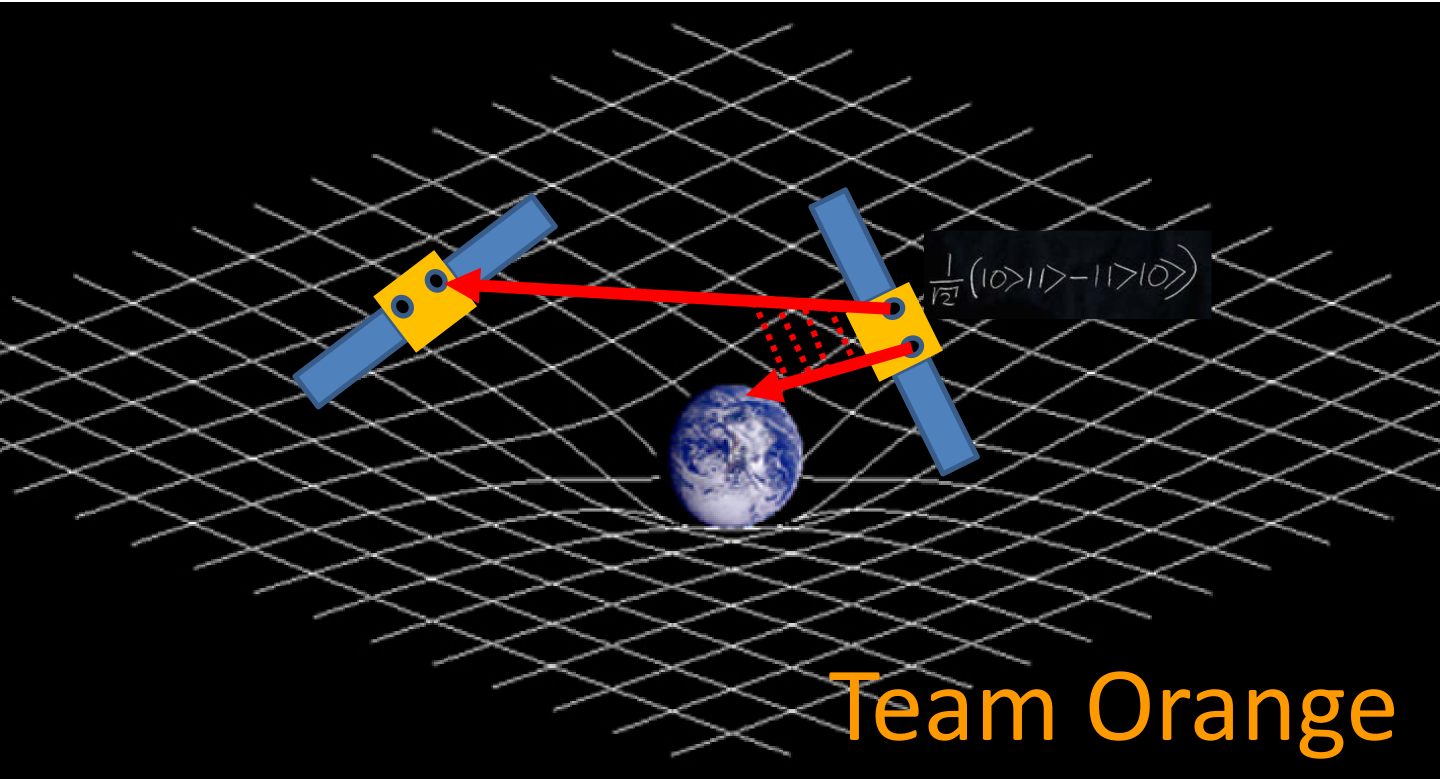
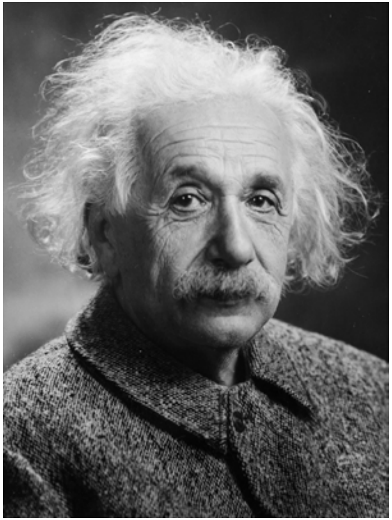
Entanglement Propagation in Gravity

EPIG



Team Orange

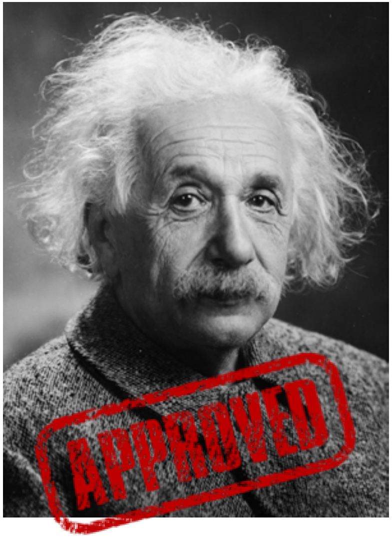
General Relativity / Quantum Theory



Albert Einstein

Erwin Schrödinger

General Relativity / Quantum Theory



Albert Einstein

Erwin Schrödinger

General Relativity / Quantum Theory

String theory
Loop quantum gravity
Scale Relativity
Acoustic metric
Asymptotic safety in quantum gravity
Euclidean quantum gravity
Causal dynamical triangulation
Causal fermion systems
Causal sets
Covariant Feynman path integral
Group field theory
E8 Theory

Wheeler-DeWitt equation
Geometrodynamics
Hořava–Lifshitz gravity
MacDowell–Mansouri action
Noncommutative geometry.
Path-integral based cosmology models
Regge calculus
String-nets
Superfluid vacuum theory
Supergravity
Twistor theory
Canonical quantum gravity

History of General Relativity and Quantum Mechanics

1916: Einstein (General Relativity)

1925-1935: Bohr, Schrödinger (Entanglement),

Einstein, Podolsky and Rosen (Paradox), ...

1964: John Bell (Bell's Inequality)

1982: Alain Aspect (Violation of Bell's Inequality)

1916: General Relativity

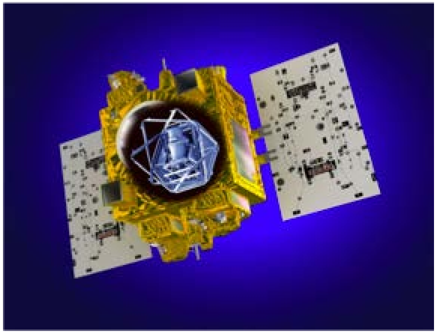
Describes the Universe on large scales

“Matter curves space and curved space tells matter how to move!”

