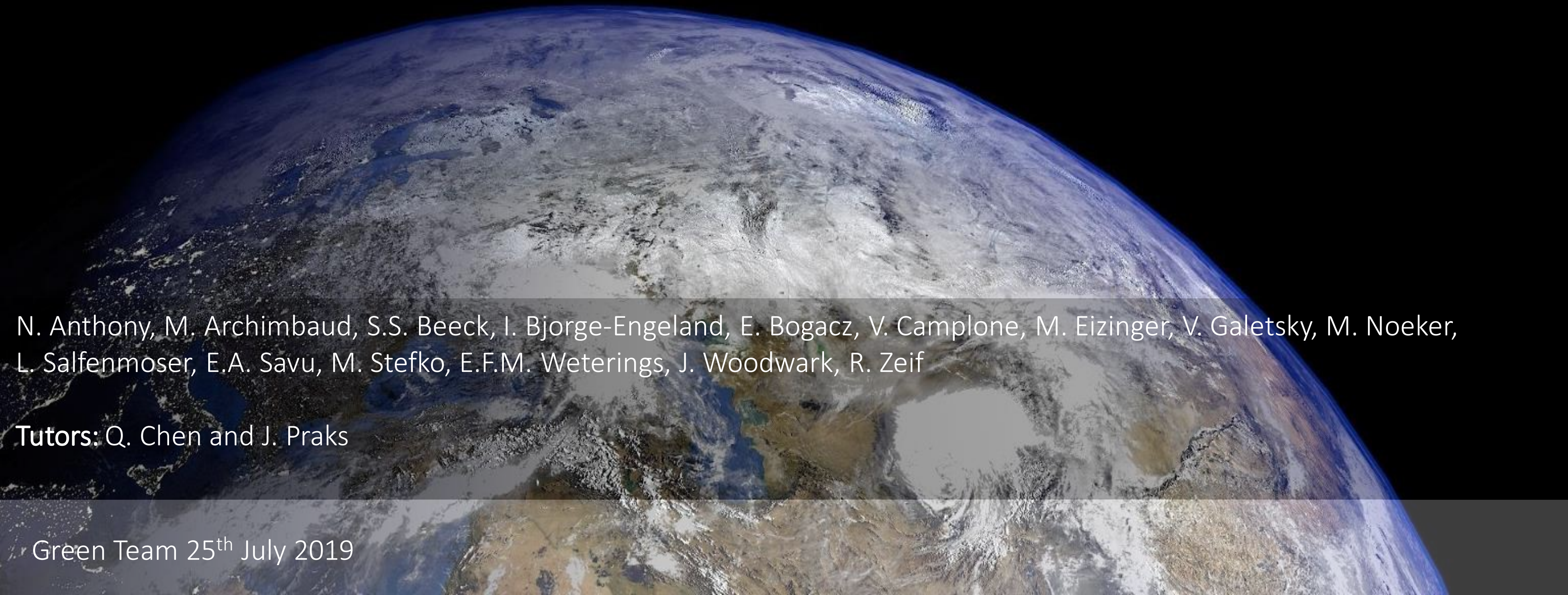
GRAVL

GRAvity observations by Vertical Laser ranging



N. Anthony, M. Archimbaud, S.S. Beeck, I. Bjorge-Engeland, E. Bogacz, V. Camplone, M. Eizinger, V. Galetsky, M. Noeker, L. Salfenmoser, E.A. Savu, M. Stefko, E.F.M. Weterings, J. Woodwark, R. Zeif

Tutors: Q. Chen and J. Praks

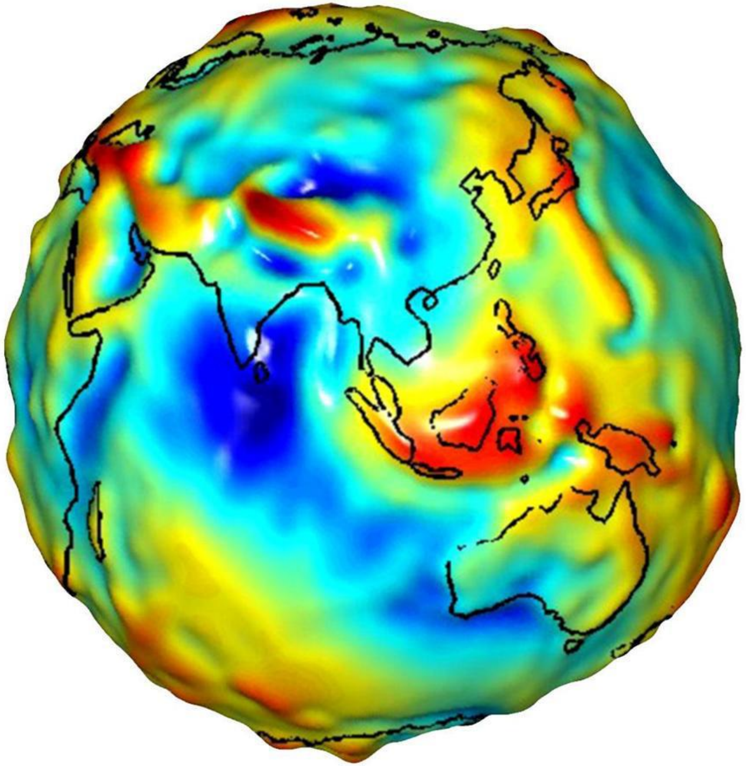
Green Team 25th July 2019

Associated Press

GRAVL

Mission statement

The GRAVL mission will measure Earth's gravitational anomalies with unprecedented ***accuracy*** *and* ***coverage*** *to significantly improve our understanding of seismic processes*



NASA Earth observatory, NASA, ESA

Presentation overview

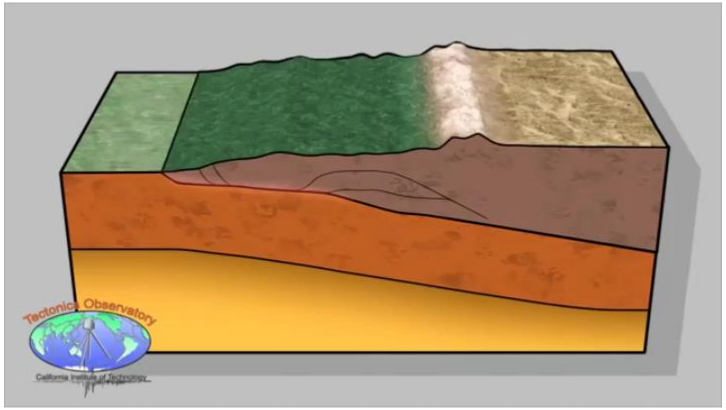
1. Science case
2. Mission concept
   - Alternatives
   - Selection
3. Engineering study
   - Overview
   - Mission profile
   - Payload
   - Spacecraft design
4. Programmatics
   - Technological Readiness Level
   - Schedule
   - Risks
   - Outreach

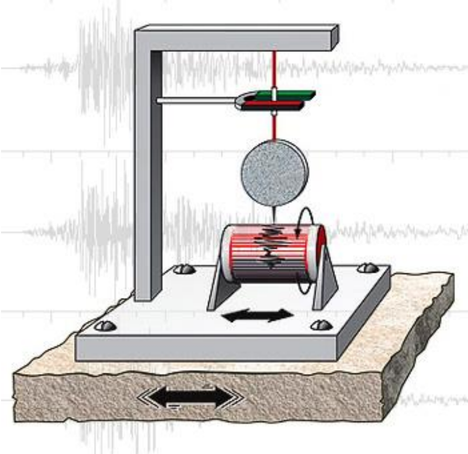
Science case

Science introduction

Seismology = science of earthquakes and the related vibrations of the earth

- Movement of tectonic plates causes stress accumulation and (sudden) releases: **earthquakes**
- Surface vibrations measured with **seismographs**
- Investigation enables modelling of tectonic sub-surface processes and helps **improve the understanding of plate tectonics**





Dollynarak: FAL license

Science Objective 1/3

Improve models of tectonic processes

How does the Earth's upper mantle and crust behave before, during, and after earthquakes?

Science requirement: measure pre-, co-, and post- seismic mass movements of earthquakes down to Mw 6.5

Science Objective 2/3

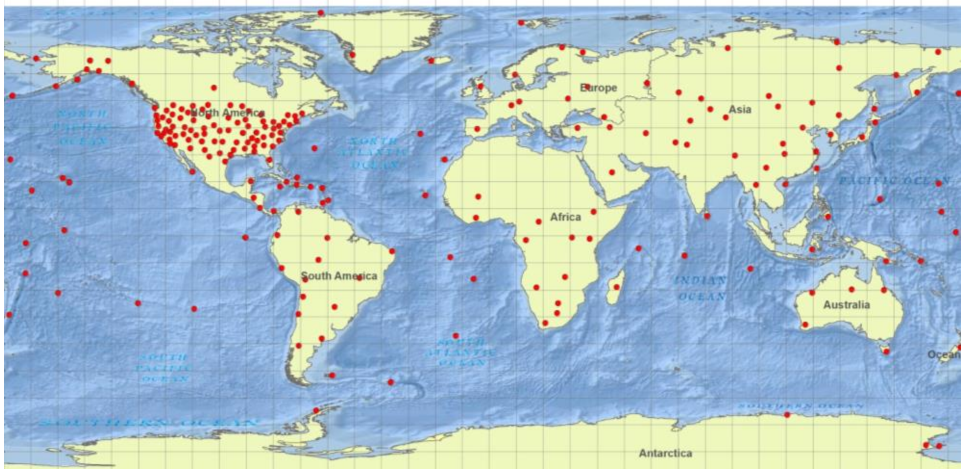
Develop an understanding of silent earthquakes

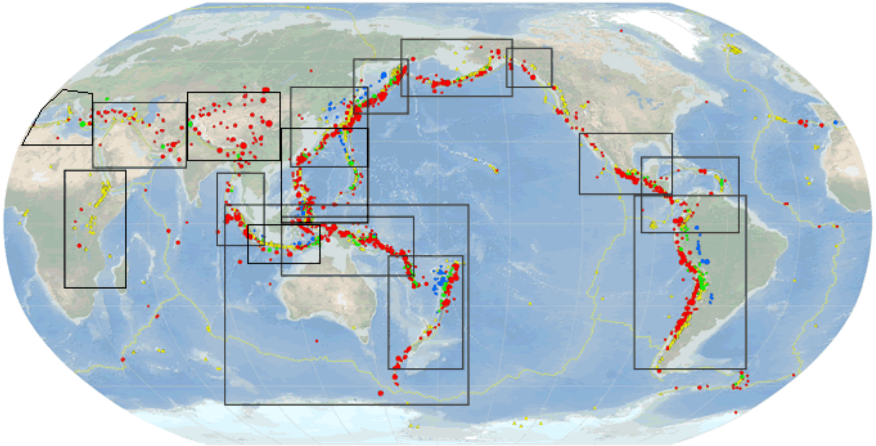
What are the characteristics of “silent” or “slow” earthquakes, and how are they related to tectonic movements and sudden earthquakes?

Science requirement: measure mass redistribution related to silent earthquakes

Science Objective 3/3

Improve knowledge of mass movement in areas with sparse surface measurement



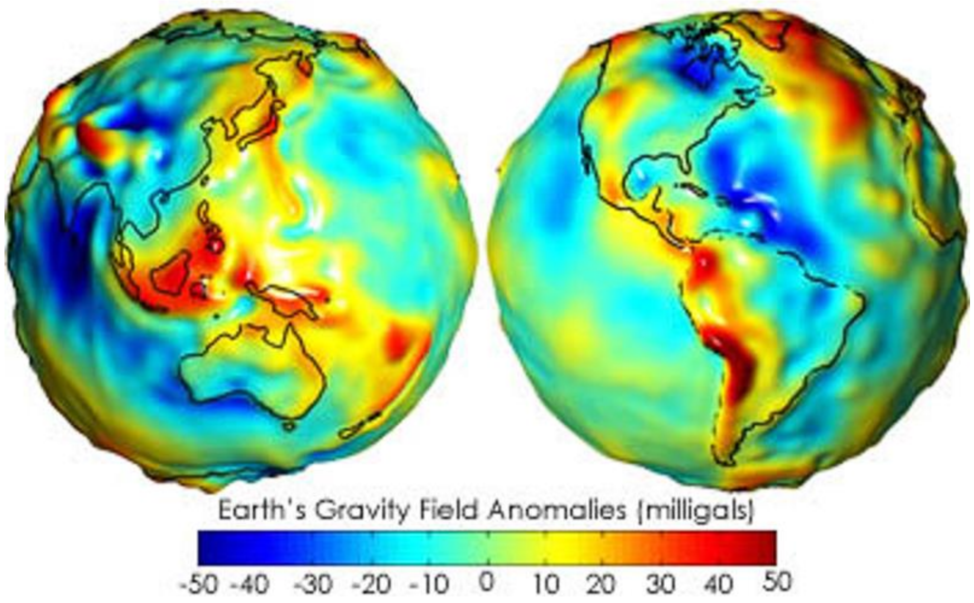


IRIS and the U.S. Geological Survey

Science requirement: measure gravity changes caused by tectonic movements in non-accessible regions

Gravimetry from space

- **Gravimetry** = measurement of magnitude of gravitational field
- Gravity anomalies of order mGal (static) and µGal (temporal)



NASA Earth observatory, NASA, ESA

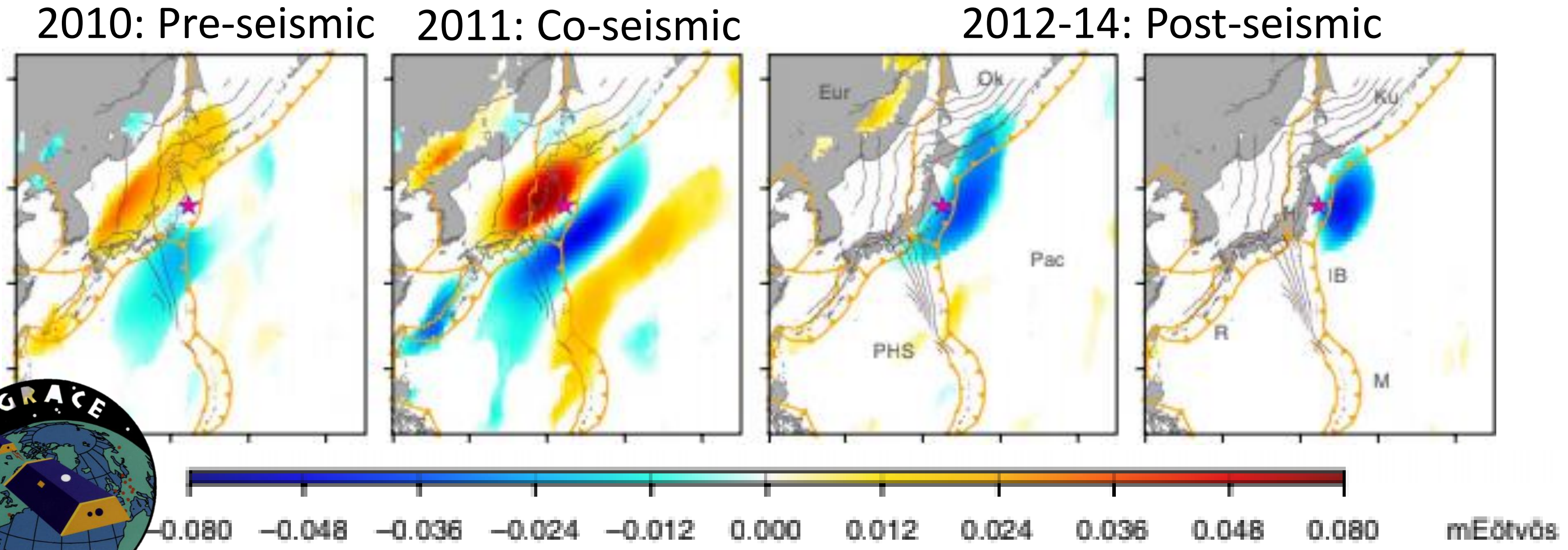
Gravitational seismology

Tectonic processes changes in the gravitational field. This can be observed from space by means of **gravitational seismology**.

- Global coverage with satellite constellations
- Good spatial resolution from space based measurements can outperform unevenly distributed ground-based network
- Less resources required for operations
- Nano- or micro-satellites relatively cost-efficient

Gravitational seismology: state-of-the-art

- GRACE demonstrated feasibility with detection limit > Mw 8.3
- Constellations: global coverage with resource-efficient operations


2010: Pre-seismic

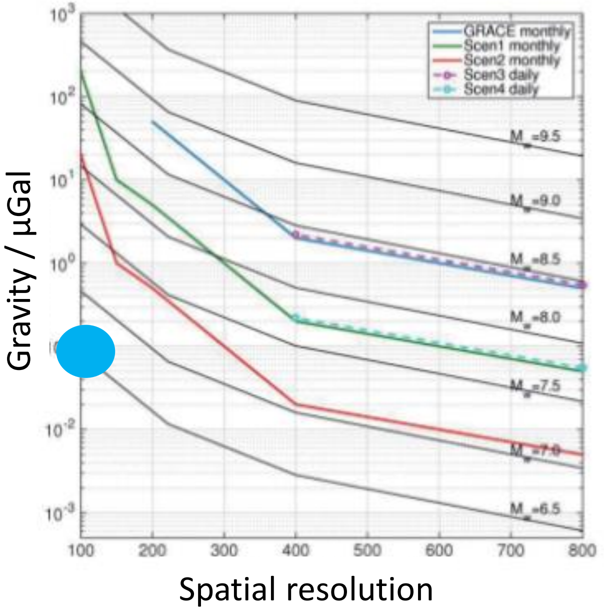
2011: Co-seismic

2012-14: Post-seismic

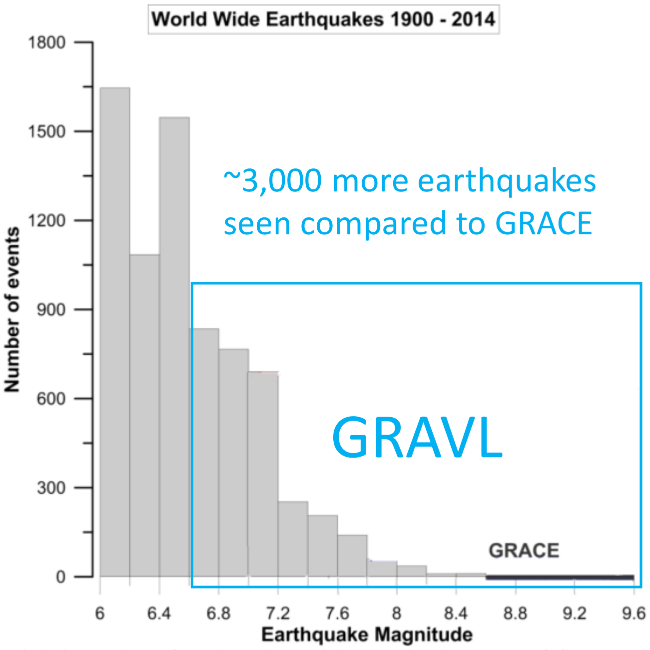
Panet et al., Nature Geoscience, 2018

Observation requirements

Importance of sensitivity to lower magnitude events



Pail et al, DGK report 320, 2015

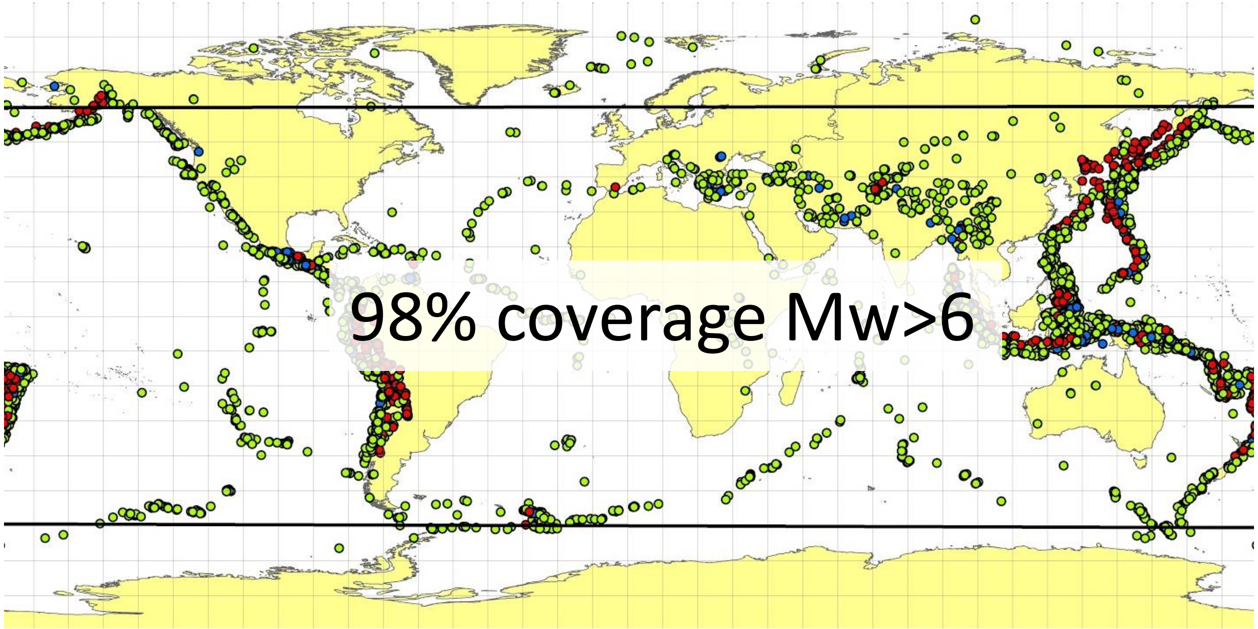


~3,000 more earthquakes seen compared to GRACE

Requirement	Value
Spatial resolution	100 km
Sensitivity	0.1 µGal
Temporal resolution	3 days
Measurement duration	7 years
Coverage	± 60° latitude

