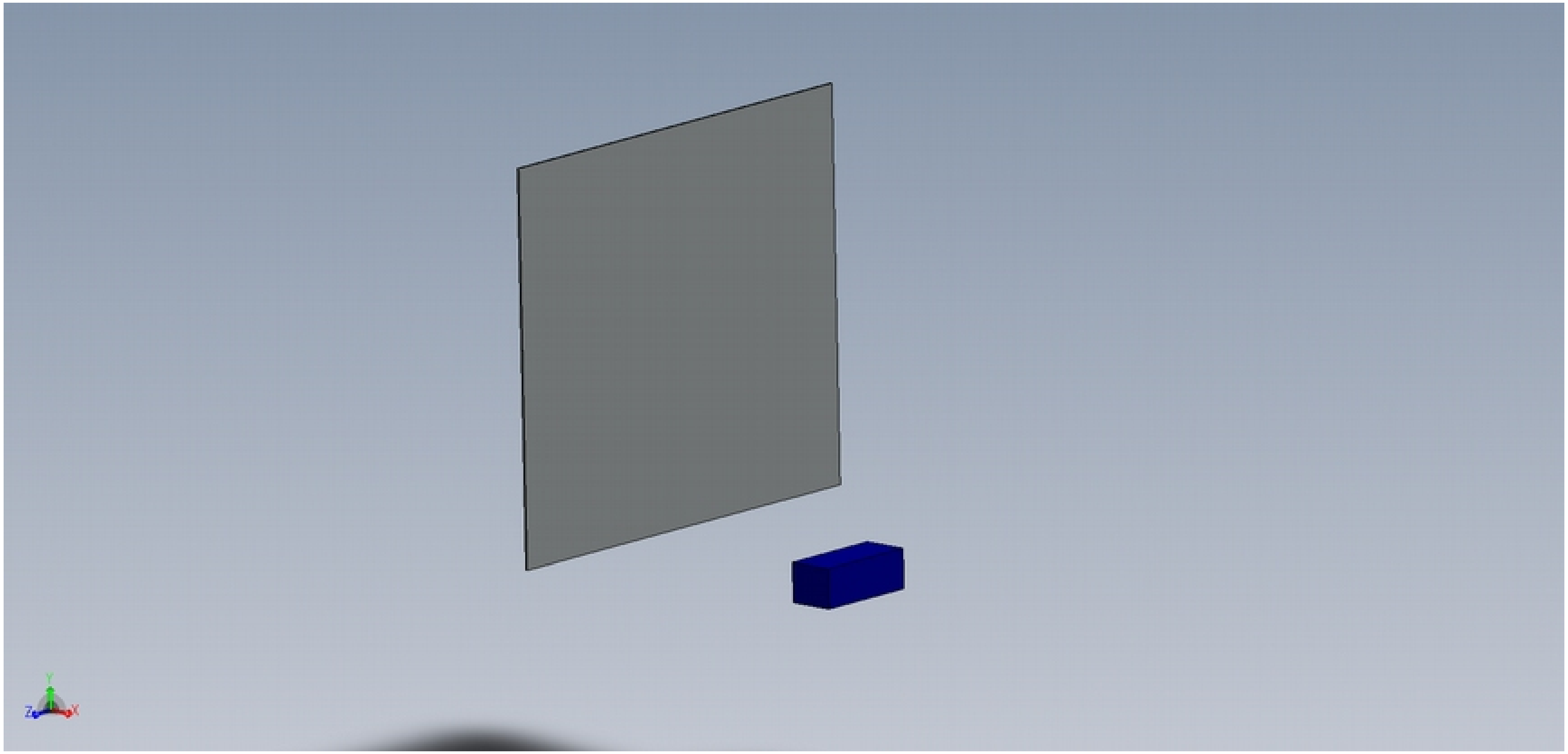
Reaction wheels



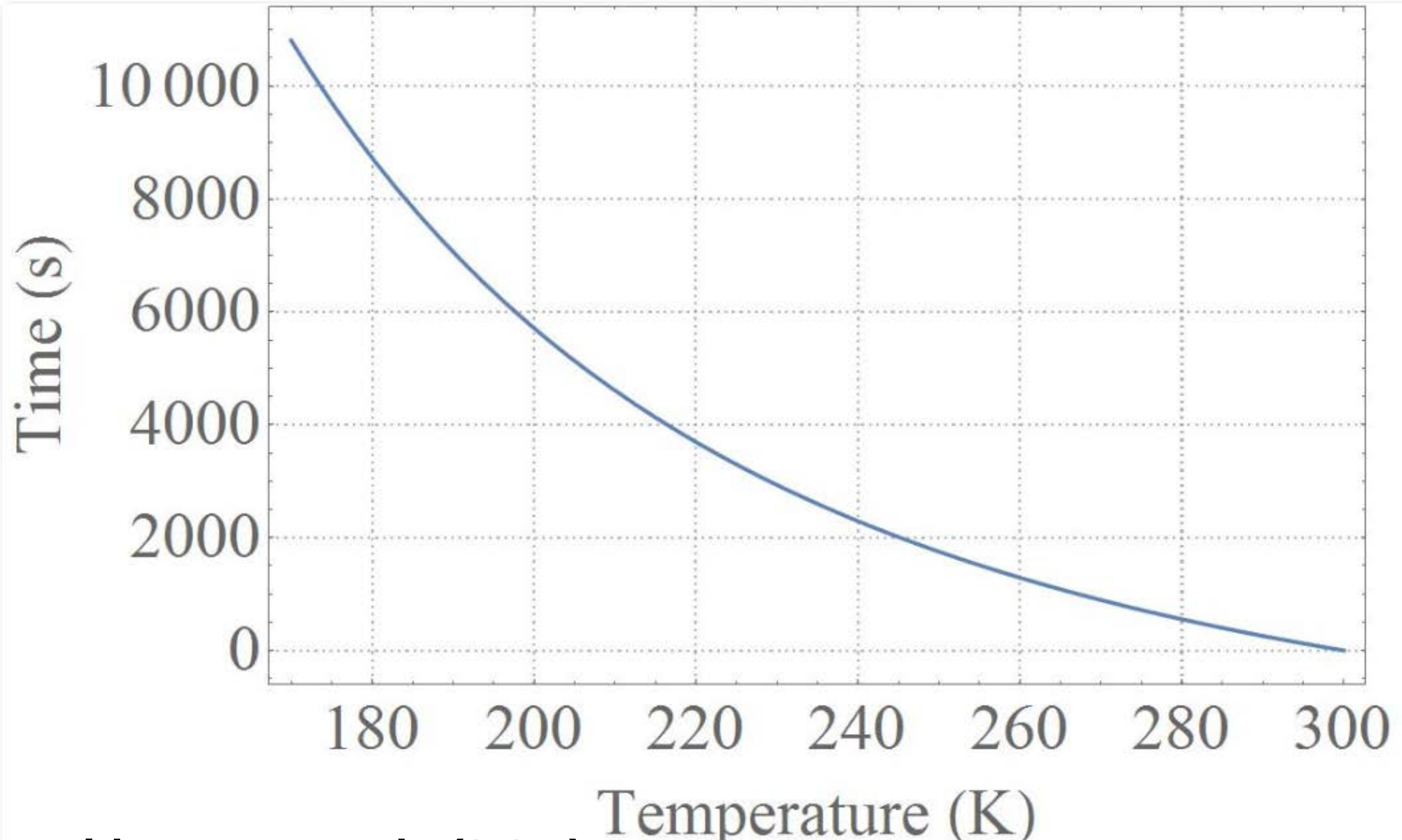
Control system



Power system



Temperature variation during an eclipse



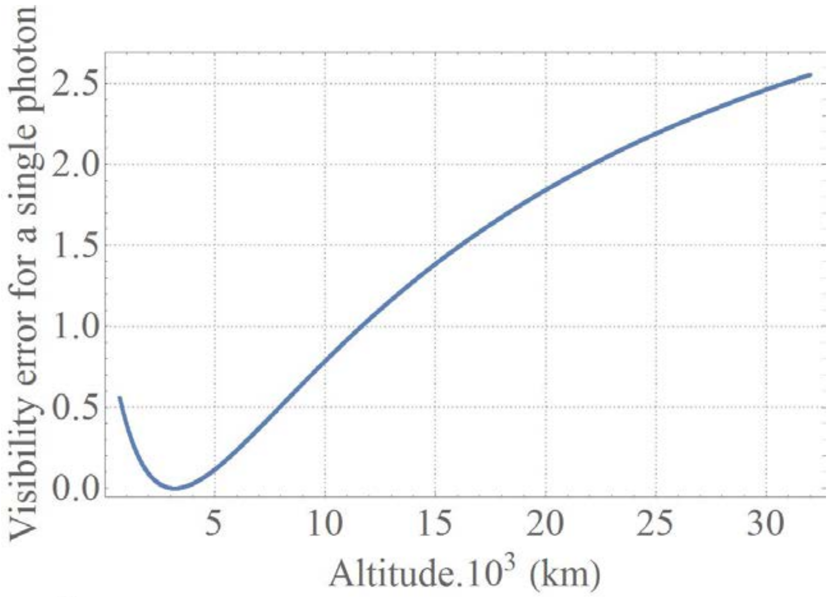
Worst cold case scenario (2-3%)
Planetary radiation,
J_p= 149,54 W/m²
Internal dissipation,
Q = 300 W/m²

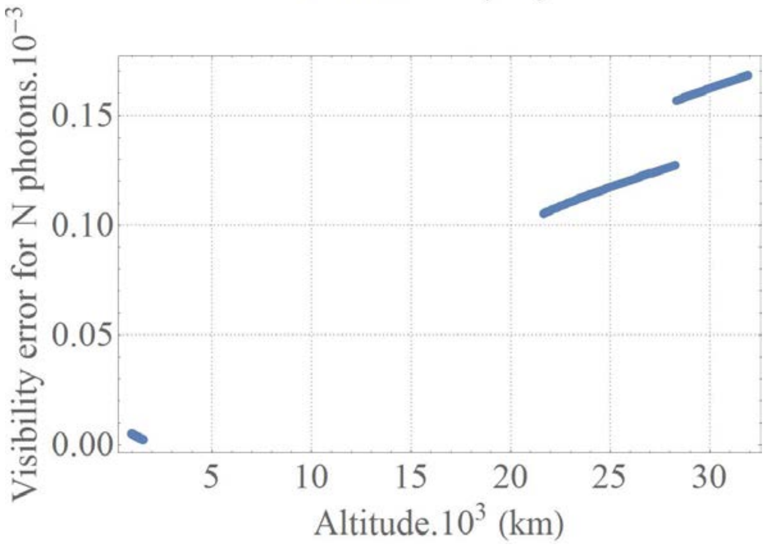
<u>Conclusion</u>: For an eclipse of 1 hour, the temperature of the satellite decreases by 50 degrees.

Potential outcomes

Fringe contrast	Phase Match	Consequences
Newtonian model	yes	high confidence - single quanta couple differently to general relativity than classical matter
Einsteinian model	yes	High confidence - single quanta couple to gravity identically to classical light
Newtonian model	yes, and frame dragging	drop in visibility too hard to resolve
Newtonian model	no	systematic error present
Einsteinian model	no	systematic error present
Einsteinian model	yes, and frame dragging	single photons are also susceptible to frame dragging effects as well as GR

Relative error of Visibility





Alpbach Summer School 2015
Team Blue