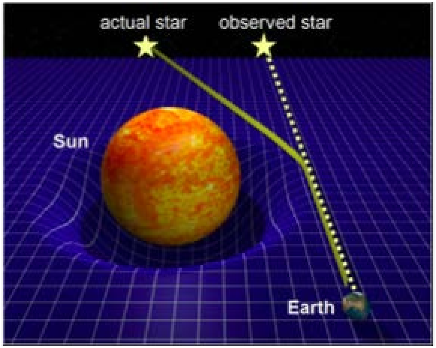
Testing General Relativity

Experimental attempts to probe the validity of general relativity:

Test mass
MICROSCOPE



Light Bending effect

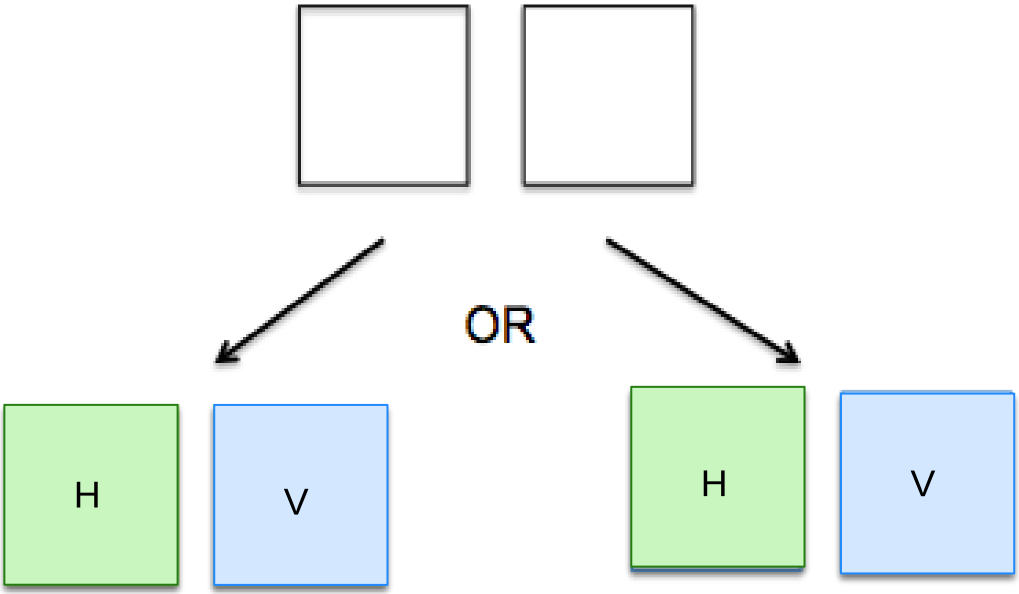


Quantum Theory

Describes the Universe on atomic and subatomic scales:

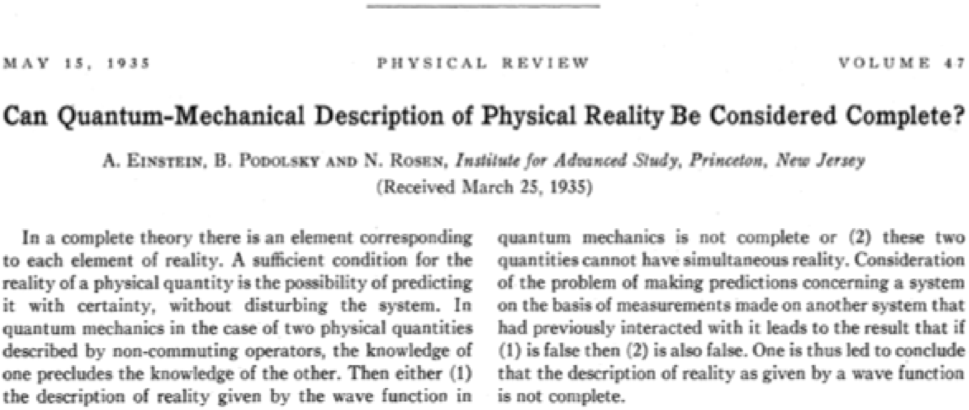
- Quantisation
- Wave-particle dualism
- Superposition, Entanglement
- ...

1935: Schrödinger (Entanglement)



1935: EPR Paradox

Quantum theory predicts that states of two (or more) particles can have specific correlation properties violating ‘local realism’ (a local particle cannot depend on properties of an isolated, remote particle)



MAY 15, 1935 PHYSICAL REVIEW VOLUME 47

Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?

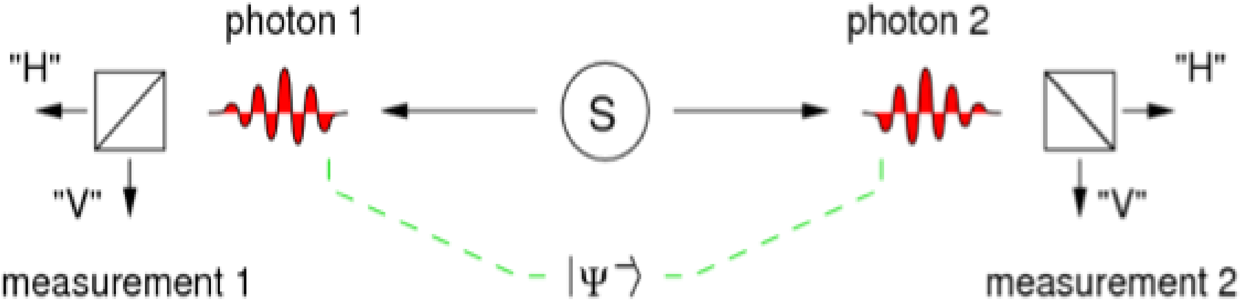
A. EINSTEIN, B. PODOLSKY AND N. ROSEN, *Institute for Advanced Study, Princeton, New Jersey*

(Received March 25, 1935)

In a complete theory there is an element corresponding to each element of reality. A sufficient condition for the reality of a physical quantity is the possibility of predicting it with certainty, without disturbing the system. In quantum mechanics in the case of two physical quantities described by non-commuting operators, the knowledge of one precludes the knowledge of the other. Then either (1) the description of reality given by the wave function in quantum mechanics is not complete or (2) these two quantities cannot have simultaneous reality. Consideration of the problem of making predictions concerning a system on the basis of measurements made on another system that had previously interacted with it leads to the result that if (1) is false then (2) is also false. One is thus led to conclude that the description of reality as given by a wave function is not complete.