Observation requirements

Importance of latitudinal coverage



ANSS - USGS

Requirement	Value
Spatial resolution	100 km
Sensitivity	0.1 µGal
Temporal resolution	3 days
Measurement duration	7 years
Coverage	± 60° latitude

Secondary science objectives

1. Improve the understanding of ocean currents
2. Improve our ability to monitor the hydrological cycle

Background signals:

- Ocean tides
- Atmospheric air masses
- Glacial Isostatic Adjustment

Mission concept

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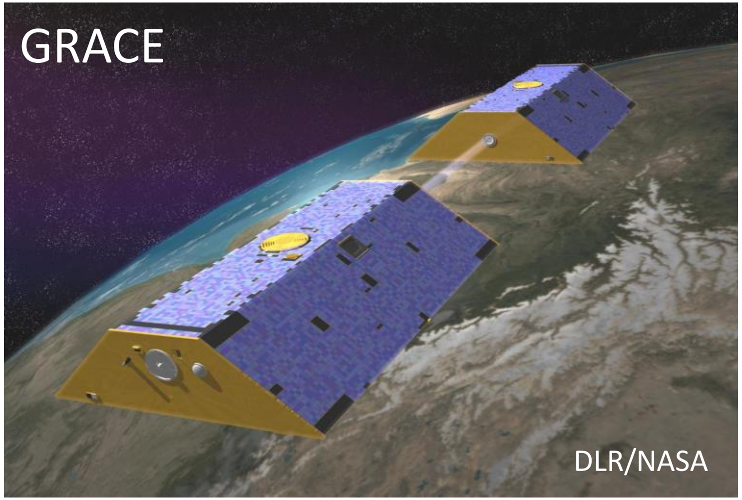
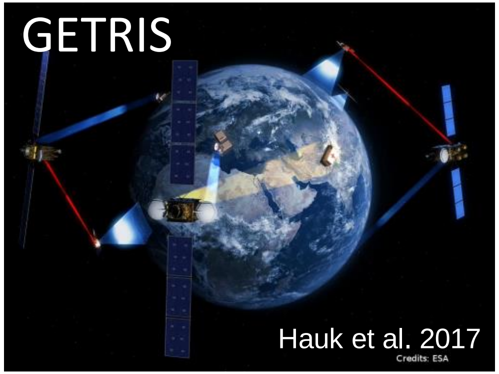
Existing concepts and missions


GRACE

DLR/NASA


GOCE

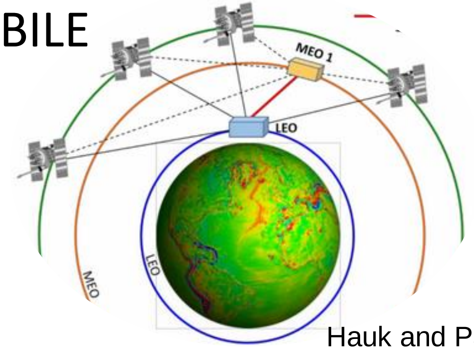
ESA


GETRIS

Hauk et al. 2017

Credits: ESA

MOBILE

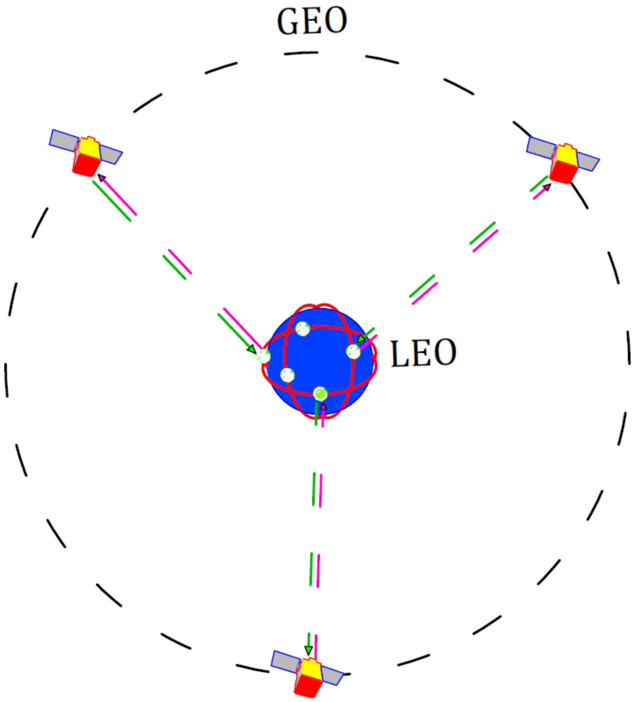


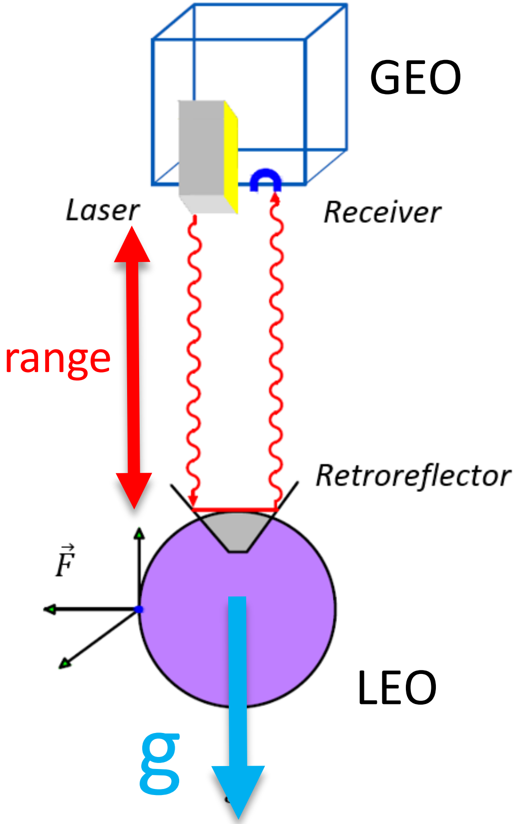
Hauk and Pail 2019

Concept 1/2

Vertical distance ranging

- Radial distance measurements between free-falling test masses
- Non-gravitational forces compensated and/or kept track of
- **Measurement of radial component is key advantage**
- Improves error profile: isotropic distribution

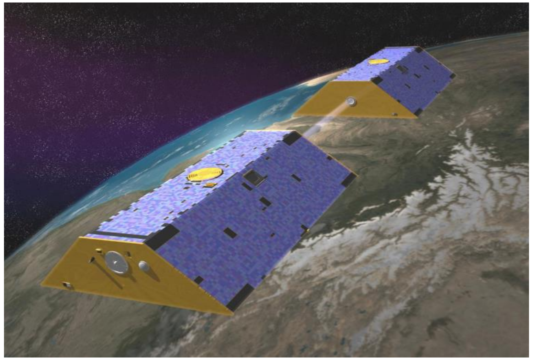




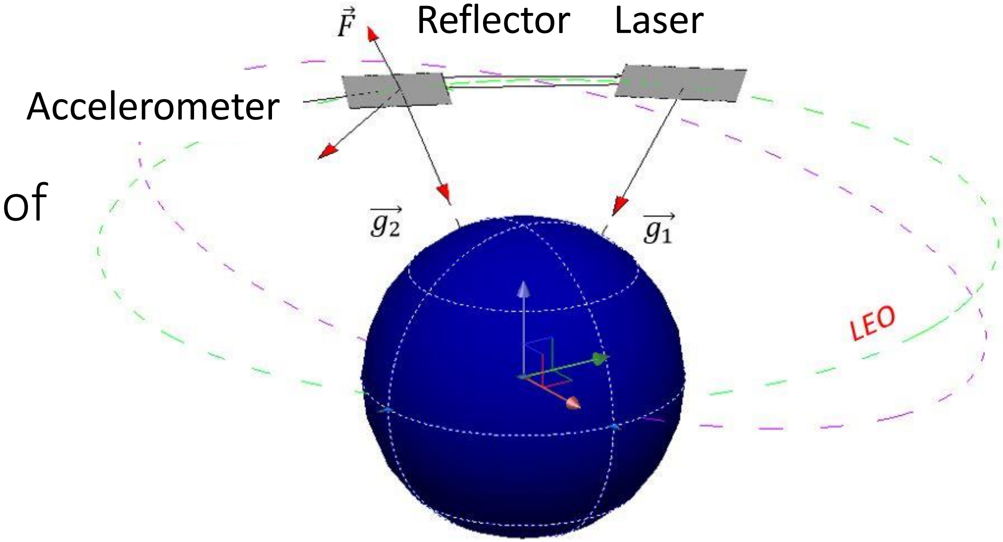
Concept 2/2

Horizontal distance ranging a la GRACE

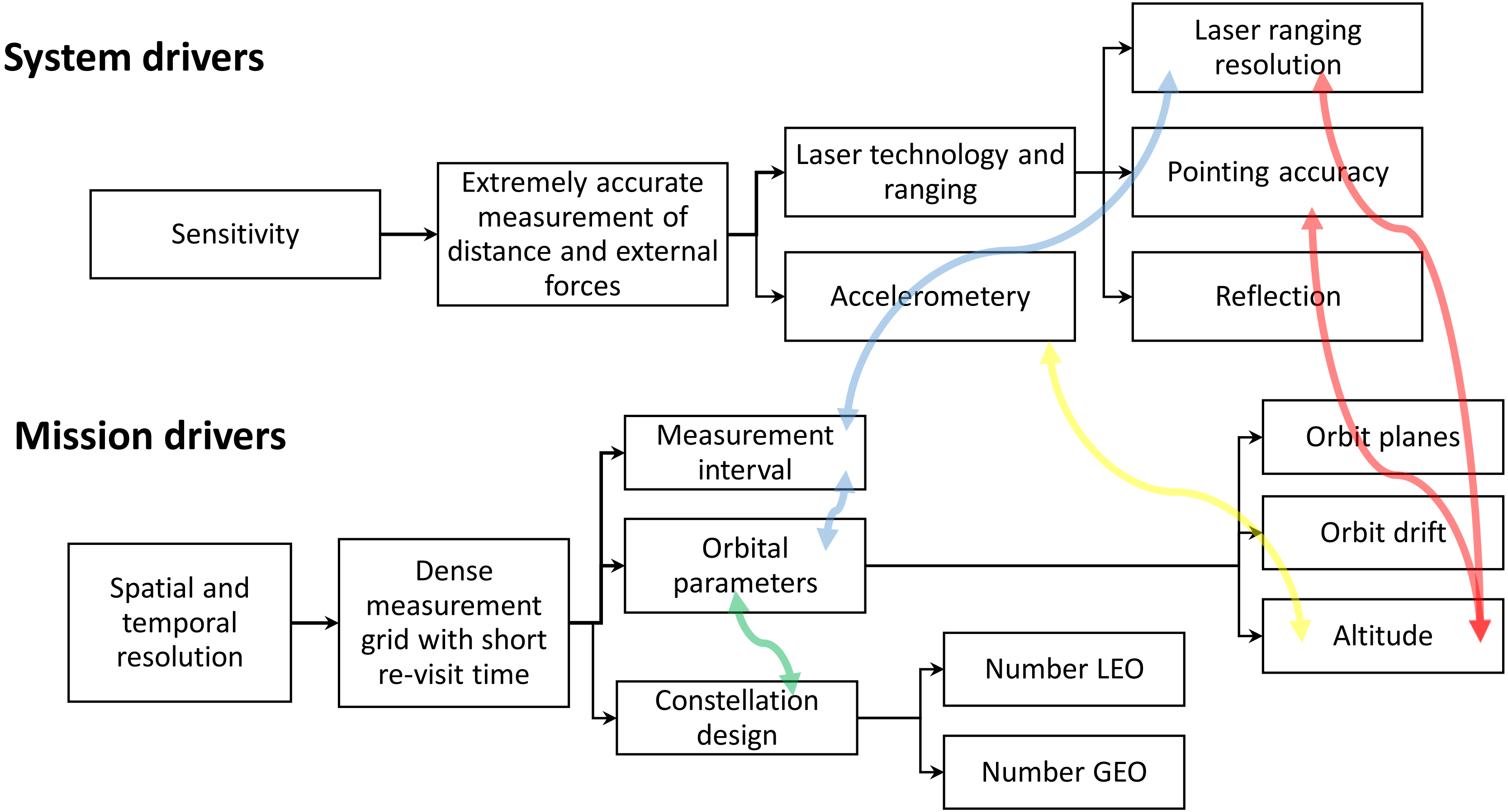
- Longitudinal distance measurements between free-falling test masses
- Non-gravitational forces compensated and/ or kept track of



DLR



Key system and mission drivers



System drivers

Sensitivity

Extremely accurate measurement of distance and external forces

Laser technology and ranging

Accelerometery

Laser ranging resolution

Pointing accuracy

Reflection

Mission drivers

Spatial and temporal resolution

Dense measurement grid with short re-visit time

Measurement interval

Orbital parameters

Constellation design

Orbit planes

Orbit drift

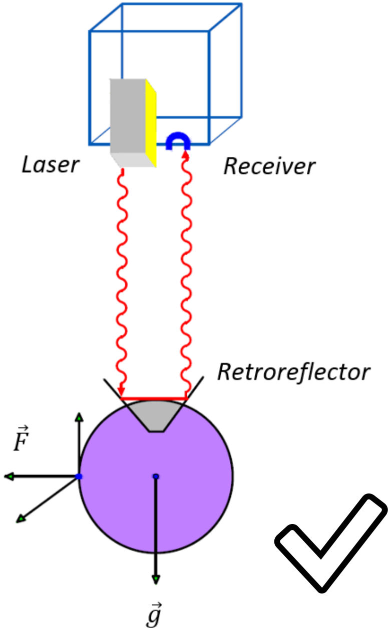
Altitude

Number LEO

Number GEO

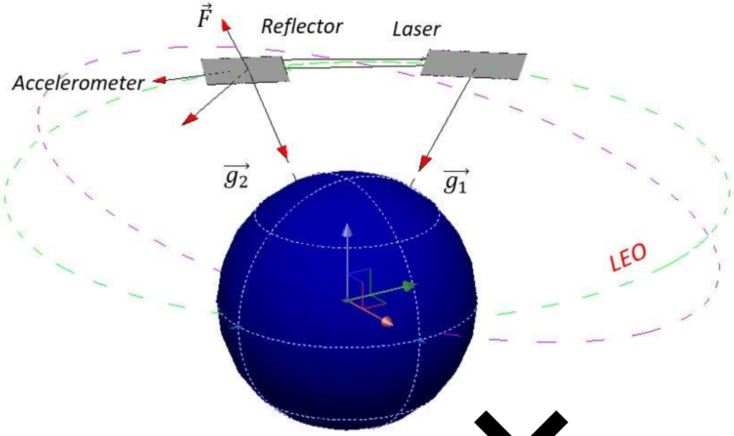
Mission concept trade-off

Concept 1: Vertical distance ranging



✓

Concept 2: Horizontal distance ranging



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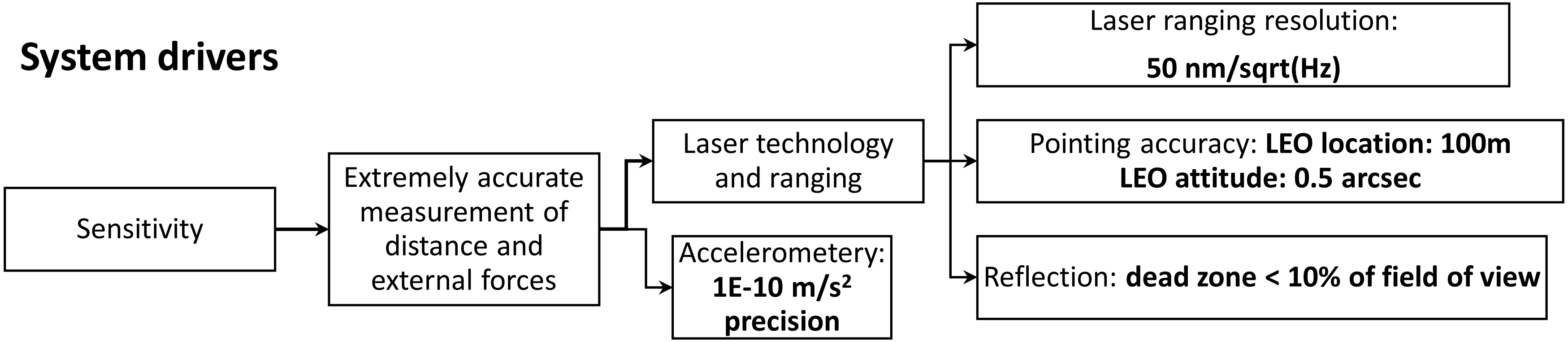
Mission and instrument requirements for orbit design and payload can be derived