1964: Testing Quantum Mechanics

Bell's tests: Testing the completeness of quantum mechanics by measuring correlations of entangled photons

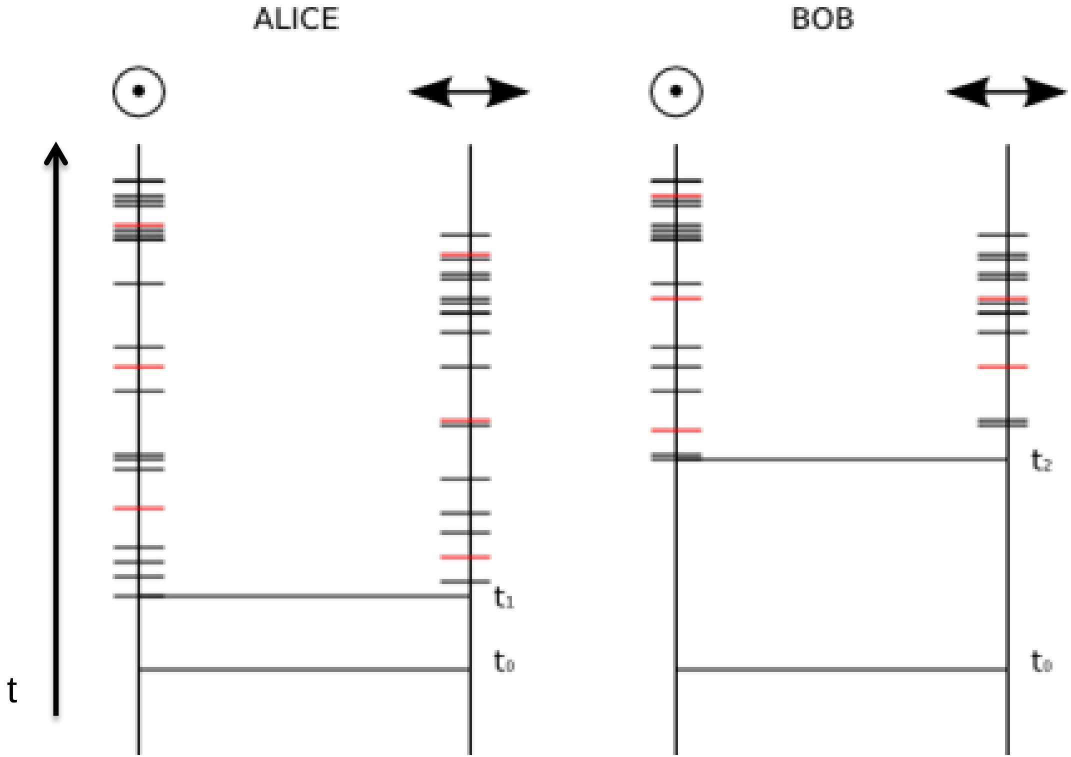


$E_{HV,\pm} := (N_{H,+} + N_{V,-} - N_{H,-} - N_{V,+}) / N_T$

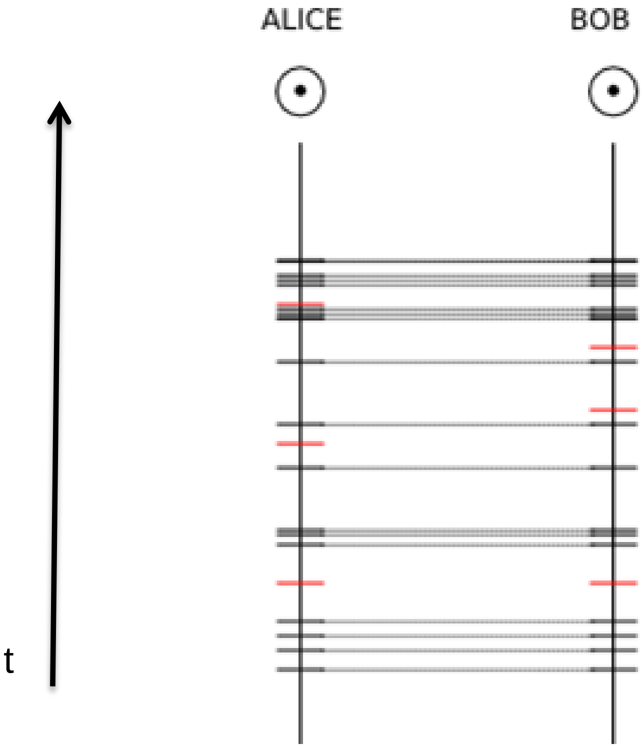
$S := E_{a,b} - E_{a',b} + E_{a,b'} + E_{a,b'}$

N: counts
E, S: correlation functions

Coincidence Counts

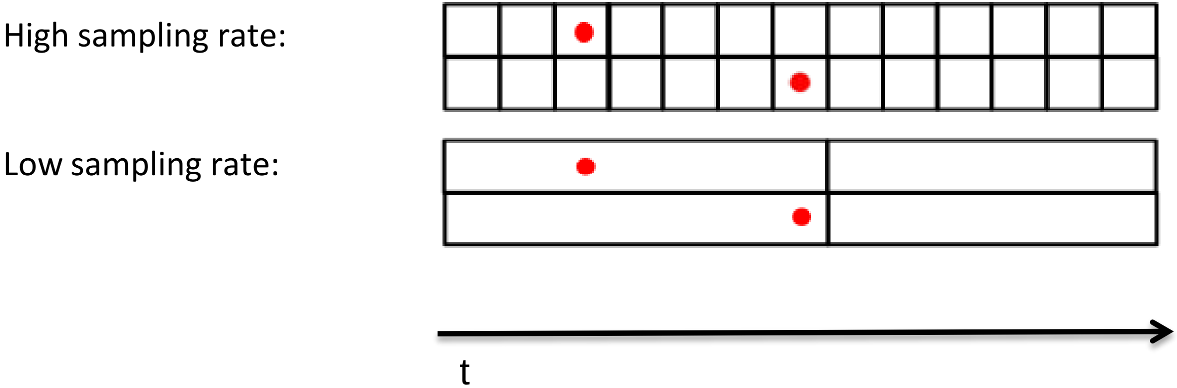


Coincidence Counts



Accuracy Analysis

Single and entangled photons are to be **detected** and **time stamped** by single photon detectors. Wrong coincidence counts can be avoided if the **timing resolution** is sufficiently high to sample nearly-simultaneously occurring pairs of singles.