Key system and mission drivers

System drivers



Sensitivity

Extremely accurate measurement of distance and external forces

Laser technology and ranging

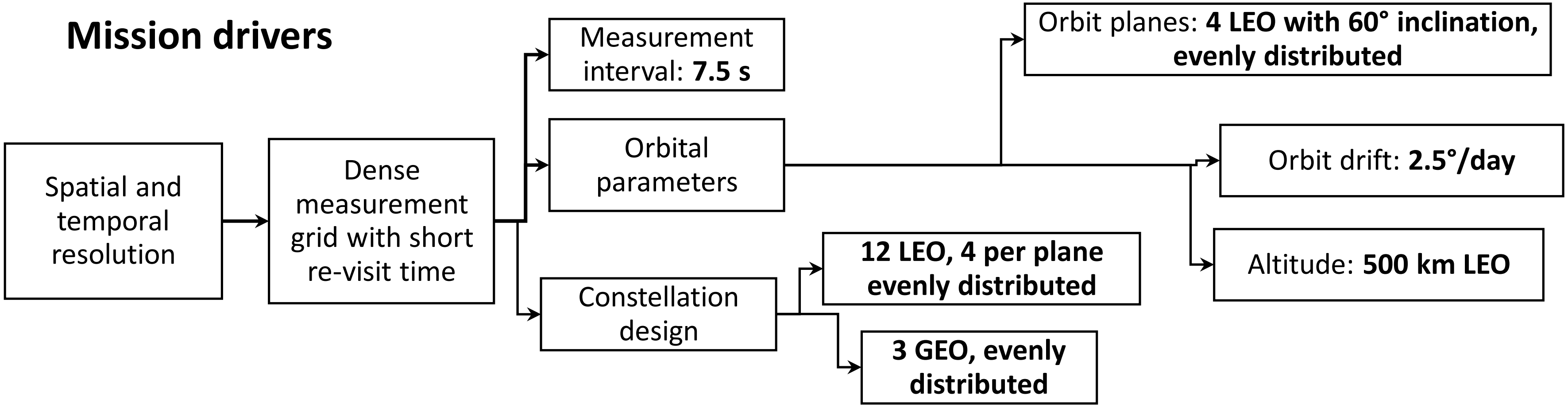
Accelerometery: **1E-10 m/s² precision**

Laser ranging resolution: **50 nm/sqrt(Hz)**

Pointing accuracy: **LEO location: 100m LEO attitude: 0.5 arcsec**

Reflection: **dead zone < 10% of field of view**

Mission drivers



Spatial and temporal resolution

Dense measurement grid with short re-visit time

Measurement interval: **7.5 s**

Orbital parameters

Constellation design

Orbit planes: **4 LEO with 60° inclination, evenly distributed**

Orbit drift: **2.5°/day**

Altitude: **500 km LEO**

12 LEO, 4 per plane evenly distributed

3 GEO, evenly distributed

Traceability matrix

Science Objective	Science Requirement	Observation requirement	Instruments	Instrument Requirements	Mission Requirements	Data products
What do you want to find out?	What phenomena you need to characterize?	What do you need to measure (units, direction etc.)?		What is the instrument or method? What is the needed performance of instrument (with accuracy, resolution, range)?	What does it mean to overall system? Power, pointing, scanning, stability.	
Develop an understanding of silent earthquakes	Measure mass redistribution related to silent earthquakes.	sensitivity 0.1 μGal	Laser ranger	Noise level of laser ranging system shall be at most 50 nm/sqrt(Hz) at altitude 500km	Prior position knowledge of LEO target shall be known to within 100m. Laser pointing accuracy & divergence need to hit this 100m spot. With spot size 1500m, this means pointing accuracy shall be 6 arcsec to hit within 1000m of target.	Range values bet GEO-LEO pairs.
					Targeting mirror shall stabilize after movement within 500ms to a state where the laser ranging distortion by its displacement is less than 100nm.	
				Each LEO orbiter's range shall be measured at least once per 7 seconds.	Total time to perform a single acquisition including beam positioning and ranging shall be lower than 1000ms.	
			Retroreflector	Retroreflector fields of view shall not overlap.		
				Retroreflector dead zone shall not exceed 10% of the field of view.		
				Uncertainties in attitude knowledge shall not cause retroreflector displacement correction error of more than 100nm.	Attitude determination accuracy of LEO orbiters shall be 0.5 arcsec.	
			GNSS positioning	Localization precision for GEO and LEO satellites using GNSS shall be 1 cm.		Positions of LEO satellite (knowled within centimeters time). This positioning is processing so can onboard sat and r afterwards
			Accelerometer	Measurable range of accelerations shall be at least up to 5 μm/s2. Precision of acceleration measurements shall be better or equal to 1e-10 m/s2.		Acceleration data compensation of non-gravitational
		coverage: +-60 degrees latitude			Orbital inclination of LEO orbiters shall be at least 60 degrees.	
		time series length: 7 years for 99% probability of detecting 1 earthquake			Operations and spacecraft design shall ensure lifetime of mission of at least 7 years.	
		spatial resolution 180 km			Mean spacing between acquired data points over one temporal step shall be at most 90km.	
		temporal resolution 3 days			Mean across-track separation of ground tracks over a 3 day period shall be at most half of the spatial resolution.	
		temporal resolution: 1 day sparse even coverage for atmosphere subtraction			All covered area shall be evenly covered by ground	
			Laser ranger	Noise level of laser ranging system shall be nm/sqrt(Hz) at altitude	Prior posit	

Engineering overview

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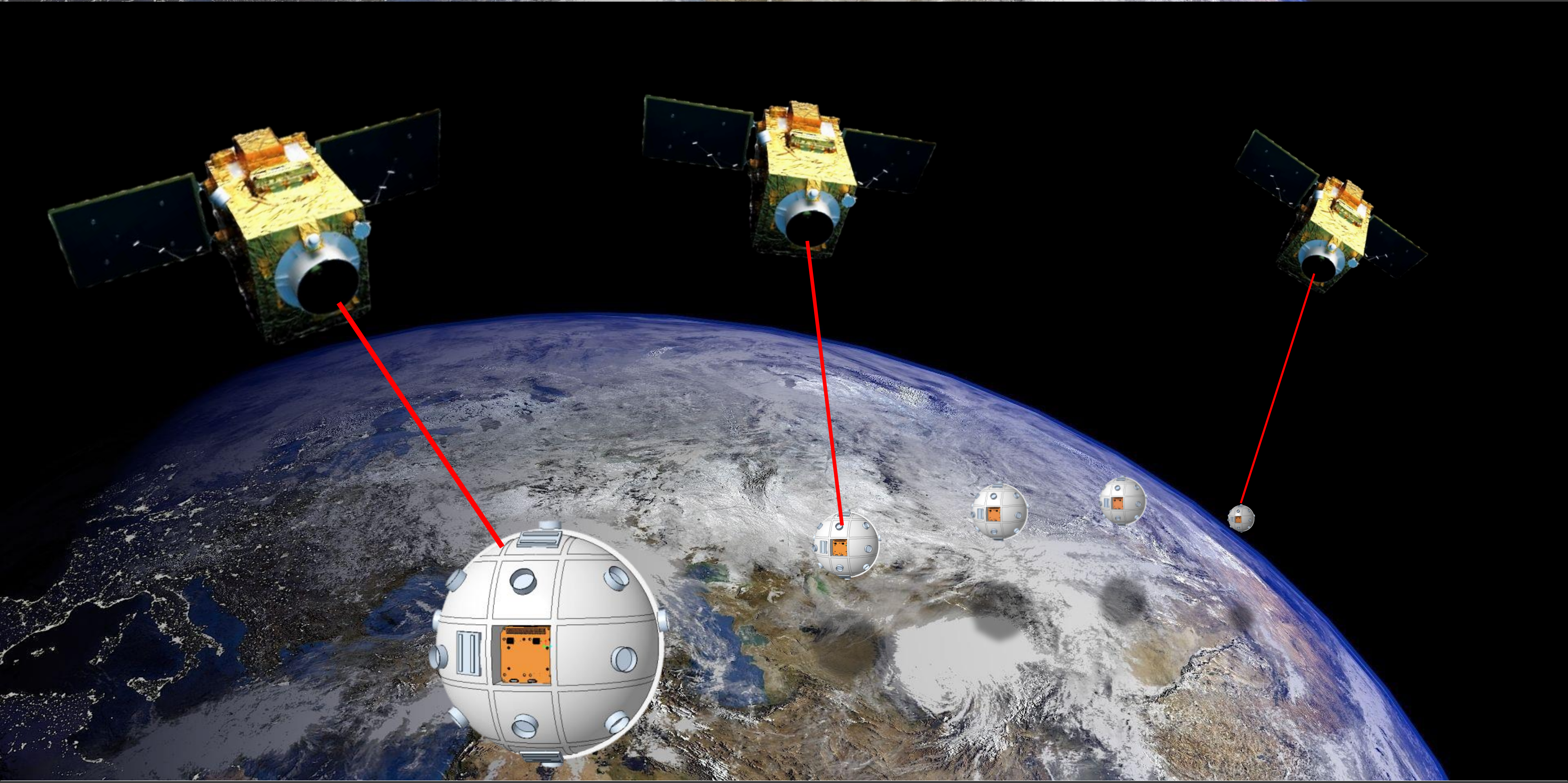
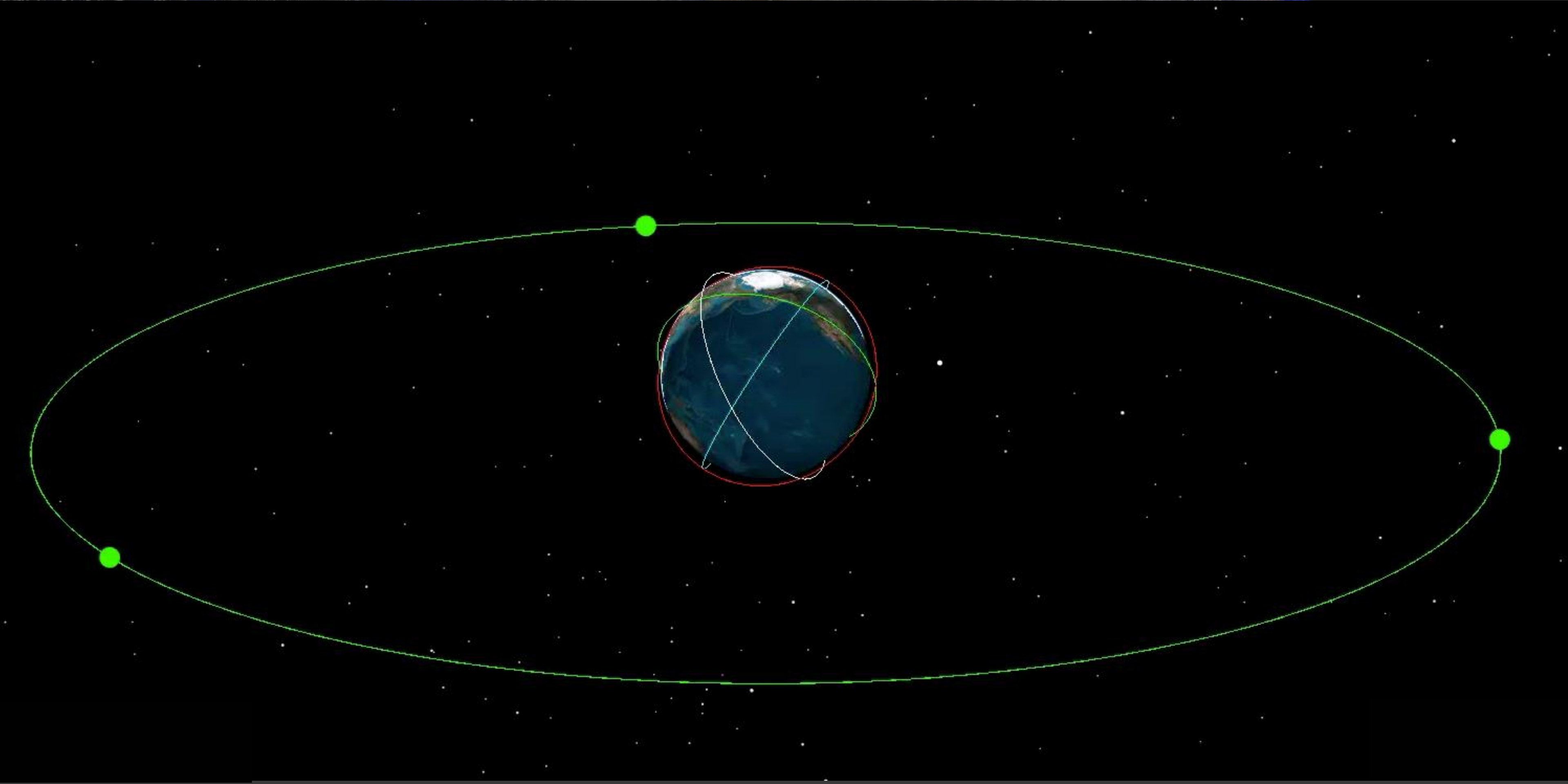
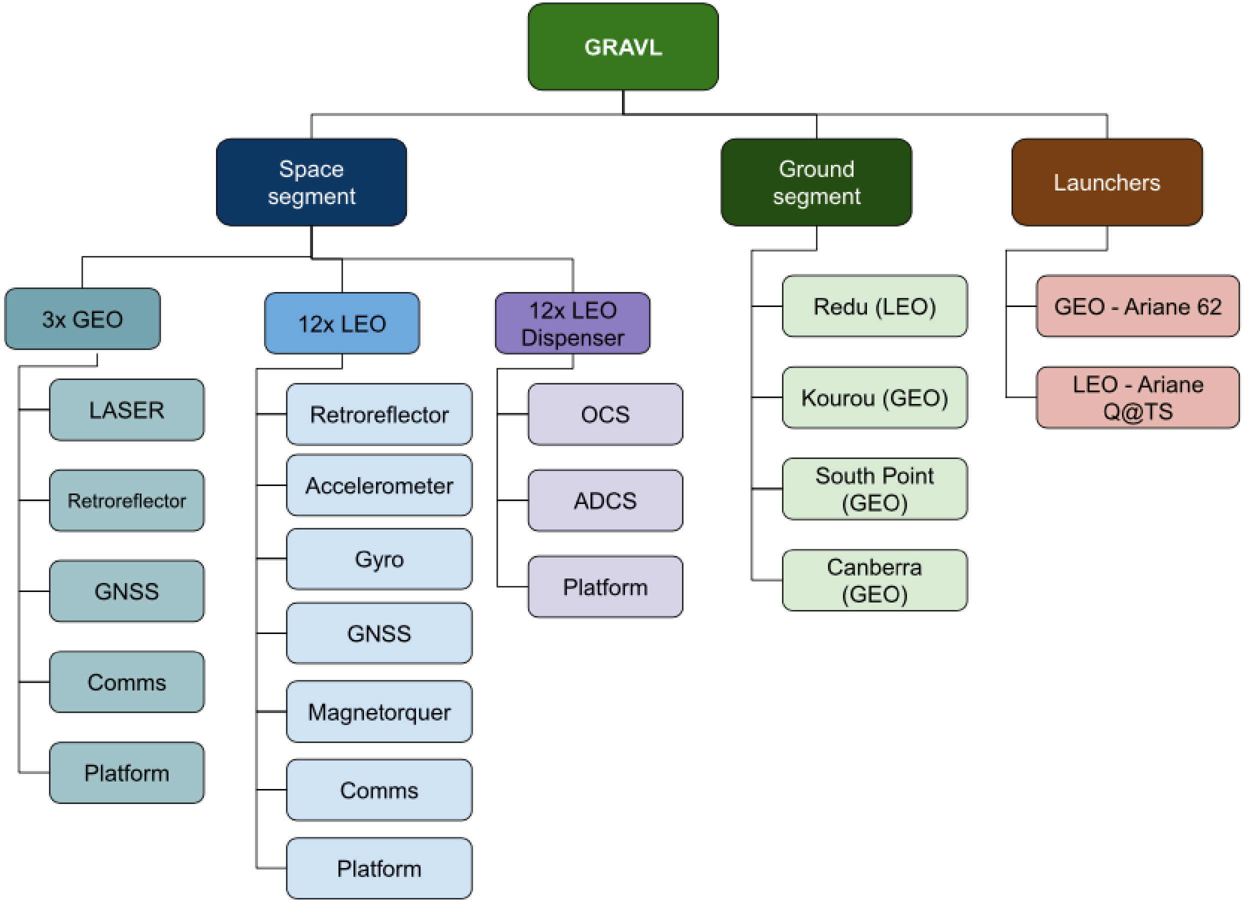
System overview



Overview



System overview



Data products

Level	Description	GRAVL Product
L0	Unprocessed full-resolution payload & telemetry data	Raw data from laser ranger, attitude sensors, GNSS sensors, S/C telemetry...
L1	Calibrated & processed sensor data	Ranging, positioning, attitude...
L2	Derived geophysical variables at same resolution as L1	MASCONS / Spherical harmonics / ...
L3	Geophysical variables mapped on an uniform temporal/spatial grid	Mass grids / gravity anomaly grids / ...
L4	Model outputs, analysis results	Earthquake maps, gravity maps, ...

Mission Profile

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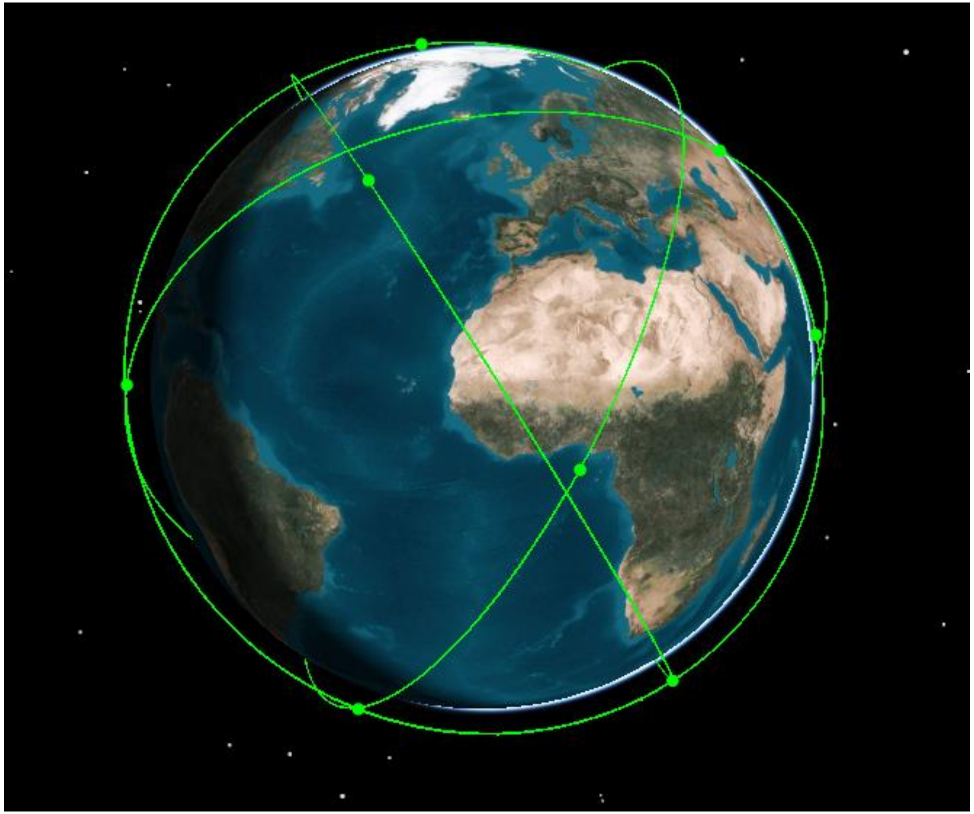
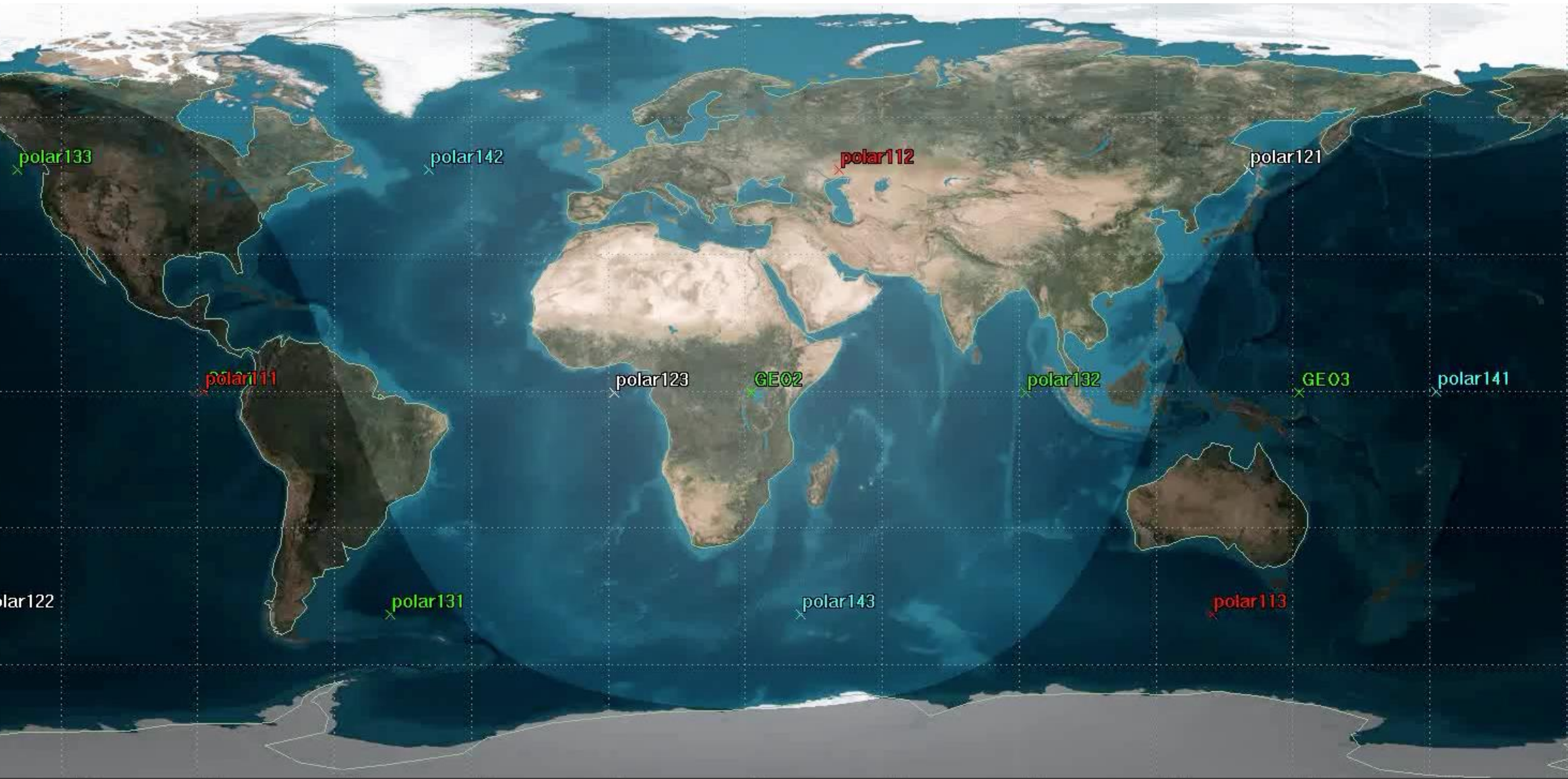
LEO component

- Four equally-spaced planes
- Three equally-spaced spherical satellites in each plane
- 60° inclination



LEO component



LEO component

Launcher

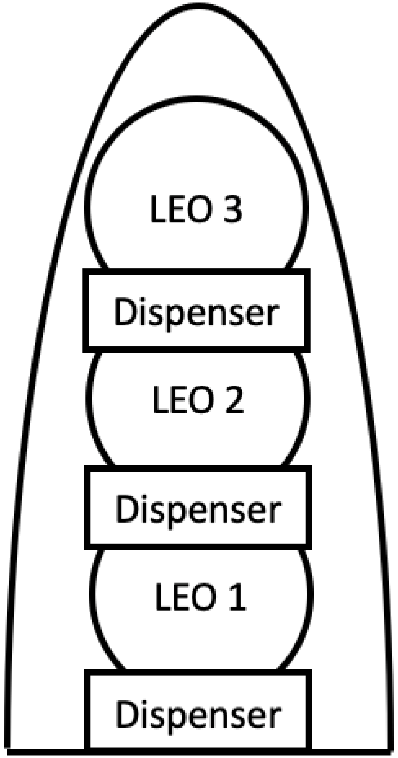
- Q@TS by ArianeSpace: 2.5M€ per launch
- 4 launches every 2 years
- 16 launches over lifetime
- Launch payload: 350 kg

ArianeSpace

LEO component

Launch configuration

LEO spacecraft with dispensers for successive deployment

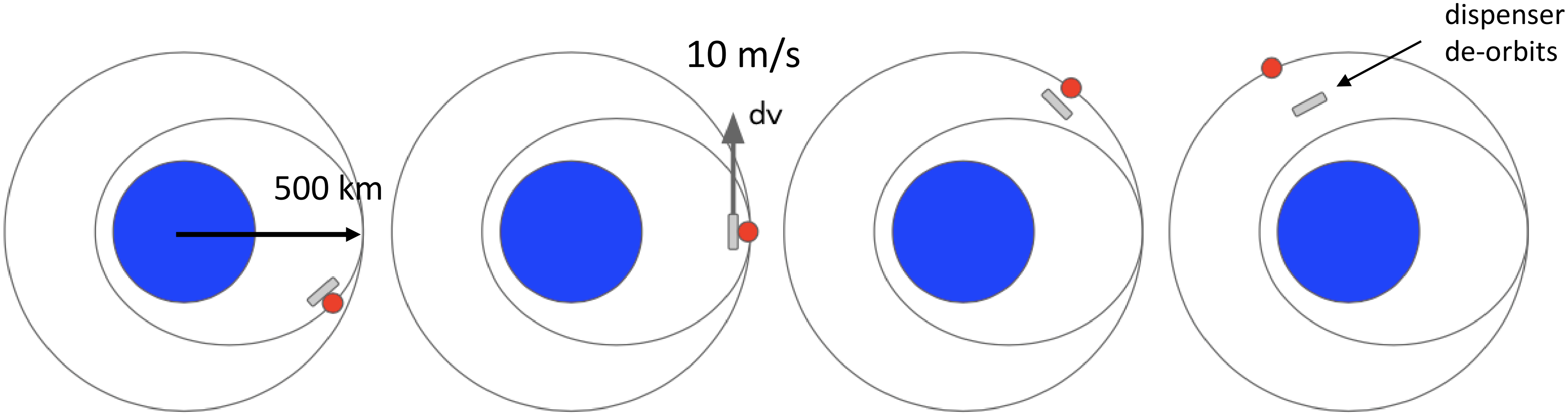


LEO component

Orbital insertion

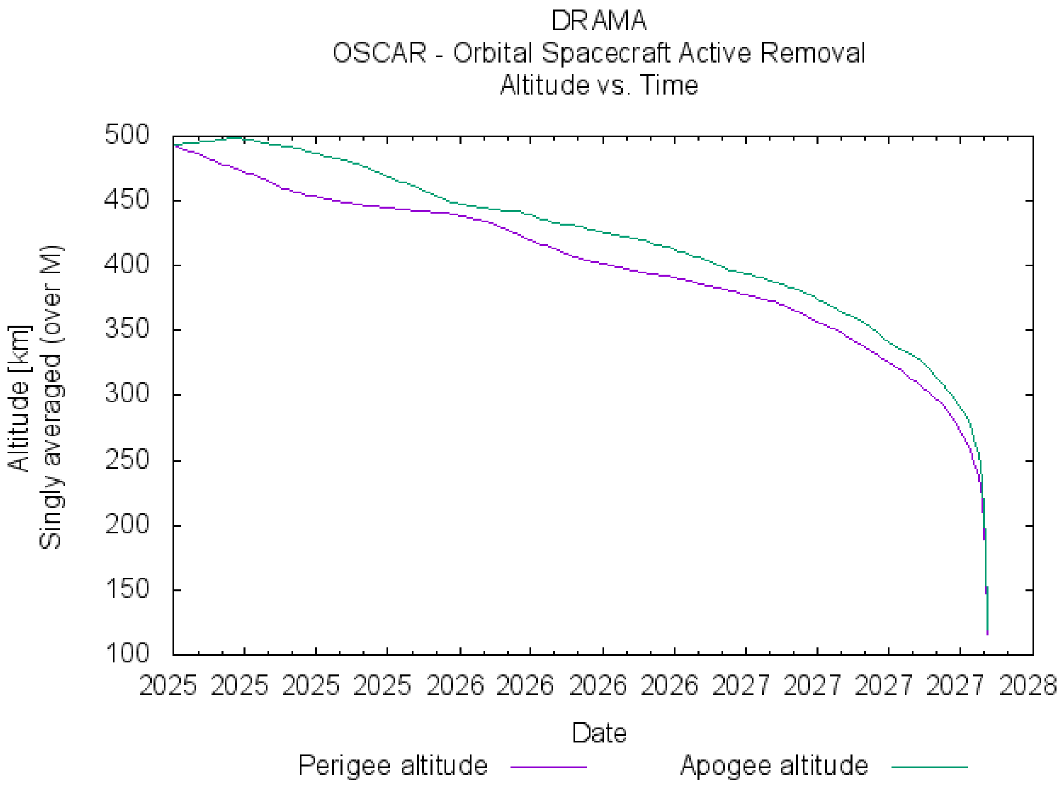
One-time-use dispensers

- Launch into elliptical orbit
- Circularization burn
- Burn delay between satellites to achieve 120º true anomaly separation



LEO component

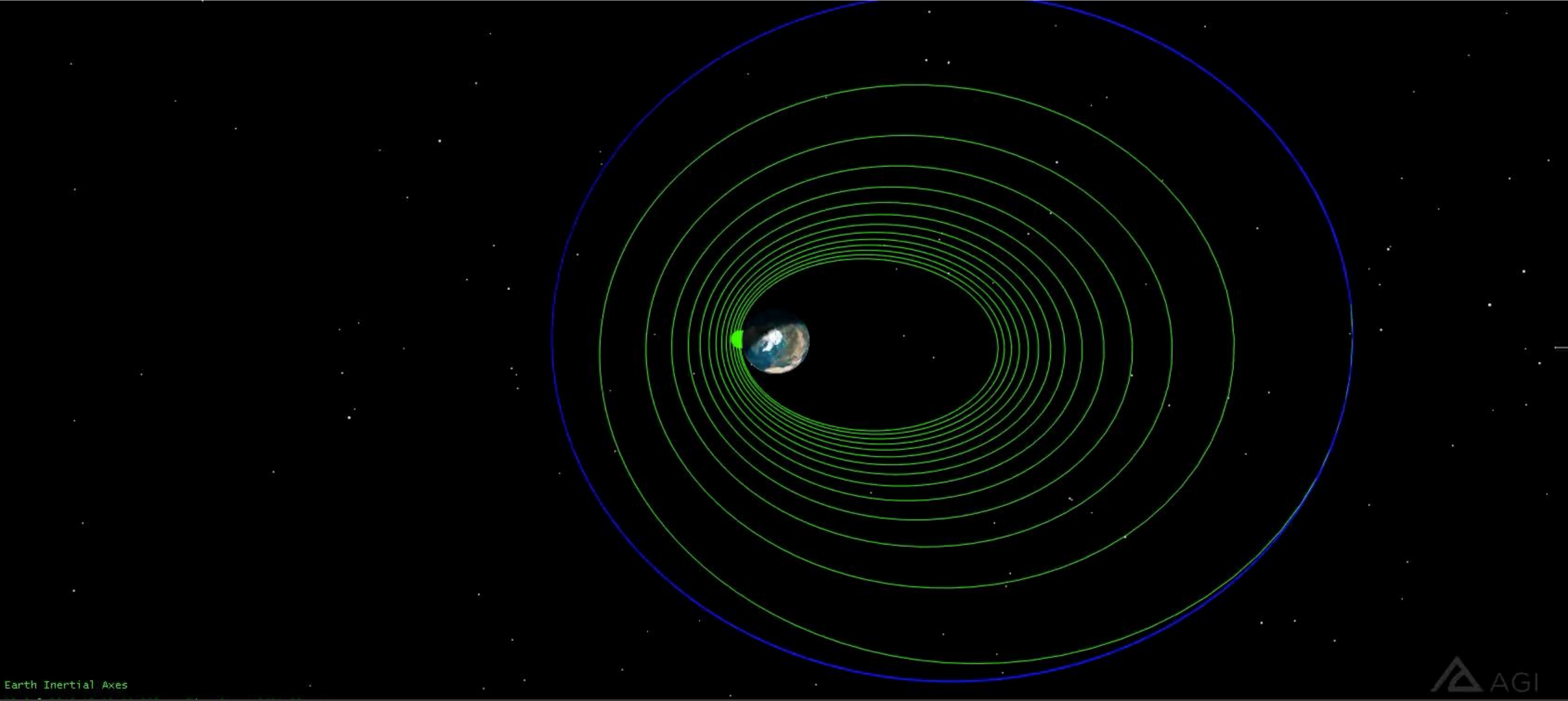
De-orbit



- LEO end of life simulation in DRAMA, OSCAR tool
- Three years to de-orbit in worst-case

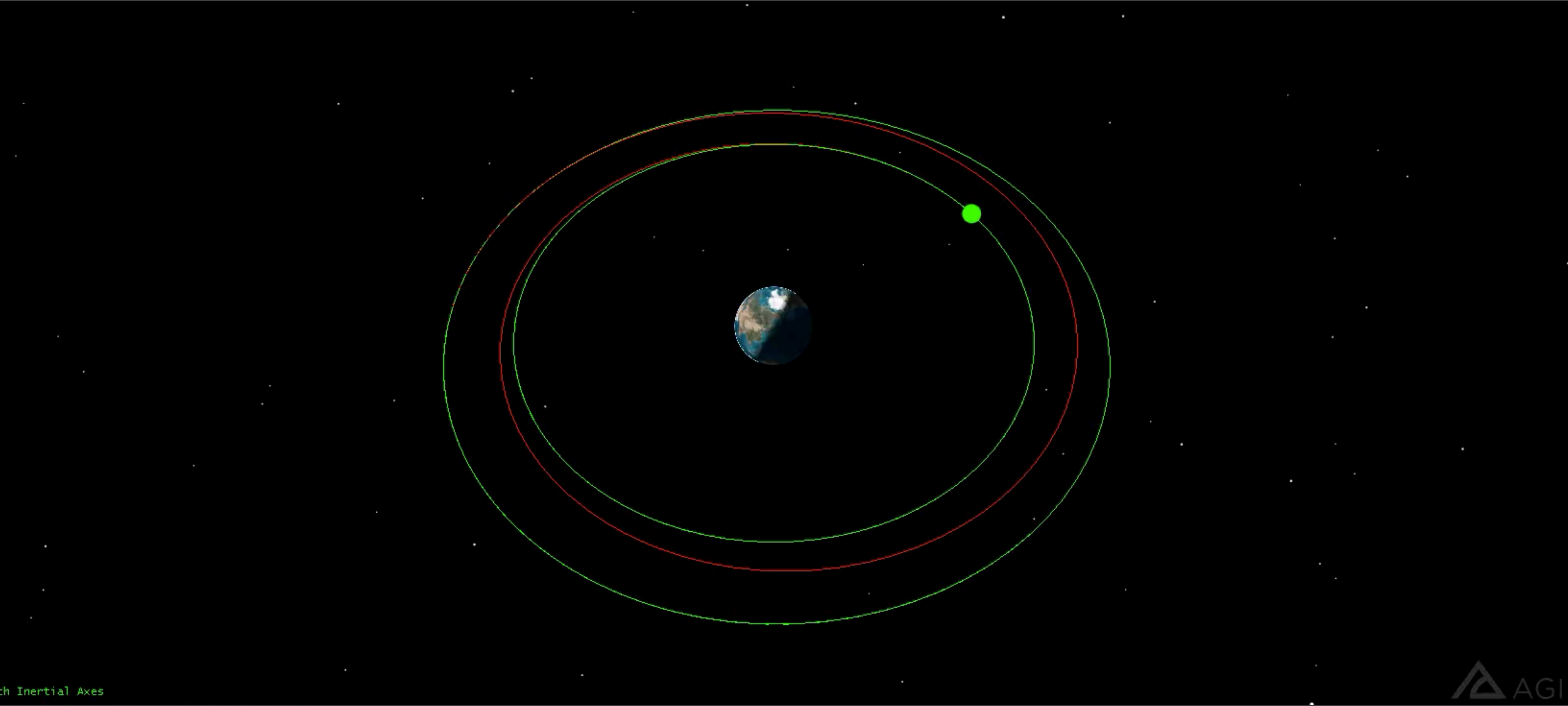
GEO component

Transfer and insertion



GEO component

End of life



GEO component

Launcher

- Total payload: 849 kg (283 kg per satellite)

Launcher : Ariane 6.2

- 1 launch in Kourou, Guyana
- 75 M€
- 5000 kg to GTO capability

ArianeSpace

Operations and ground segment

- Each LEO sat downlinks 3.5 MB/day
- Each GEO sat downlinks 47.3 MB/day
- GEO gets LEO position update
- Equatorial stations for GEO
  - Kourou
  - South Point
  - Canberra
- Redu ground station for all LEO satellites

ESA Ground Station Network

Payload design

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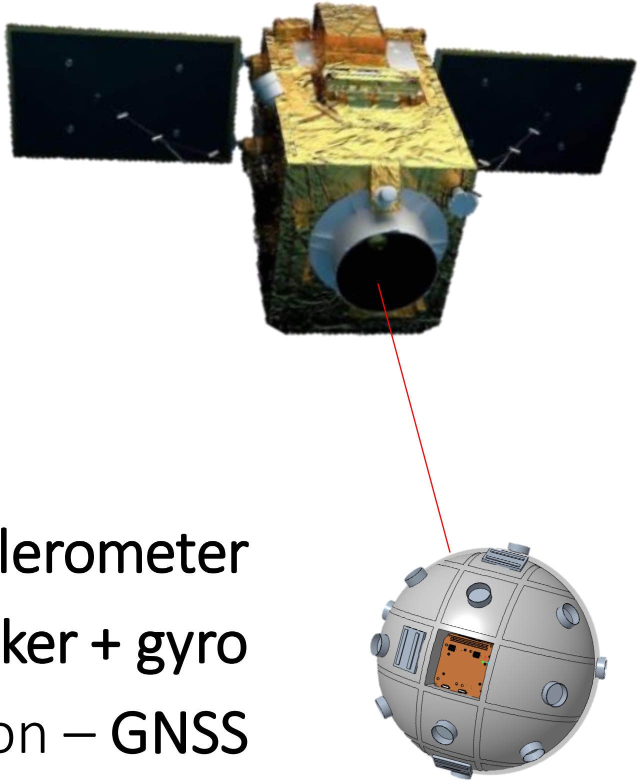
Payload components