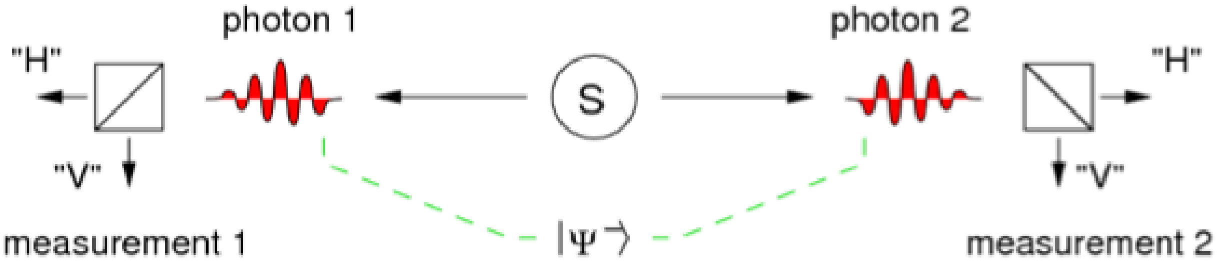
High sampling rate:

Low sampling rate:

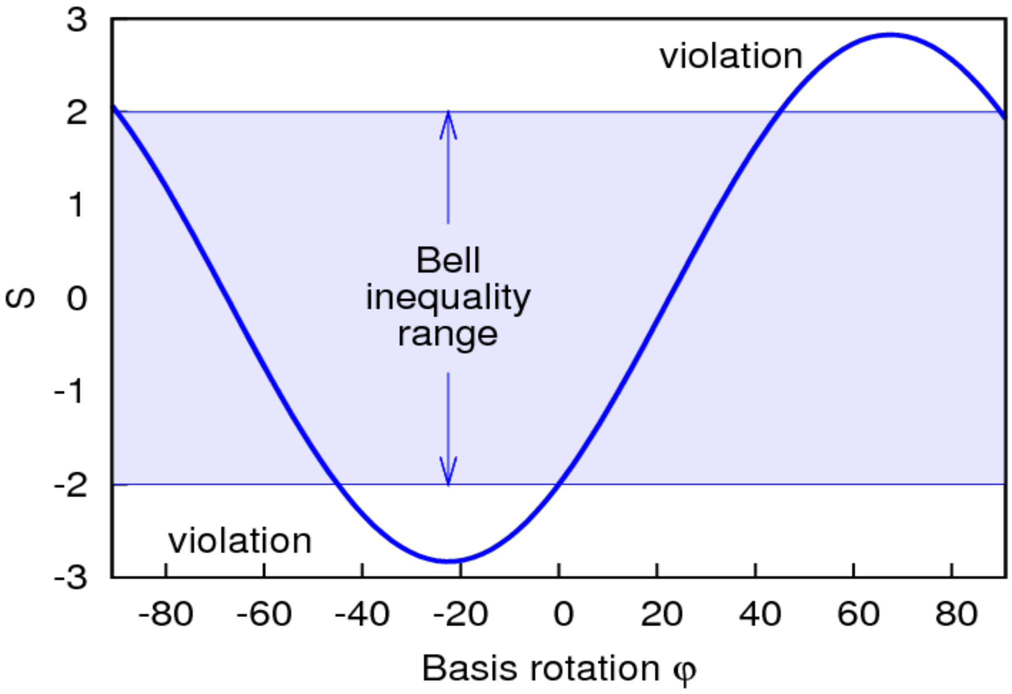
1982: Violation of Bell's Inequality

Testing the Bell inequality with polarization entangled photons proved that quantum mechanics is complete!

$$|\Psi^-\rangle = 1/\sqrt{2}\,(|H_1H_2\rangle - |V_1V_2\rangle)$$



Bell curve


3
2
1
0
-1
-2
-3
S
violation
Bell
inequality
range
violation
-80
-60
-40
-20
0
20
40
60
80
Basis rotation φ

" Why not come up with an experiment that combines quantum properties and general relativity?”