Radial position – **laser ranging LEO-GEO**



LEO acceleration – **accelerometer**

LEO attitude – **star tracker + gyro**

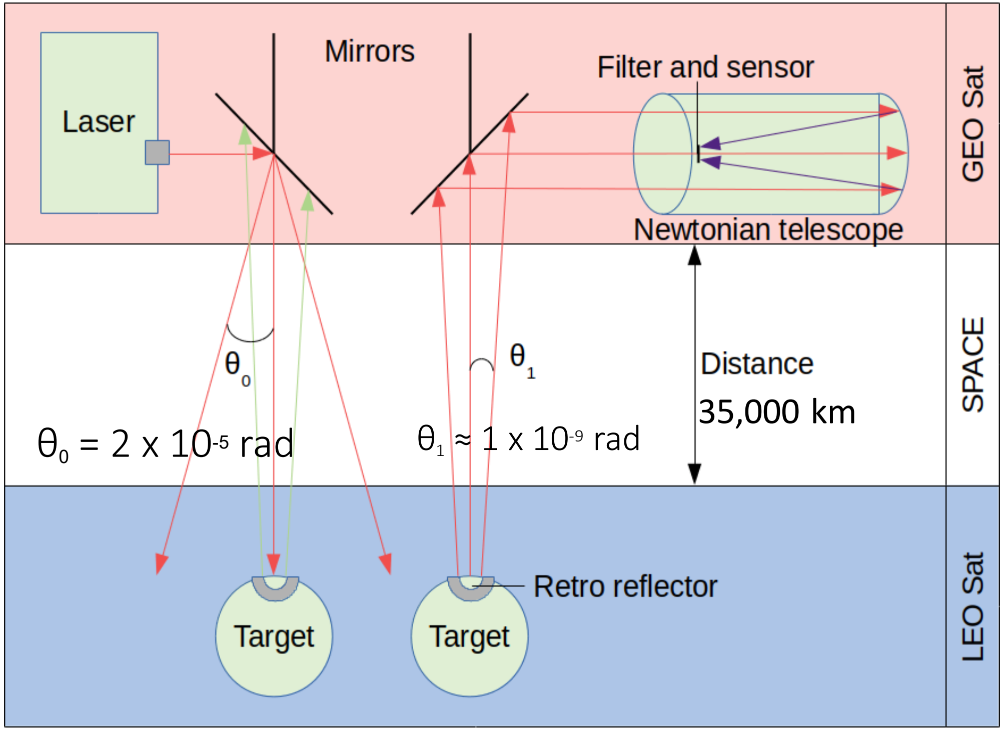
LEO position – **GNSS**

Laser Ranging System

Measurement principle

*GEO-LEO distance changes → **radial** gravity field*

1. Short laser pulses sent from GEO satellite, clock starts
2. Pulses reflected by retro reflector on LEO satellite
3. Laser pulses received in GEO by photodiode
4. When photodiode charge threshold is reached clock stops and TOF is recorded



Laser ranging system

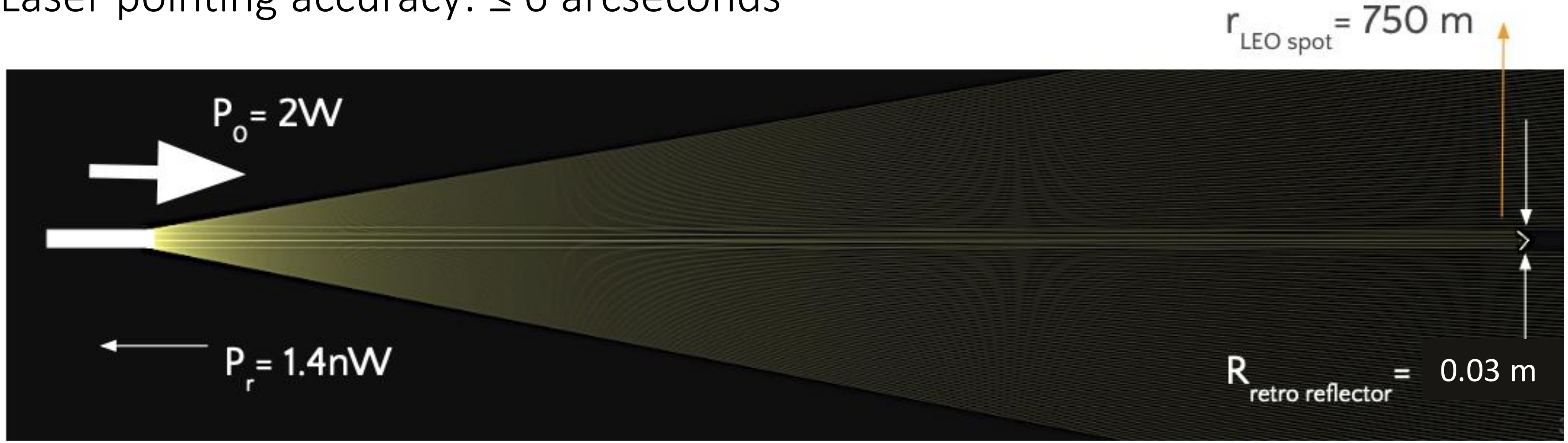
Laser power

- 2W GEO laser (LISA pathfinder):

Power received ≈ **74 – 93 nW** depending on retroreflector orientation

- Laser pointing accuracy: ≤ 6 arcseconds

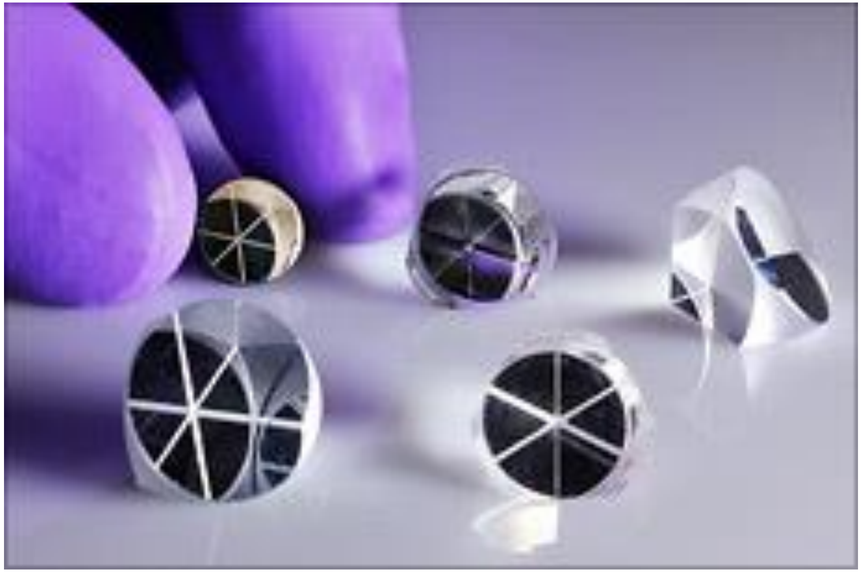
$$P_r = P_o \frac{\pi . r^2_{retroreflector}}{\pi . r^2_{LEO\ spot}}$$



Laser ranging system

Retroreflector

- Equally distributed on surface of spherical LEO satellite
- Acceptance angle of 20° so only one reflector is seen at each time
- Radius of 30 mm

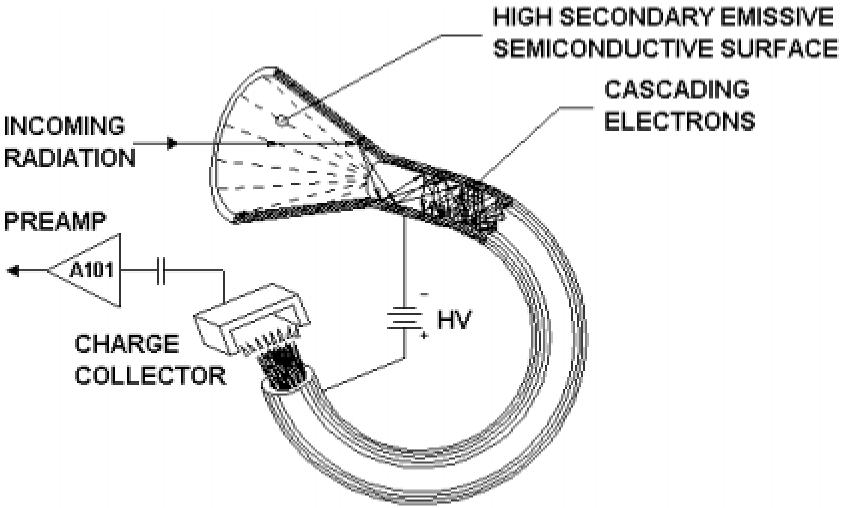


Laser ranging system

Signal amplification

- 12 cm aperture Newtonian telescope
- Channel electron multiplier amplifies signal
- Clock, CEM and comparator shall be mounted as close as possible to each other and system needs to be calibrated

CEM system



Laser ranging system

Clock

Ranging precision of 200 nm → clock precision of 3.33E-16 s

Device: **CSAC GPSDO**

- **Precision:** 1.433E-17 s equivalent of **8.6 nm**
- **Volume:** 64 x 77 x 18 mm^3
- **Power:** 1.4 W

LEO accelerometer

- Use SuperStar accelerometer (GRACE/GRACE-FO heritage)
- Sensitive y- and z-axis will be mounted in along-cross-track-plane (strongest influence of perturbations)
- Mount at center of mass (C.O.M.)
- Volume 1 U, mass 3.5 kg, power 19W

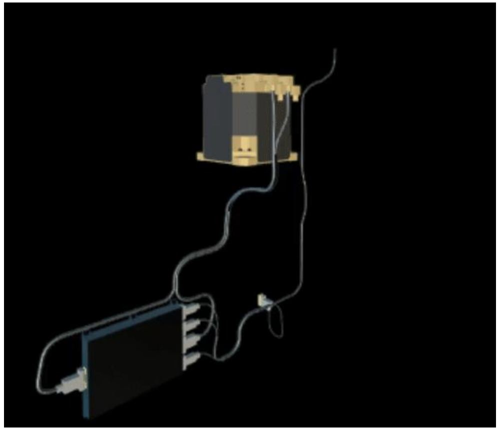


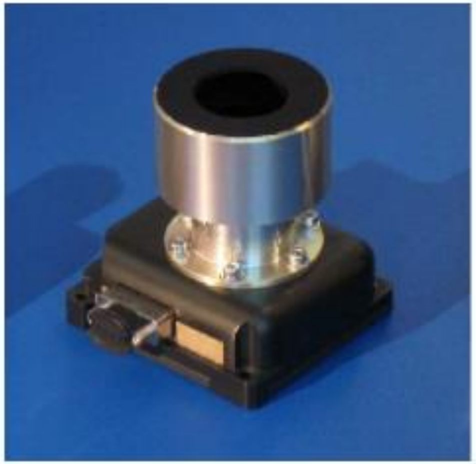
Table 1: *Estimated drag perturbing acceleration for spherical LEO s/C (d=0.5 m) at 500 km orbital altitude.*

low activity	mid activity	high activity
$1.547 \cdot 10^{-8}$ m/s^2	$1.788 \cdot 10^{-7}$ m/s^2	$8.566 \cdot 10^{-7}$ m/s^2

LEO attitude knowledge

- Ring laser gyro: bias stability 0.003°/h, drift 0.0035°/$h^{1/2}$
- Startracker: 5 arcsec (rms) absolute accuracy (cross bore-sight)

High-Precision Gyroscope



Startracker

LEO GNSS

- Live on-orbit precision not required (1-2 m)
- Precise orbit determination for post processing/science case to **cm precision**
- Multichannel GNSS receivers

LEO spacecraft design

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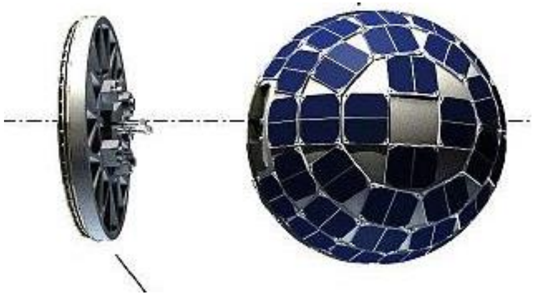
LEO spacecraft

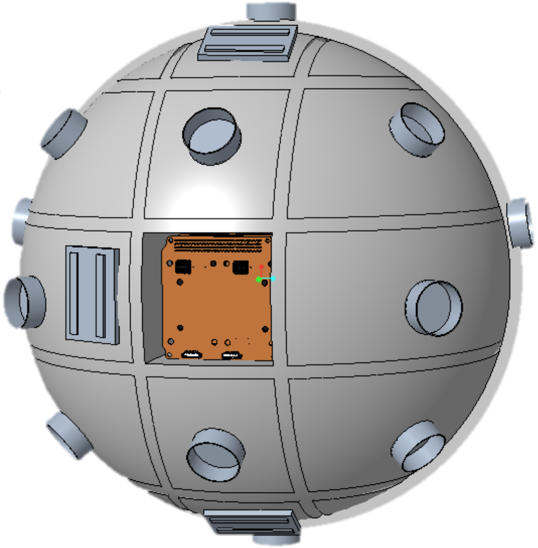
System design concept

DANDE
(University of Colorado Boulder)

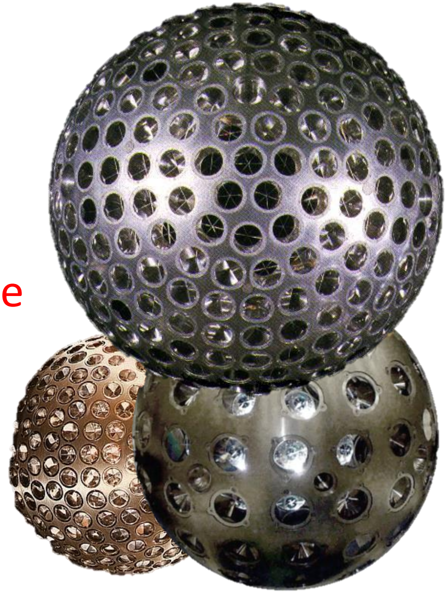


LEO Spacecraft is a combination of two proven concepts

active



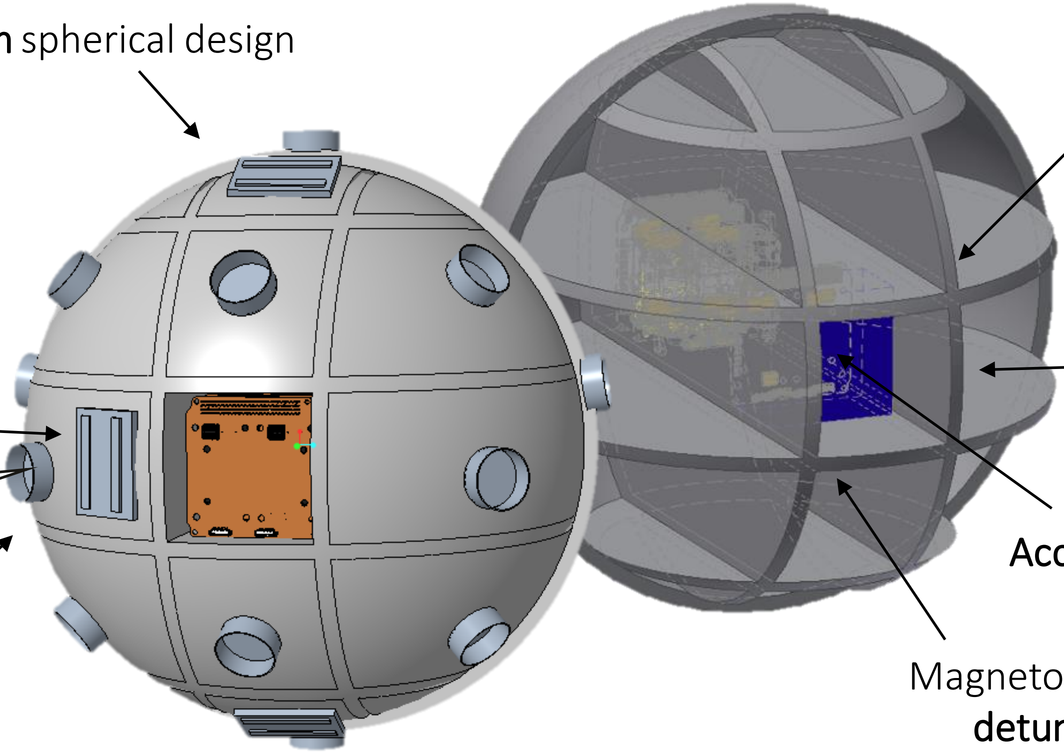
passive



LAGEOS-I and II (NASA)
LARES (ASI)

LEO spacecraft

System design concept



Custom spherical design

Good **ballistic coefficient** 0.008 m²/kg

Solar panels

Passive **retroreflectors** 20° acceptance angle

GNSS for **position** knowledge

Sensors for **attitude** knowledge

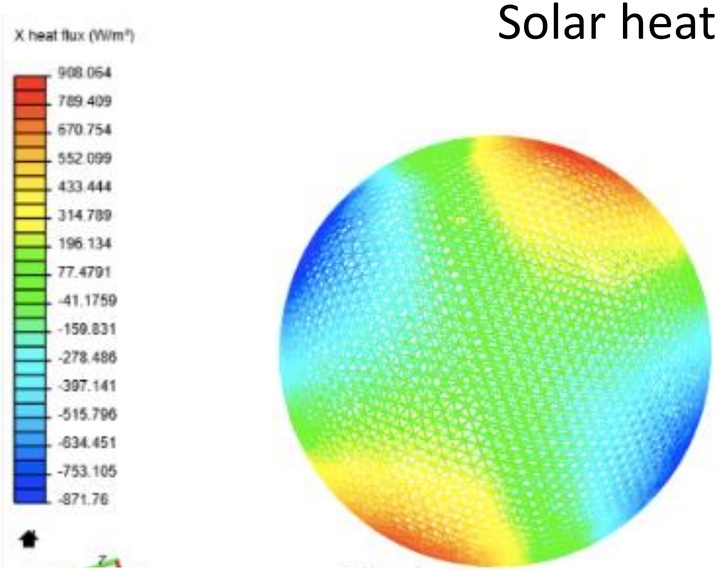
Accelerometer at C.O.M

Magnetorquers for **detumbling**

LEO spacecraft

Thermal considerations

- Rough simulation in extreme conditions where sphere is not rotating
- With rotational movement we expect a mean thermal equilibrium in the system

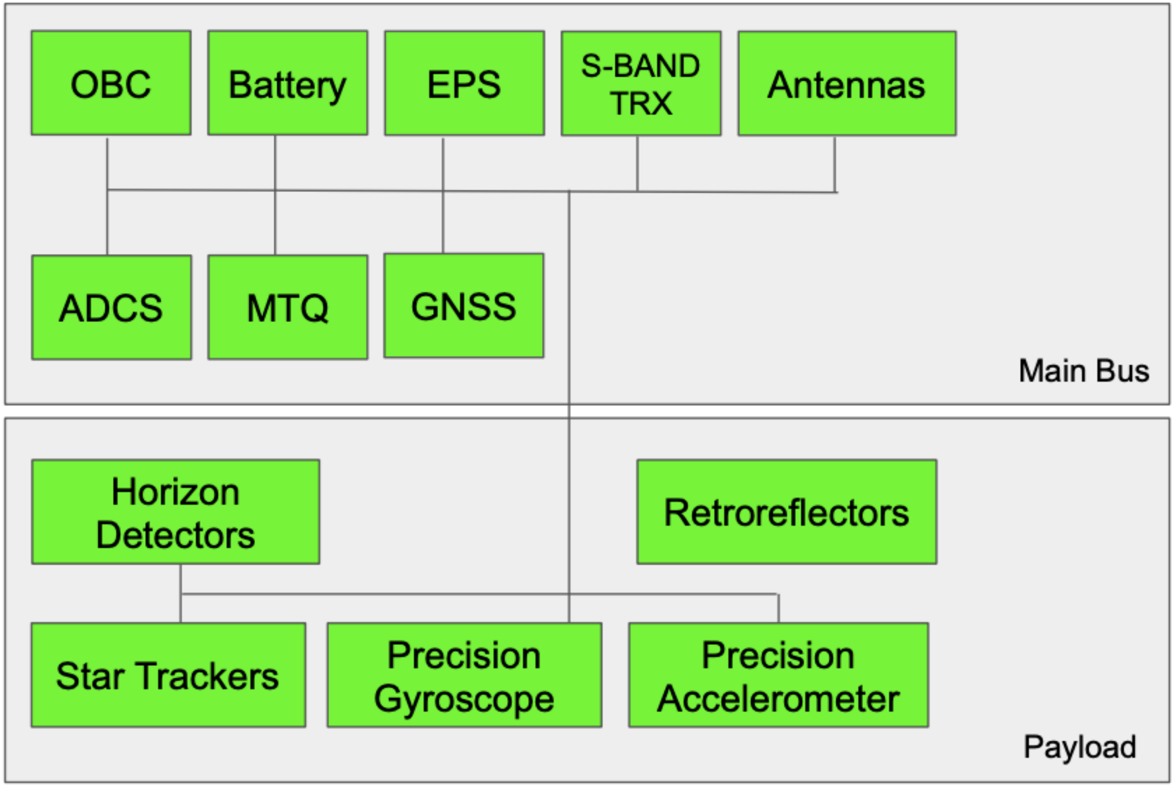


Solar heat flux

Albedo

LEO spacecraft

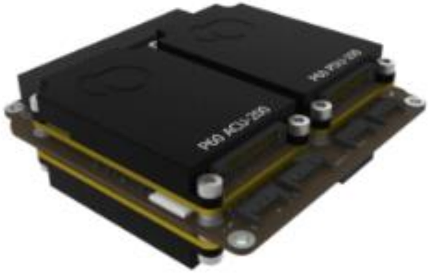
System breakdown



LEO spacecraft

Main bus components

Nano-Dock DMC-3

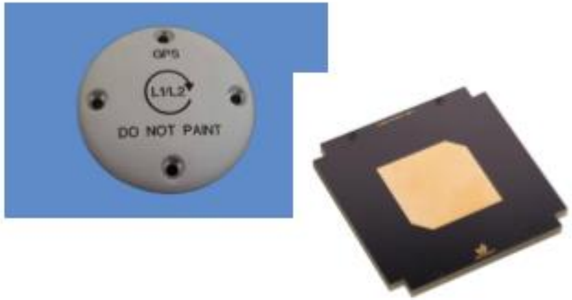


NanoPower EPS

NanoPower battery pack

Syrlinks S-Band Transceiver

GNSS Receiver



GNSS and S-Band Antenna

Solar panels

LEO spacecraft

Budgets: summary

	Mass / kg	Science Mode Power / W	Safe Mode Power / W	Daily Data Budget / MB	Link Budget Margin / dB
Structure	12				
Main bus	4	6	4	0.5	> 6
Payload	11	27	0		
Total	27	33	4	0.5	> 6

GEO spacecraft design

Green Team 25th July 2019

GEO spacecraft

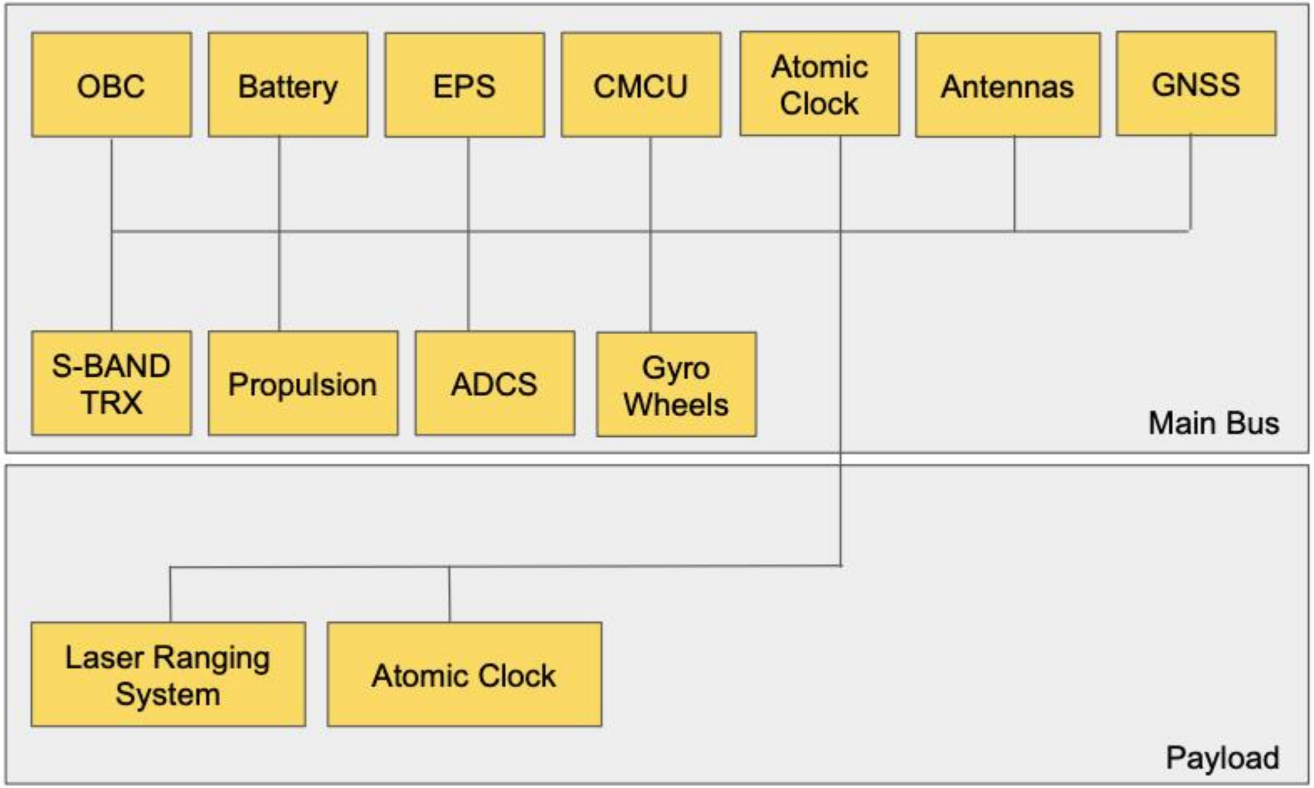
System design concept

Airbus Astrium

- AstroBus-S:
    - 100x100x170 cm
    - < 430 kg
    - 7 year design life
    - Power Generation < 4kW

GEO spacecraft

System breakdown



MERLIN mission (CNES, DLR)

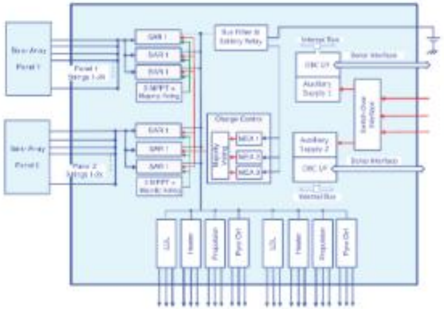
GEO spacecraft

Main bus components

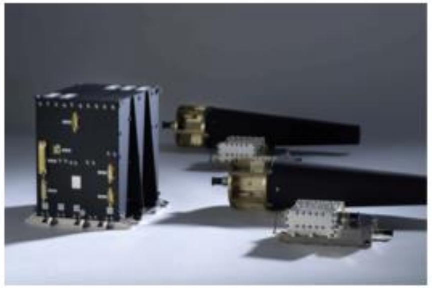
- COTS whenever possible designed for GEO environment (radiation, mechanical etc.)
- Many suppliers like Astrium, OHB, …
- Performance vs. Costs - but GEO demands high quality
- Qualified and Flight Proven Microsatellite Components

Thrust

Airbus/Astrium OSCAR on board computer

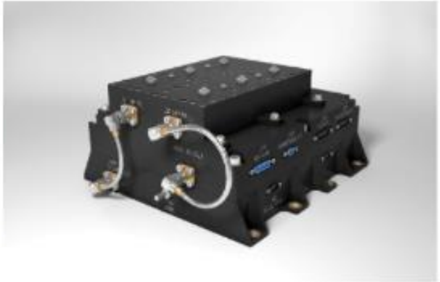


Airbus/Astrium PCDU



Airbus/Astrium LION

CMCS clock



Transceiver / transmitter

GEO spacecraft

Budgets: summary

	Mass / kg	Science Mode Power / W (avg. per orbit)	Safe Mode Power / W (avg. per orbit)	Daily Data Budget / MB	Link Budget Margin / dB
Structure	65				
Main bus	173	452	396	6	> 5
Payload	45	88	0		
Total	283	546	396	6	> 5

Programmatics

TRL, schedule, risks, costs

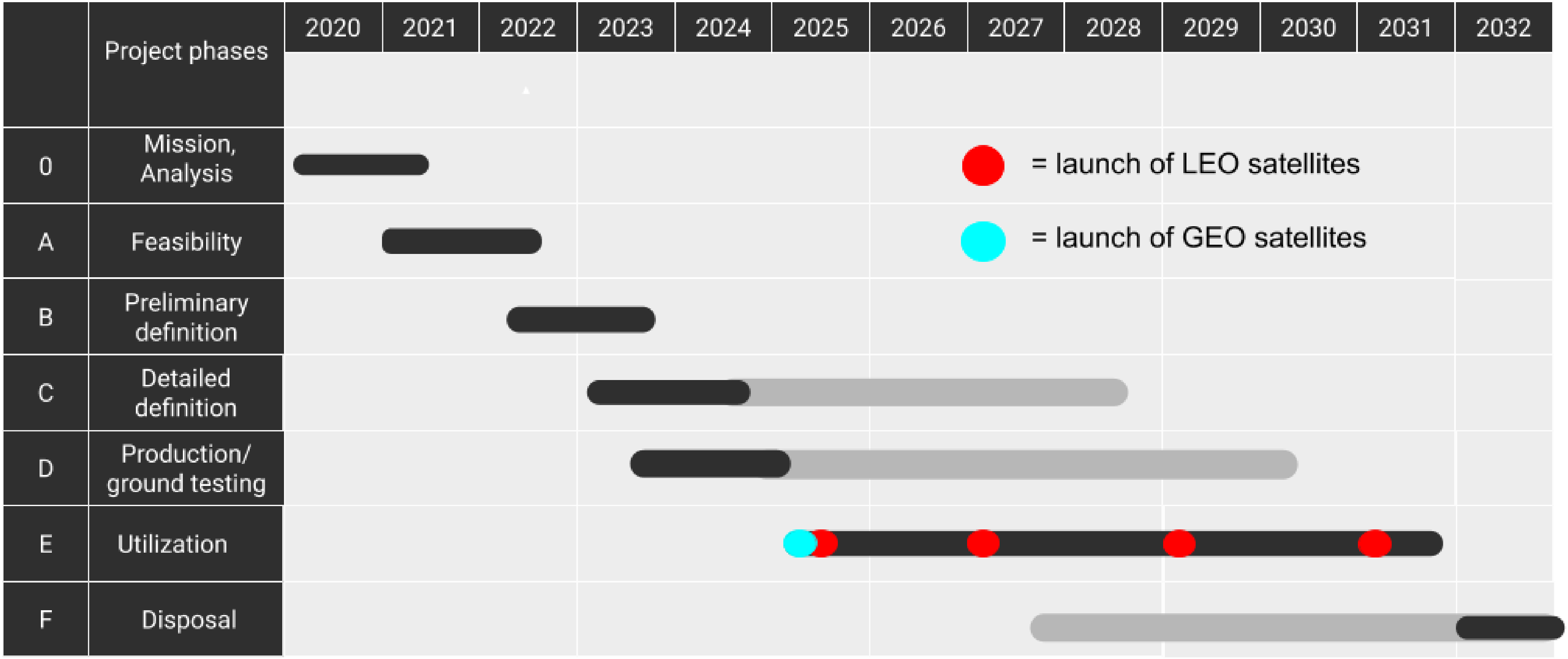
Green Team 25th July 2019

Critical technology (TRL)

System component	TRL
Laser detector	4
Attitude determination systems	6
Retroreflectors	8
Laser transmitter	8
Accelerometer	9
GNSS	9
Power, Thermal, TT&C	9

TRL 4	Component and/or breadboard validation in laboratory environment.
TRL 5	Component and/or breadboard validation in relevant environment.
TRL 6	System/subsystem model or prototype demonstration in a relevant environment (ground or space)
TRL 7	System prototype demonstration in a space environment
TRL 8	Actual system completed and “flight qualified” through test and demonstration (ground or space)
TRL 9	Actual system “flight proven” through successful mission operations

Schedule


Project phases
2020
2021
2022
2023
2024
2025
2026
2027
2028
2029
2030
2031
2032
0
Mission, Analysis
A
Feasibility
B
Preliminary definition
C
Detailed definition
D
Production/ ground testing
E
Utilization
F
Disposal
● = launch of LEO satellites
● = launch of GEO satellites

Risks

Risk	Likelihood /5	Severity /5	Mitigation
Lifetime of the mission not sufficient to capture entire duration of long term seismic events	1	2	Increase lifetime of the mission
Micro launcher technology not available	3	1	Use more expensive launches
Laser ranger receiver technology not available	2	4	Longer development time

Costs

	Item	Cost per item (M€)	Number of items	Total cost (M€)
Development	LEO satellites			10.00
	GEO satellites			8.00
	LEO dispenser			1.00
Industrial	LEO satellites	0.51	48	24.48
	GEO satellites	18.30	3	54.90
	LEO dispenser	0.28	48	13.44
Payload	LEO satellites	0.87	48	41.96
	GEO satellites	1.92	3	5.76
Test facilities				5.00
Launch	LEO satellites	3.00	16	48.00
	GEO satellites	75.00	1	75.00
Mission operation		2.20	7	15.40
Science operations and archiving		1.50	7	10.50
Management				30.00
PR and outreach		0.10	7	0.70
Margin				36.47
Total mission cost (M€)				**380.61**

Cost category and de-scoping options

De-scoping: Decrease lifetime from 7 years to 6 years

Category	Amount	Each (M€)	Total (M€)
Launches	4	3	12
LEO satellites	12	1.38	16.56

Total Saving: 29 M€
Original Mission Cost: 381 M€
Saving in Percent: 8%

De-scoping impacts science: fewer earthquakes observed

Outreach

Social media:

"How attractive are you?"- game on social media page

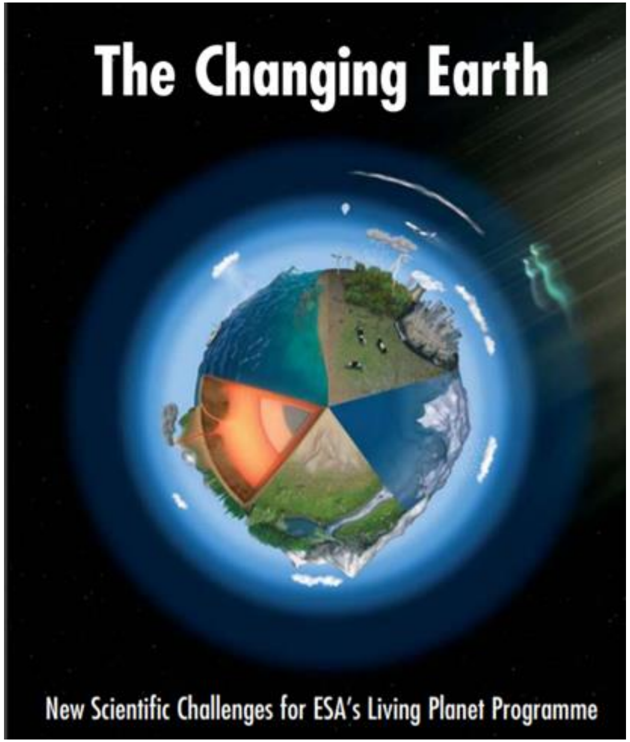
Events:

Earthquake simulators

School tour in Science bus:

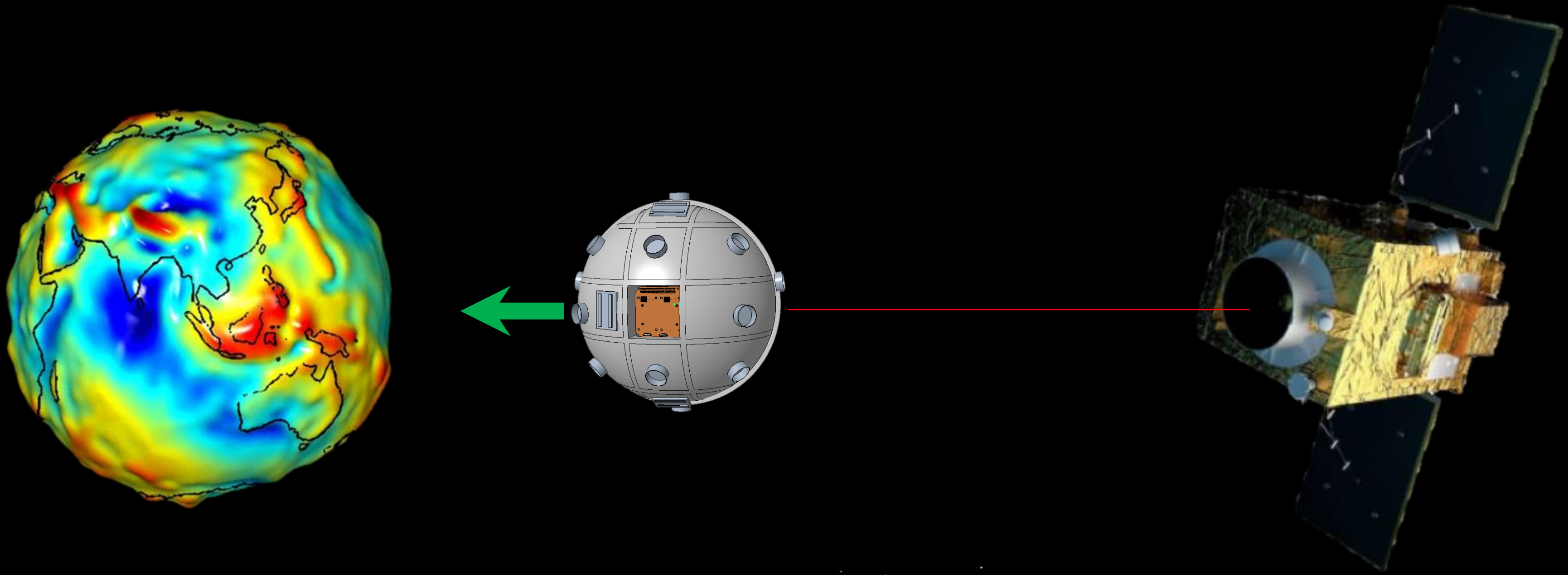
- Design your own mission using the GEO platforms
- Lectures on geophysics
- Space footballs

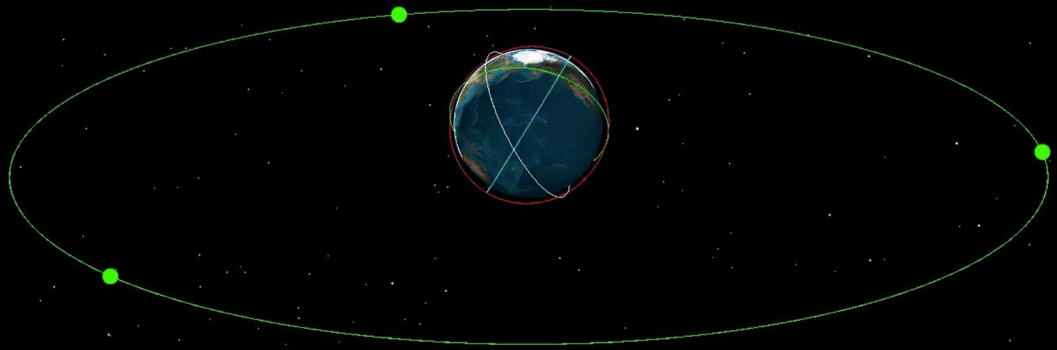
Link to ESA Living Planet Programme



The Changing Earth: New scientific Challenges for ESA's Living Planet Programme

"The Challenges of the Solid Earth:
Challenge 1: Identification and quantification of physical signatures associated with volcanic and earthquake processes – from terrestrial and space-based observations."





GRAVL

Thank you!

Any questions before launch?