Testing general relativity using quantum mechanical properties

Milburn 1991

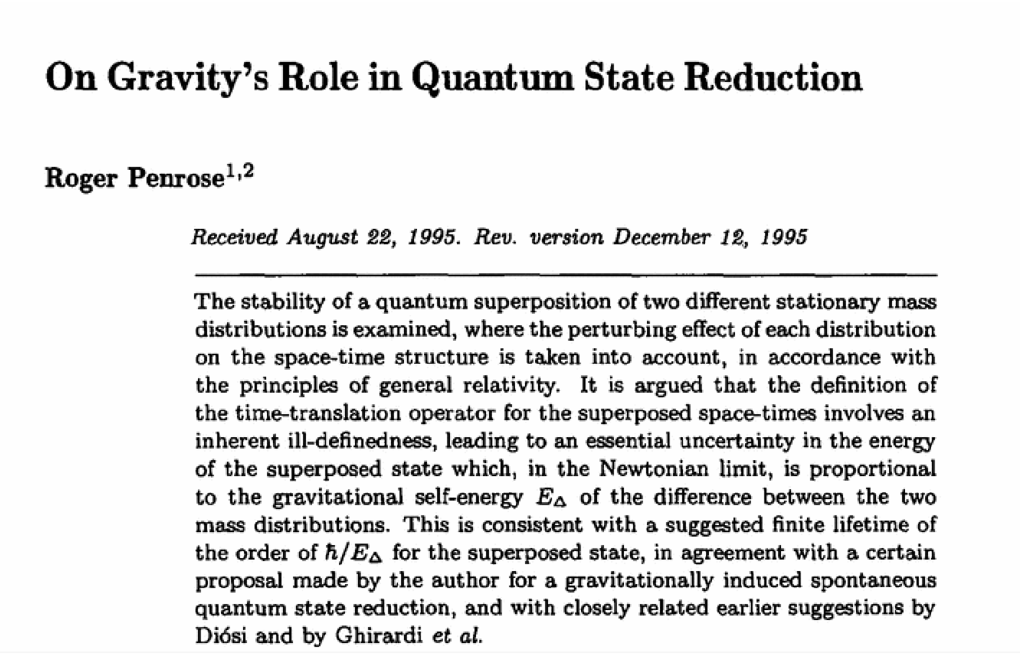
Ralph 2004

Penrose 1994

Diosi 1987

Deutsch 1991

Adler 2004



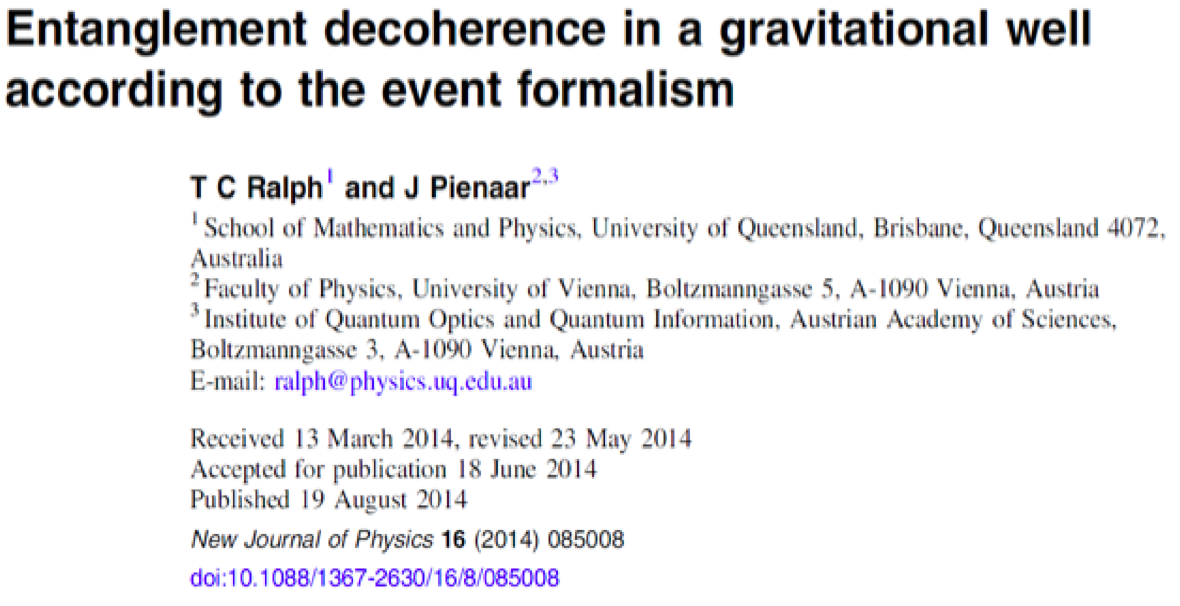
On Gravity's Role in Quantum State Reduction

Roger Penrose[1,2]

Received August 22, 1995. Rev. version December 12, 1995

The stability of a quantum superposition of two different stationary mass distributions is examined, where the perturbing effect of each distribution on the space-time structure is taken into account, in accordance with the principles of general relativity. It is argued that the definition of the time-translation operator for the superposed space-times involves an inherent ill-definedness, leading to an essential uncertainty in the energy of the superposed state which, in the Newtonian limit, is proportional to the gravitational self-energy E_Δ of the difference between the two mass distributions. This is consistent with a suggested finite lifetime of the order of $\hbar/E_\Delta$ for the superposed state, in agreement with a certain proposal made by the author for a gravitationally induced spontaneous quantum state reduction, and with closely related earlier suggestions by Diósi and by Ghirardi *et al.*

New theory for predicting gravity effects on quantum states



Entanglement decoherence in a gravitational well according to the event formalism

T C Ralph[1] **and J Pienaar**[2,3]

[1] School of Mathematics and Physics, University of Queensland, Brisbane, Queensland 4072, Australia
[2] Faculty of Physics, University of Vienna, Boltzmanngasse 5, A-1090 Vienna, Austria
[3] Institute of Quantum Optics and Quantum Information, Austrian Academy of Sciences, Boltzmanngasse 3, A-1090 Vienna, Austria
E-mail: ralph@physics.uq.edu.au

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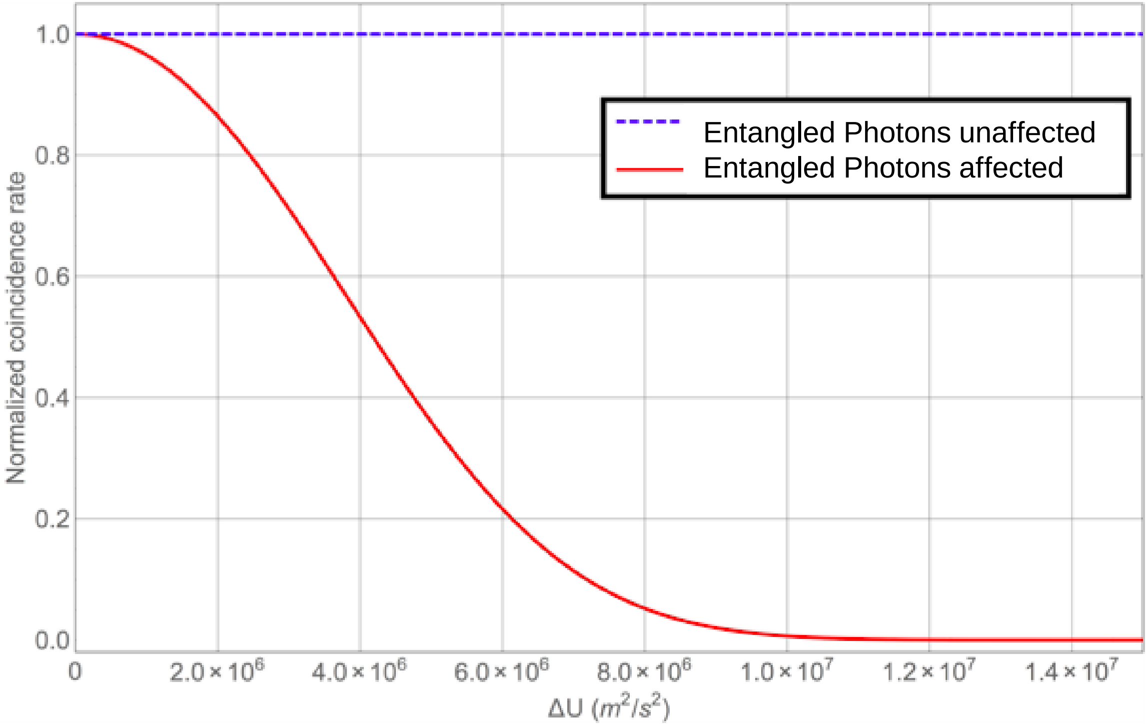
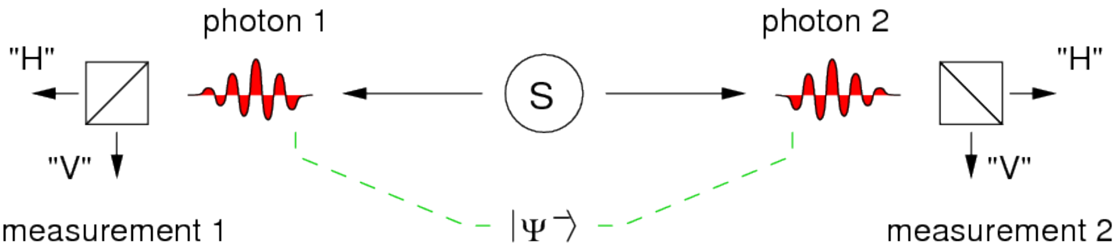
doi:10.1088/1367-2630/16/8/085008