Bonus material

Science

Green Team 25th July 2019

Mission requirements

- Mean spacing between data points is half of the spatial resolution: sampling rate 7s
- Inclination at least 60 deg
- Separation of orbits at least 0.5 * spatial resolution over 3 days
- LEO Orbit drift per day: 2.5°
- LEO ground tracks: daily rough coverage
- LEO orbit altitude 500km
- Operations for whole length of mission time

Instrument requirements

Derivation of requirements on:

- Laser ranging distance precision: 200 nm
- Laser ranging vector knowledge precision: Ca. one µrad (worst case for reflector in “equatorial” plane, field of view 90°)
- LEO satellite accelerometry: 0-5µm/s^2 1E-10 m/s^2
- LEO satellite position: prior knowledge 100 metres, reconstruction to cm precision

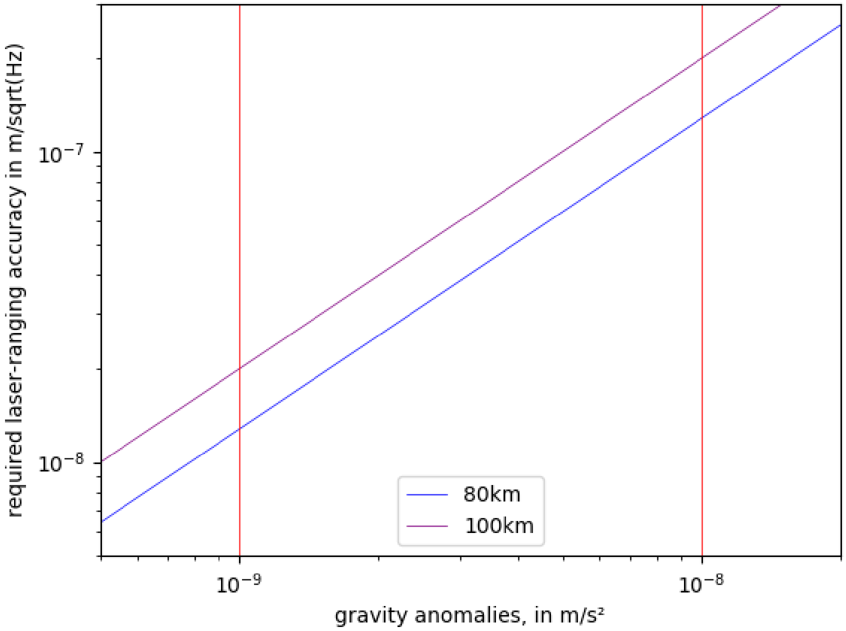
Gravity sensitivity → ranging precision

Laser must resolve $\Delta s = \frac{1}{2} a (1 / f)^2$

a = gravity anomaly at satellite altitude
f = sampling frequency (defined by spatial resolution and satellite altitude)

Resolution hardly depends on altitude, @500km:

- 0.1 μGal @ 80km: 28.76 nm/$\text{Hz}^{1/2}$
- 0.1 μGal @ 100km: 50.23 nm/$\text{Hz}^{1/2}$
- 1.0 μGal @ 80km: 287.55 nm/$\text{Hz}^{1/2}$
- 1.0 μGal @ 100km: 502.33 nm/$\text{Hz}^{1/2}$

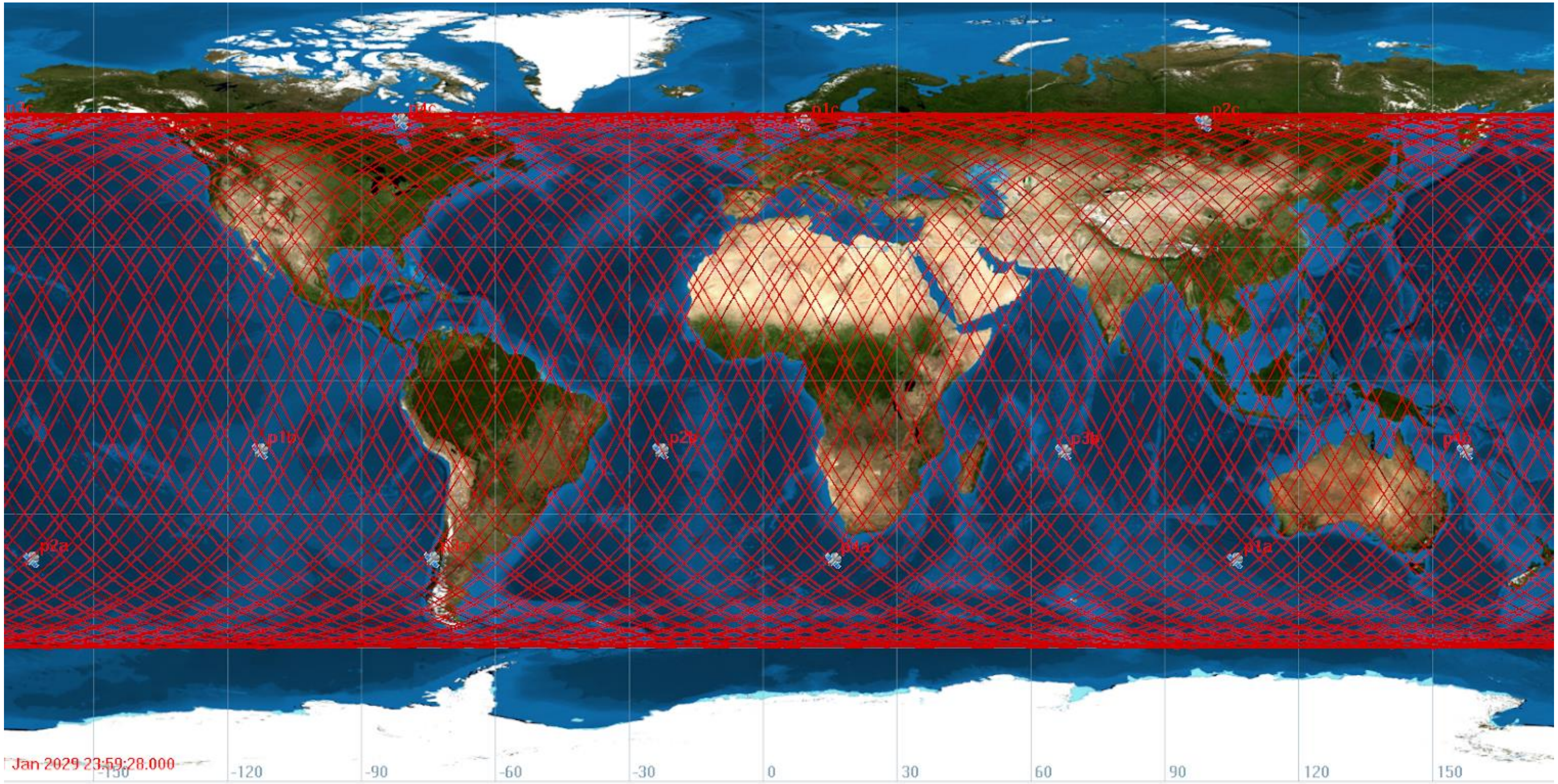


Engineering

Green Team 25th July 2019

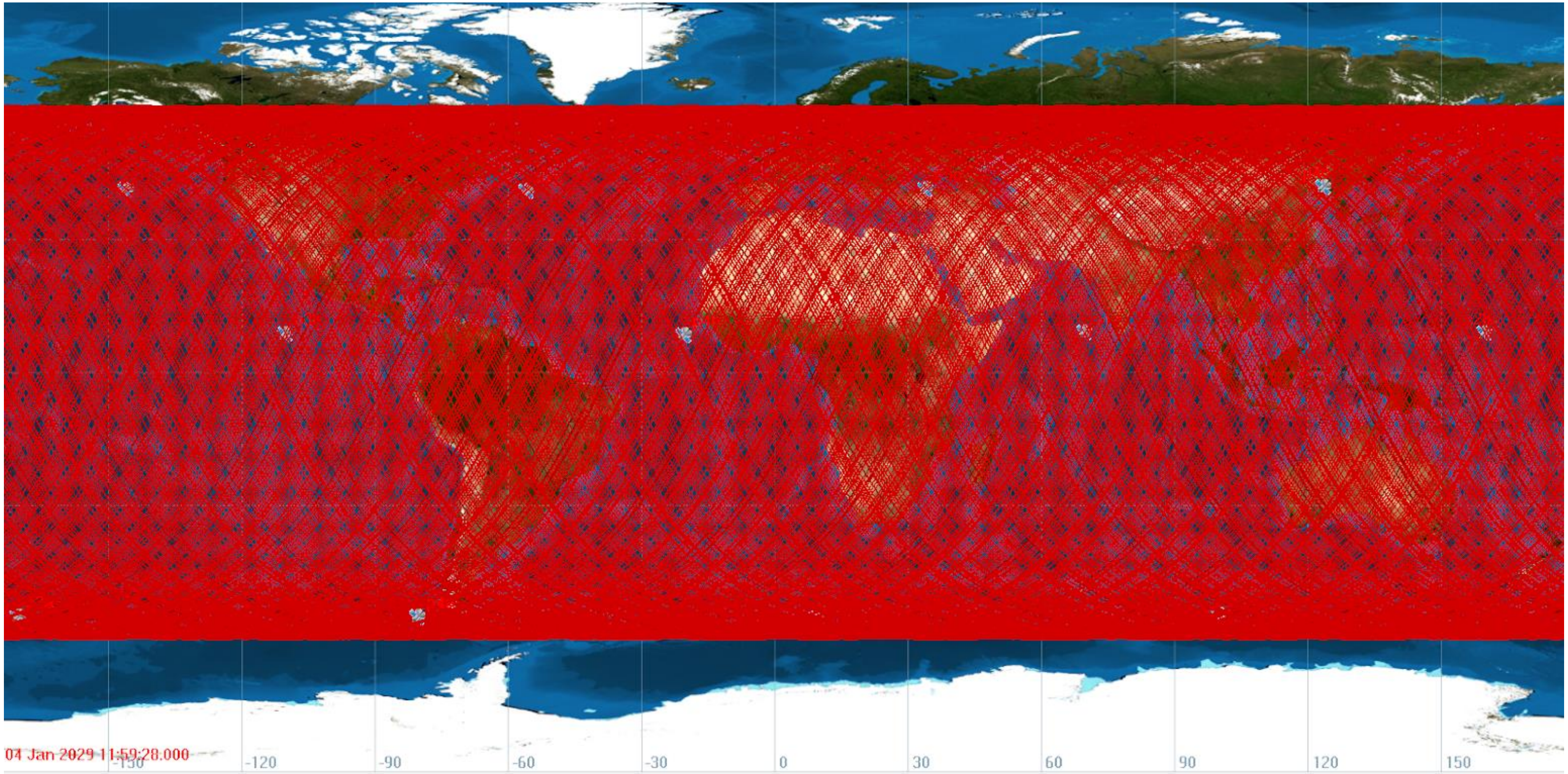
LEO component

Half day coverage



LEO component

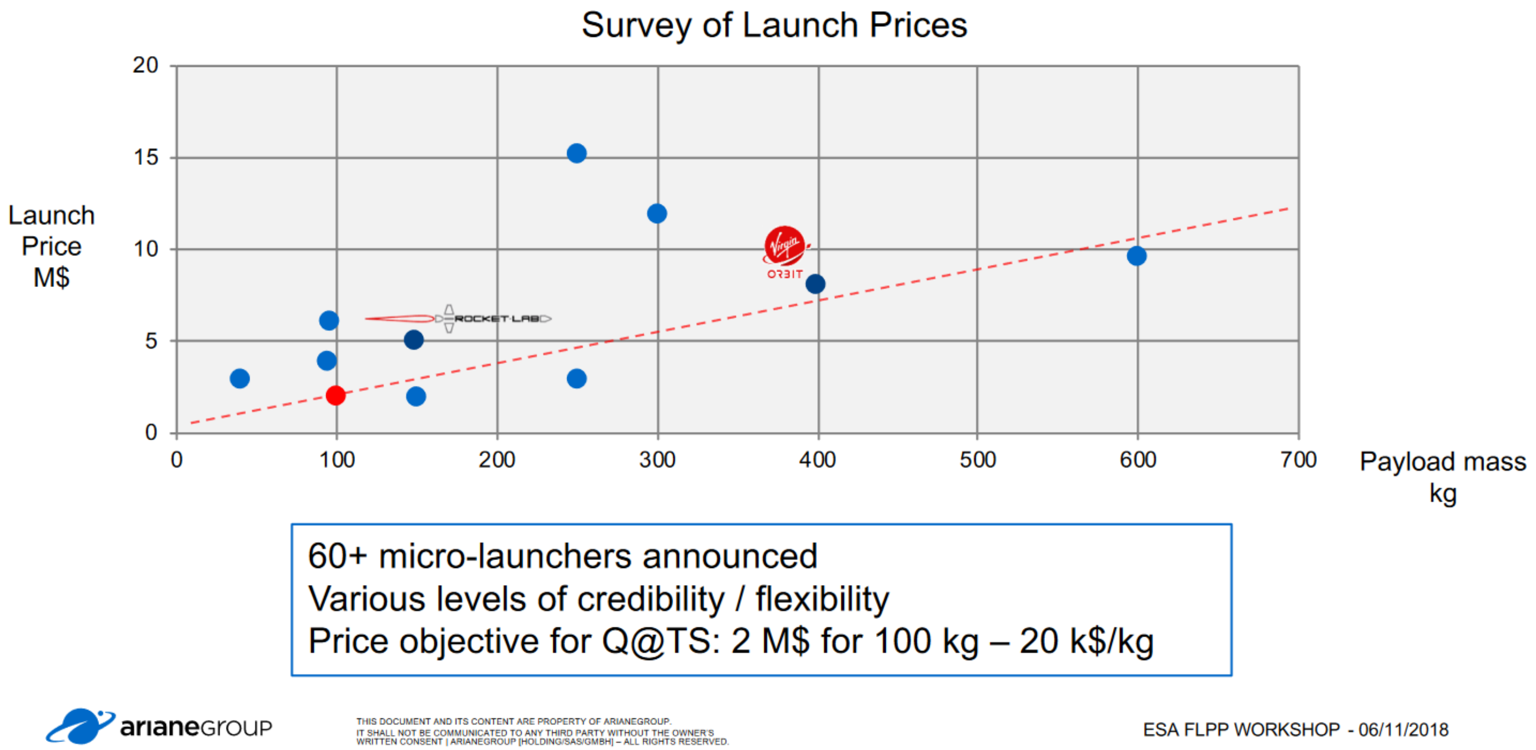
3 day fine coverage



LEO component

Orbital insertion

- One-time-use insertion boosters - orbit
- Insertion at apogee (altitude = 500 km)
- Perigee altitude ≈ 470 km => period ≈ 5654 s
- After 100 orbits (i.e. approx 6.5 days): 120° true anomaly phase
- For circular-to-elliptical-to-circular: dv ≈ 17 m/s
- For 37 kg dry mass and 250 s Isp: mfuel ≈ 0.13 kg
- For 2 N thrust: thrust ≈ 315 s



Survey of Launch Prices

60+ micro-launchers announced
Various levels of credibility / flexibility
Price objective for Q@TS: 2 M$ for 100 kg – 20 k$/kg

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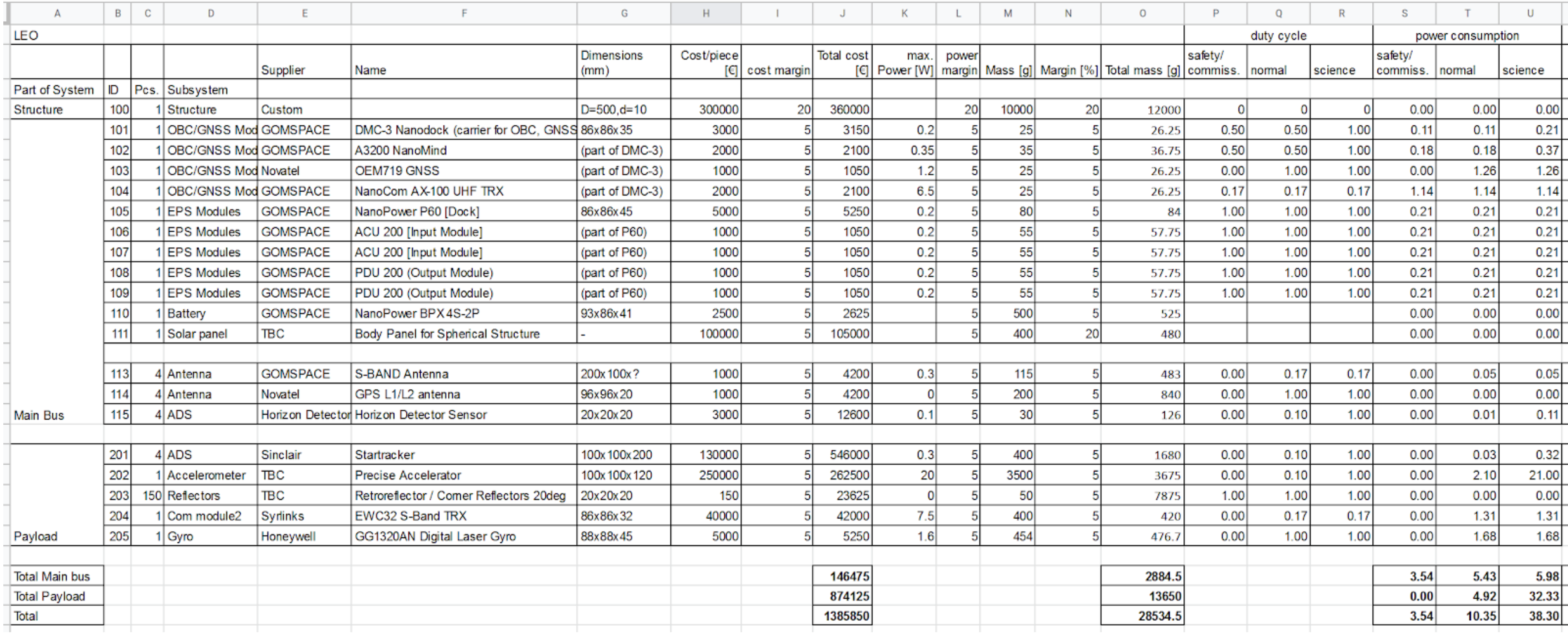
ESA FLPP WORKSHOP - 06/11/2018