Ralph and Pienaar model



Observables C_{norm}

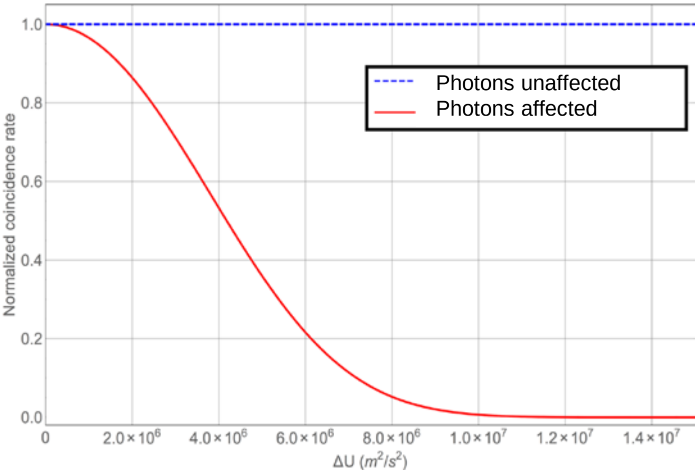


$$C_{norm} = \frac{N_{C,\Delta U}/N_{S,\Delta U}}{N_{C,\Delta U=0}/N_{S,\Delta U=0}}$$

N_C: coincidence counts
N_S: single counts

$\Delta U = 0$: local measurement

ΔU induces coincidence loss for entangled photons



Science Objective

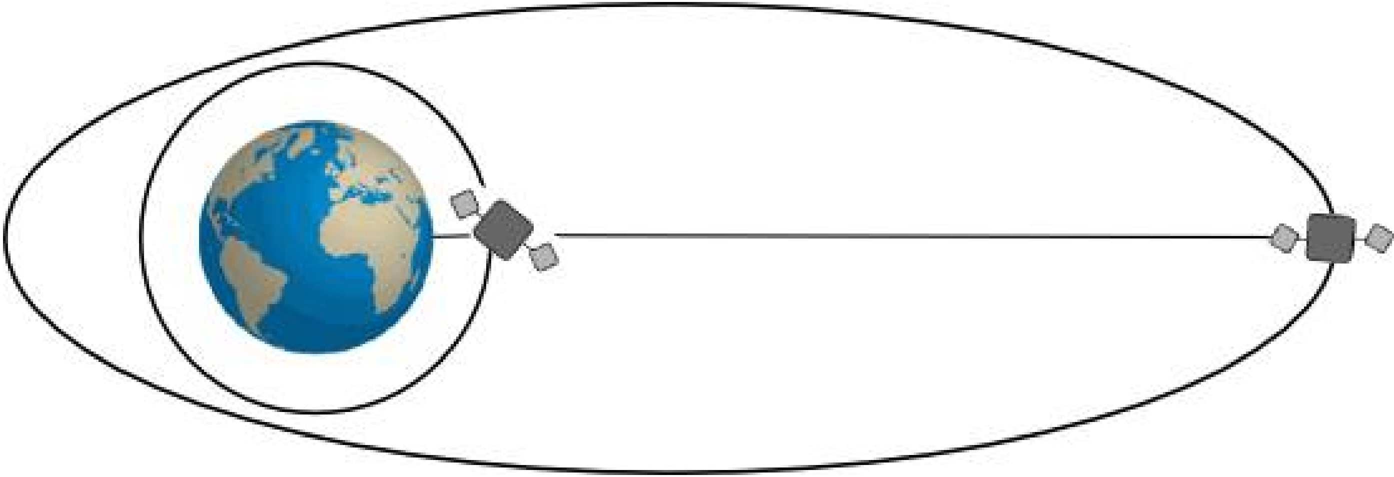
“Observe the interaction between gravity fields and entangled quantum states over a wide range of parameters.”

Science Requirements 1

Measure **variance** in normalised coincidences C_{norm} of entangled and non-entangled photons travelling through gravitational potential differences ΔU ranging from

0 - 13 km^2/s^2

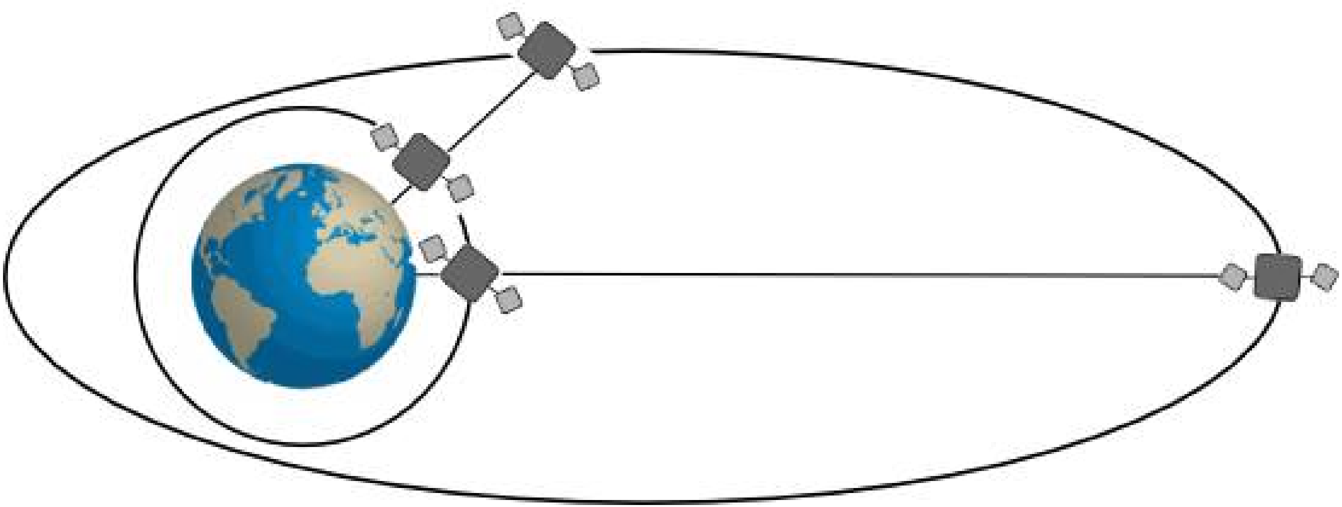
with an accuracy better than 5 sigma and a sampling distance of 0.15 km^2/s^2.



Science requirement 2.1

Conduct a measurement that characterizes S and C_{norm} in the range of the photon **travelling distance D**

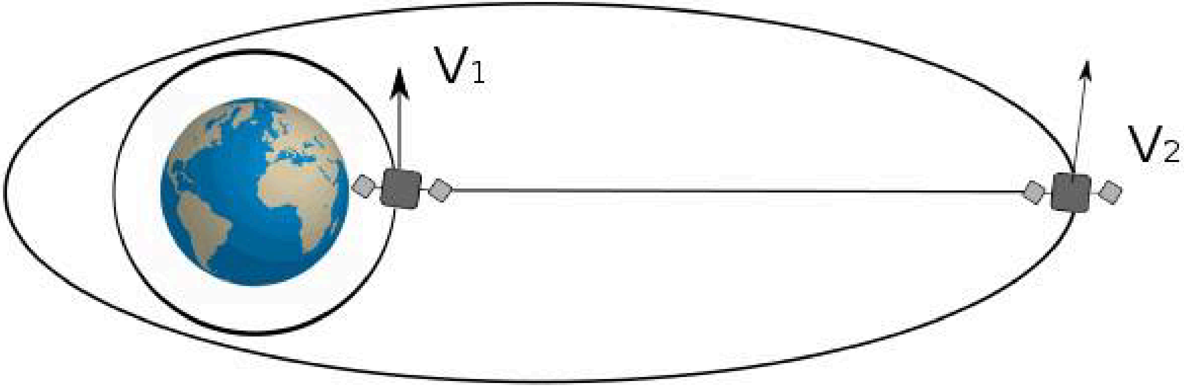
200 km to 2000 km



Science requirement 2.2

Conduct a measurement that characterizes S and C_{norm} in the range of the **relative velocity Δv_{rel}** between photon source and detector of

1 km/s to 13 km/s


V_1
V_2

Science requirement 2.3

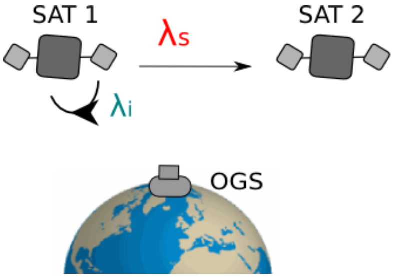
Conduct a measurement that characterizes S and C_{norm} in the range of the **angle α between the photon propagation vector and the gravity field gradient** of

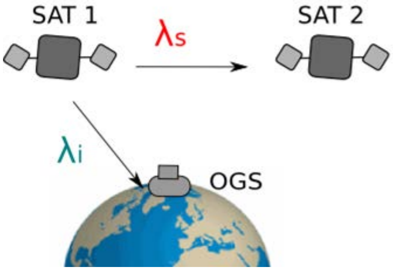
0 and 180°

Science requirement 3

Conduct a measurement that characterizes S and C_{norm} of two entangled photons with:

local detection & remote detection



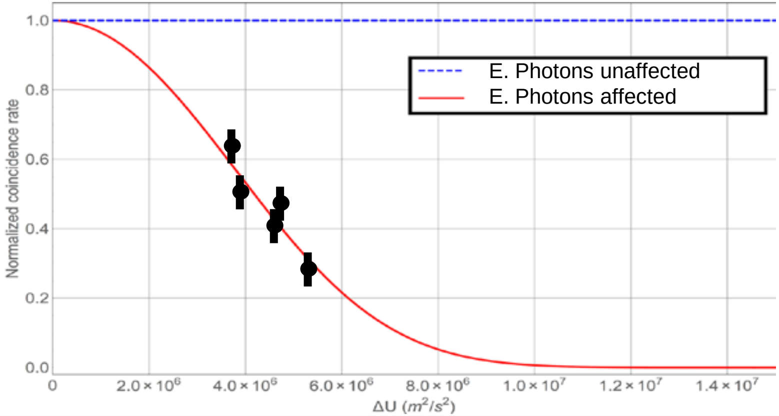


Accuracy analysis: count rates

From small ΔU values, the accuracy of the C_{norm} data is mostly depending on the coincidence count number. A five sigma error is achieved if:

$$N_c = \frac{5^2}{(1 - C_{norm})^2}$$

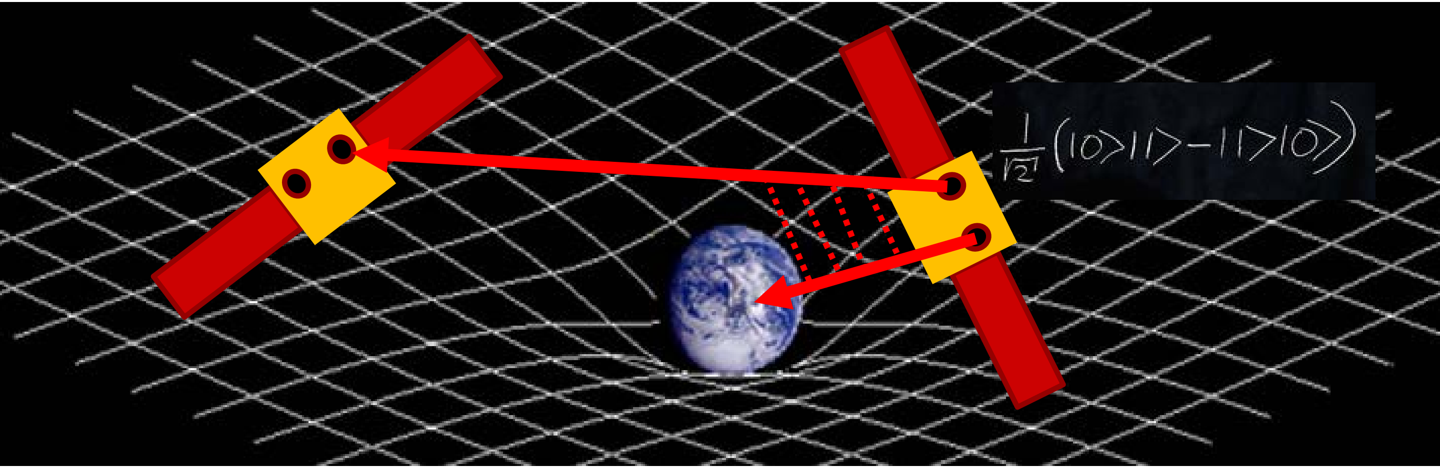
For large ΔU values, the accuracy of C_{norm} is achieved much faster ($N_c < 1000$), but at least 1000 counts per data point are required to verify $S > 2$.