ESA workshop

LEO budgets

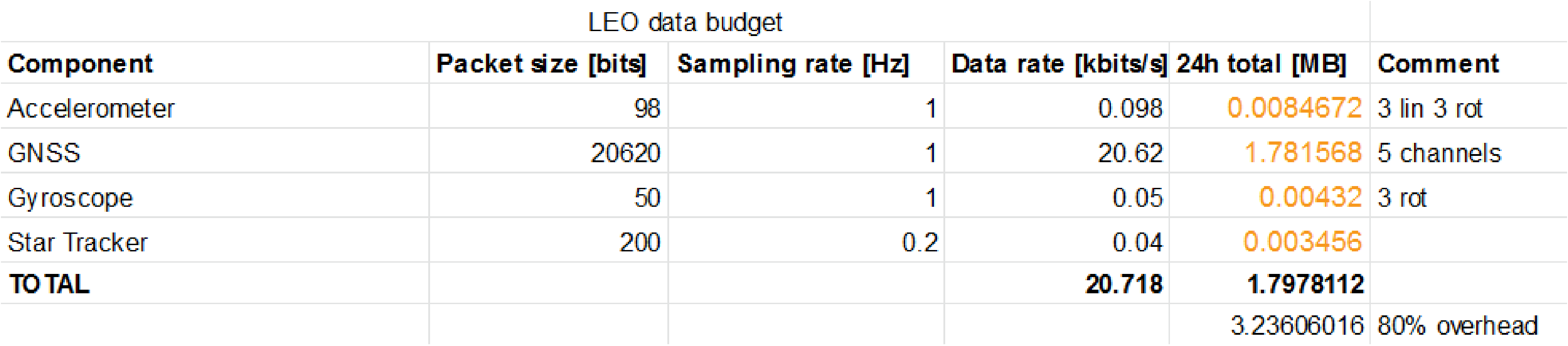


A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U
LEO																duty cycle			power consumption	
				Supplier	Name	Dimensions (mm)	Cost/piece [€]	cost margin	Total cost [€]	max. Power [W]	power margin	Mass [g]	Margin [%]	Total mass [g]	safety/ commiss.	normal	science	safety/ commiss.	normal	science
Part of System	ID	Pcs.	Subsystem																	
Structure	100	1	Structure	Custom		D=500,d=10	300000	20	360000		20	10000	20	12000	0	0	0	0.00	0.00	0.00
Main Bus	101	1	OBC/GNSS Mod	GOMSPACE	DMC-3 Nanodock (carrier for OBC, GNSS	86x86x35	3000	5	3150	0.2	5	25	5	26.25	0.50	0.50	1.00	0.11	0.11	0.21
	102	1	OBC/GNSS Mod	GOMSPACE	A3200 NanoMind	(part of DMC-3)	2000	5	2100	0.35	5	35	5	36.75	0.50	0.50	1.00	0.18	0.18	0.37
	103	1	OBC/GNSS Mod	Novatel	OEM719 GNSS	(part of DMC-3)	1000	5	1050	1.2	5	25	5	26.25	0.00	1.00	1.00	0.00	1.26	1.26
	104	1	OBC/GNSS Mod	GOMSPACE	NanoCom AX-100 UHF TRX	(part of DMC-3)	2000	5	2100	6.5	5	25	5	26.25	0.17	0.17	0.17	1.14	1.14	1.14
	105	1	EPS Modules	GOMSPACE	NanoPower P60 [Dock]	86x86x45	5000	5	5250	0.2	5	80	5	84	1.00	1.00	1.00	0.21	0.21	0.21
	106	1	EPS Modules	GOMSPACE	ACU 200 [Input Module]	(part of P60)	1000	5	1050	0.2	5	55	5	57.75	1.00	1.00	1.00	0.21	0.21	0.21
	107	1	EPS Modules	GOMSPACE	ACU 200 [Input Module]	(part of P60)	1000	5	1050	0.2	5	55	5	57.75	1.00	1.00	1.00	0.21	0.21	0.21
	108	1	EPS Modules	GOMSPACE	PDU 200 (Output Module)	(part of P60)	1000	5	1050	0.2	5	55	5	57.75	1.00	1.00	1.00	0.21	0.21	0.21
	109	1	EPS Modules	GOMSPACE	PDU 200 (Output Module)	(part of P60)	1000	5	1050	0.2	5	55	5	57.75	1.00	1.00	1.00	0.21	0.21	0.21
	110	1	Battery	GOMSPACE	NanoPower BPX 4S-2P	93x86x41	2500	5	2625		5	500	5	525				0.00	0.00	0.00
	111	1	Solar panel	TBC	Body Panel for Spherical Structure	-	100000	5	105000		5	400	20	480				0.00	0.00	0.00
	113	4	Antenna	GOMSPACE	S-BAND Antenna	200x100x?	1000	5	4200	0.3	5	115	5	483	0.00	0.17	0.17	0.00	0.05	0.05
	114	4	Antenna	Novatel	GPS L1/L2 antenna	96x96x20	1000	5	4200	0	5	200	5	840	0.00	1.00	1.00	0.00	0.00	0.00
	115	4	ADS	Horizon Detector	Horizon Detector Sensor	20x20x20	3000	5	12600	0.1	5	30	5	126	0.00	0.10	1.00	0.00	0.01	0.11
Payload	201	4	ADS	Sinclair	Startracker	100x100x200	130000	5	546000	0.3	5	400	5	1680	0.00	0.10	1.00	0.00	0.03	0.32
	202	1	Accelerometer	TBC	Precise Accelerator	100x100x120	250000	5	262500	20	5	3500	5	3675	0.00	0.10	1.00	0.00	2.10	21.00
	203	150	Reflectors	TBC	Retroreflector / Corner Reflectors 20deg	20x20x20	150	5	23625	0	5	50	5	7875	1.00	1.00	1.00	0.00	0.00	0.00
	204	1	Com module2	Syrlinks	EWC32 S-Band TRX	86x86x32	40000	5	42000	7.5	5	400	5	420	0.00	0.17	0.17	0.00	1.31	1.31
	205	1	Gyro	Honeywell	GG1320AN Digital Laser Gyro	88x88x45	5000	5	5250	1.6	5	454	5	476.7	0.00	1.00	1.00	0.00	1.68	1.68
Total Main bus									**146475**					**2884.5**				**3.54**	**5.43**	**5.98**
Total Payload									**874125**					**13650**				**0.00**	**4.92**	**32.33**
Total									**1385850**					**28534.5**				**3.54**	**10.35**	**38.30**

LEO booster budget

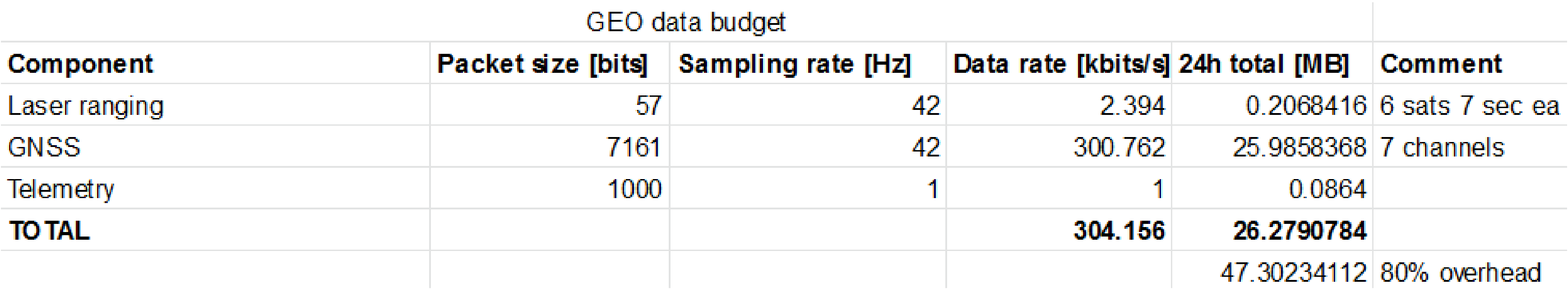
A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	
Group	ID	module type	Pcs	cost/piece [k€]	cost margin	total cost [k€]	max power [W]	power margin	mass	mass margin	total mass	safety/commiss.	normal	safety/commiss.	normal	
	101	MAI 400	2	20.0	5.0	42.0	7.0	5.0	700.0	5.0	1470	0.0	0.8	0.0	11.8	
	102	DMC-3 Nanodock	1	3	5.0	3.2	0.2	5.0	25.0	5.0	26.25	0.5	0.5	0.1	0.1	
	103	A3200 NanoMind	1	2	5.0	2.1	0.35	5.0	35.0	5.0	36.75	0.5	0.5	0.2	0.2	
	104	OEM719 GNSS	1	1	5.0	1.1	1.2	5.0	25.0	5.0	26.25	0.0	1.0	0.0	1.3	
	105	NanoCom AX-100 UHF T	1	2	5.0	2.1	6.5	5.0	25.0	5.0	26.25	0.2	0.2	1.1	1.1	
	106	NanoPower P60 [Dock]	1	5	5.0	5.3	0.2	5.0	80.0	5.0	84	1.0	1.0	0.2	0.2	
	107	ACU 200 [Input Module]	1	1	5.0	1.1	0.2	5.0	55.0	5.0	57.75	1.0	1.0	0.2	0.2	
	108	ACU 200 [Input Module]	1	1	5.0	1.1	0.2	5.0	55.0	5.0	57.75	1.0	1.0	0.2	0.2	
	109	PDU 200 (Output Module	1	1	5.0	1.1	0.2	5.0	55.0	5.0	57.75	1.0	1.0	0.2	0.2	
	110	PDU 200 (Output Module	1	1	5.0	1.1	0.2	5.0	55.0	5.0	57.75	1.0	1.0	0.2	0.2	
	111	NanoPower BPX 4S-2P	1	2.5	5.0	2.6		5.0		5.0	0			0.0	0.0	
	112	Battery	3	5.0	10.0	16.5		10.0	115.0	10.0	379.5			0.0	0.0	
Main bus																
Payload	201	BGT-X5	4			0.0	20		1500		6000	0	1	0.0	80.0	
		Total									**8280**		for 70% eff:	**3.54**	**136.42**	W

Data budgets



LEO data budget

Component	Packet size [bits]	Sampling rate [Hz]	Data rate [kbits/s]	24h total [MB]	Comment
Accelerometer	98	1	0.098	0.0084672	3 lin 3 rot
GNSS	20620	1	20.62	1.781568	5 channels
Gyroscope	50	1	0.05	0.00432	3 rot
Star Tracker	200	0.2	0.04	0.003456	
TOTAL			**20.718**	**1.7978112**	
				3.23606016	80% overhead



GEO data budget

Component	Packet size [bits]	Sampling rate [Hz]	Data rate [kbits/s]	24h total [MB]	Comment
Laser ranging	57	42	2.394	0.2068416	6 sats 7 sec ea
GNSS	7161	42	300.762	25.9858368	7 channels
Telemetry	1000	1	1	0.0864	
TOTAL			**304.156**	**26.2790784**	
				47.30234112	80% overhead

Delta V budgets

Delta-V Budget Summary	
Maneuver Name	Value (m/s)
GTO to GEO	1810
GEO to Grave	11
GEO maintenance	315
GEO total	**2136**
LEO insert	20
LEO total	**20**

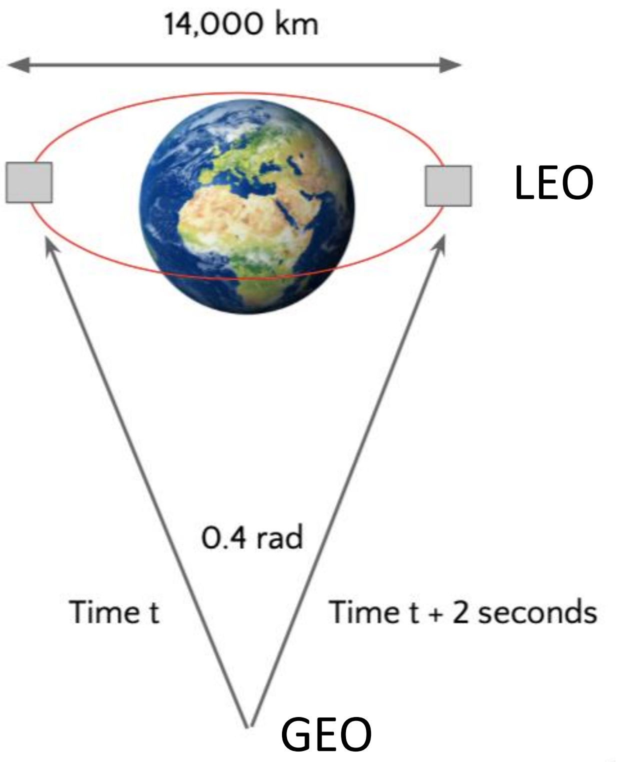
Space debris mitigation

Recognising the responsibility towards future spacefaring generations, this mission will be in compliance with ESA's space debris mitigation guidelines.

- In LEO, the s/c will deorbit 3 – 5.2 years
- similar but shorter lifetime for upper stage of the Q@TS launcher.
- the satellite dispensers foresee ΔV-budget for active deorbiting
- GEO s/c have a lifetime of 7 years and transfer to graveyard orbit 300 km above GEO
- The upper stage of Ariane 6.2 performs active deorbiting

GEO ranging

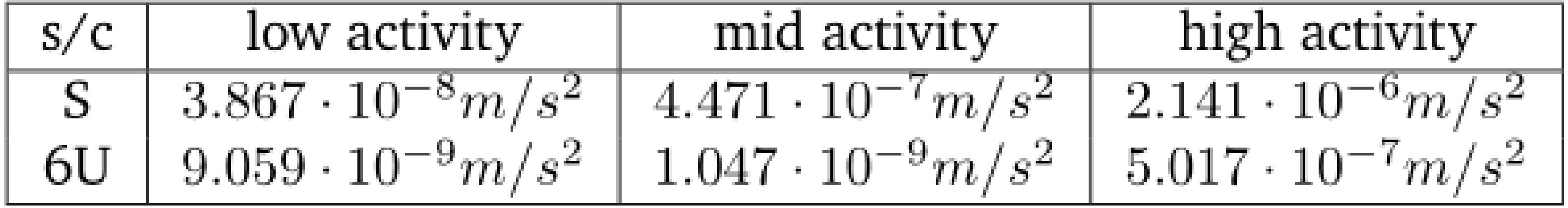
- First order approximation of laser pointing requirements
- Worst case pointing precision related to divergence of laser
- 2E-5 rad
- Worst case slew speed related to number of satellites to track and their separation
- 0.2 rad/s
- Multiple beam steering and acquisition systems allow simultaneous tracking if needed



Not to scale!

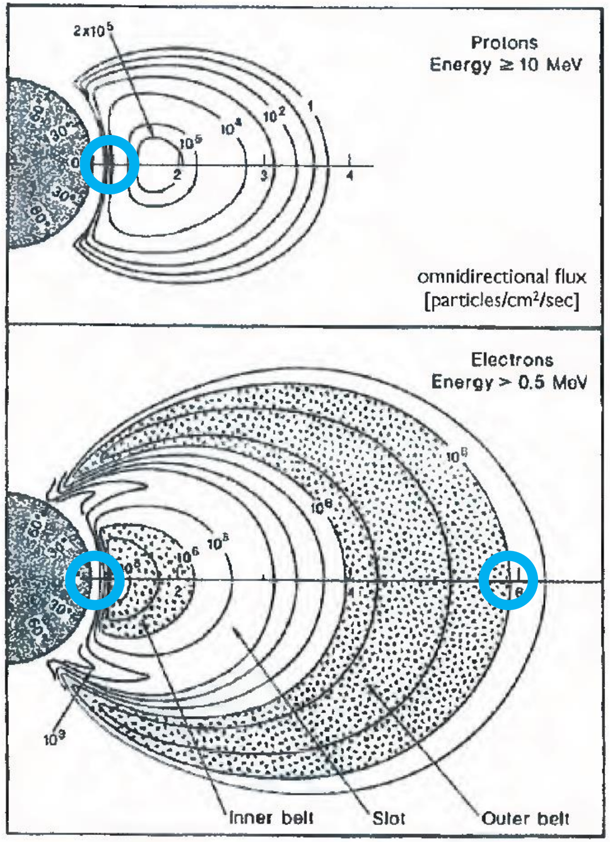
Calculation of drag

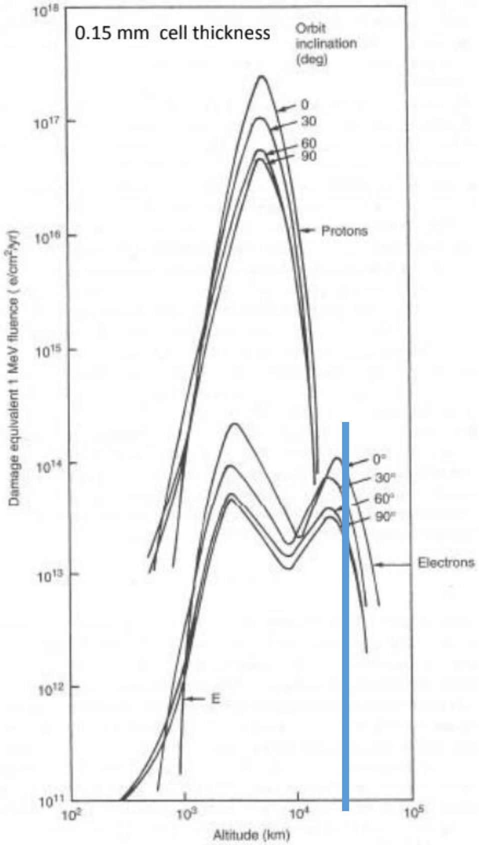
$$a_{drag} = -\frac{1}{2}\rho||v - v_{atm}||(v - v_{atm})C_D\frac{A}{m}$$



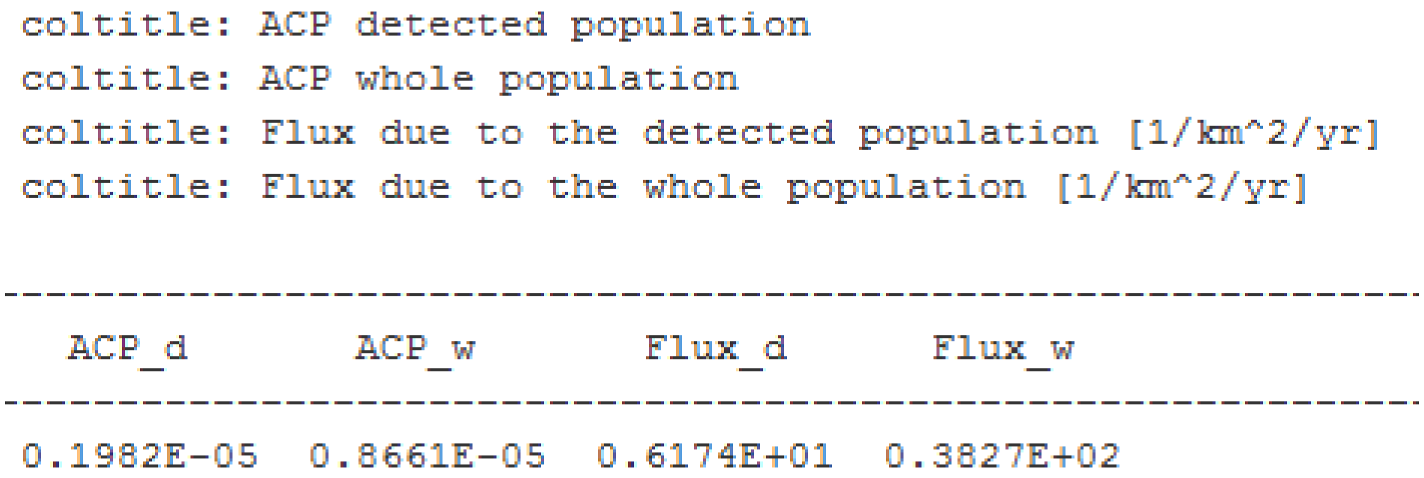
s/c	low activity	mid activity	high activity
S	$3.867 \cdot 10^{-8} m/s^2$	$4.471 \cdot 10^{-7} m/s^2$	$2.141 \cdot 10^{-6} m/s^2$
6U	$9.059 \cdot 10^{-9} m/s^2$	$1.047 \cdot 10^{-9} m/s^2$	$5.017 \cdot 10^{-7} m/s^2$

Space environment: radiation





Probability of collision with debris



```
coltitle: ACP detected population
coltitle: ACP whole population
coltitle: Flux due to the detected population [1/km^2/yr]
coltitle: Flux due to the whole population [1/km^2/yr]

-----------------------------------------------------------
  ACP_d       ACP_w       Flux_d      Flux_w
-----------------------------------------------------------
0.1982E-05  0.8661E-05  0.6174E+01  0.3827E+02
```

Simulation done with Master statistical data, and with ARES tool from DRAMA, for 1 satellite in LEO.

Programmatics

Green Team 25th July 2019

Team Green

Science: L. Salfenmoser, S.S. Beeck, I. Bjorge-Engeland, E. Bogacz, V. Camplone

Payload: E.F.M. Weterings, V. Galetsky, M. Noeker

System: N. Anthony, R. Zeif, E.A. Savu, M. Eizinger, M. Archimbaud

Systems coordinator: J. Woodwark

Team leader: M. Stefko

Tutors: Q. Chen and J. Praks

Imperial heritage