Entanglement Propagation in Gravity

EPIG

Mission design, orbits and payload



Systems driven by count rate

Measurement accuracy requires a high coincident count number which is depending on:

1. Entangled photon source pair generation rate
2. Link budget (coupling efficiencies, telescope size/pointing performance, orbital distances)
3. Single photon detector efficiency
4. Link time / orbit and total mission duration

Mission design approach

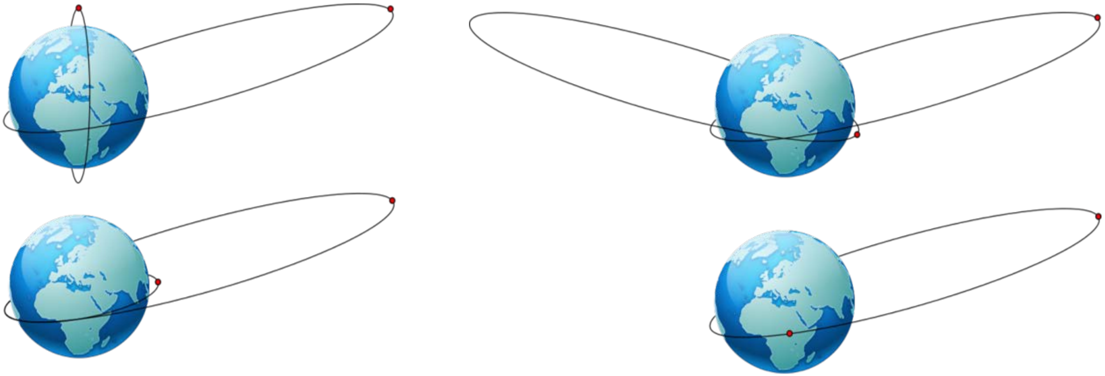
Design approach:

- Use best EPS rate currently available (10 MHz) to minimize development time
- Use largest COTS laser terminal (135 mm TESAT terminals)
- Use existing detector at medium cold temperature (60% at -30 degC)
- Drive the link budget by optimizing the orbit and mission duration

Orbit candidates

Driving Requirement:

Inter-satellite visibility maximized



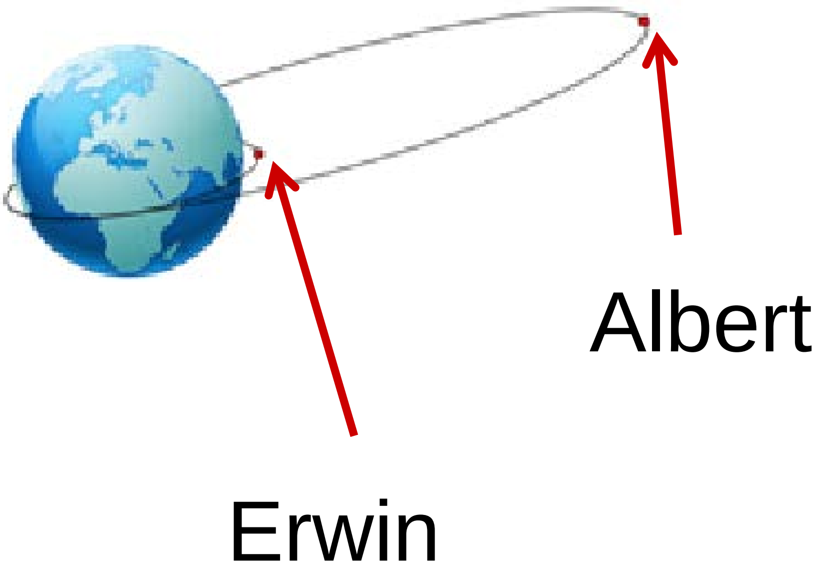
Final Orbit

Circular & Elliptical Orbit

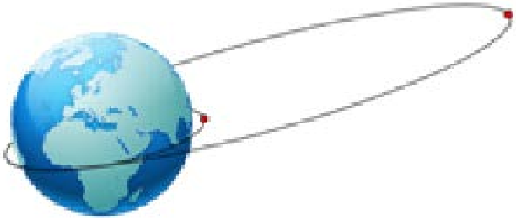
Circular 700km

Elliptical 3000x700km

Inclination 28°

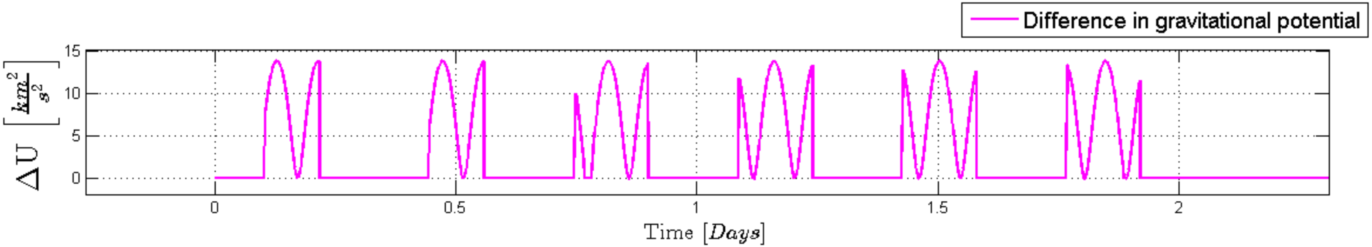


Final Orbit



Satellite Visibility:

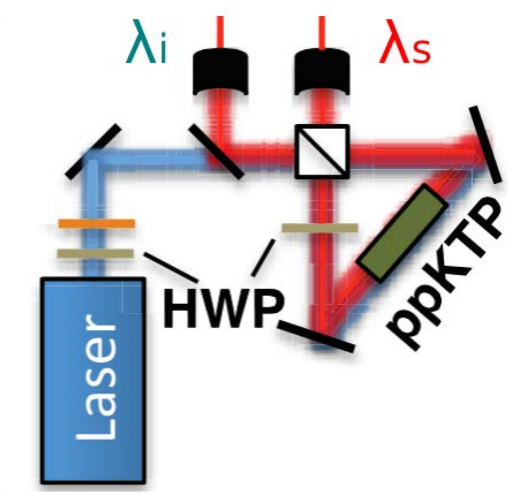
- Albert to Erwin : 33%
- Erwin to Optical Ground Station: 6% (1% due to daylight and cloud contraints)
- Albert to Optical Ground Station: 10% (2% due to daylight and cloud contraints)

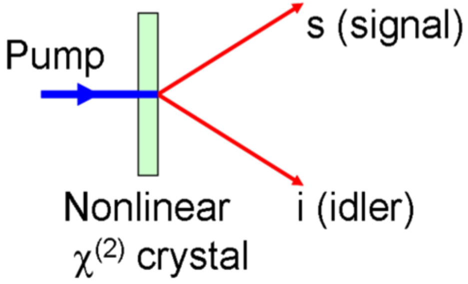


Compliant with the ΔU science requirement 0 – 13 km²/s²

Payload: Entangled Photon Source

High coincidence generation and detection rate is a key requirement to reach the high accuracies of the science requirements





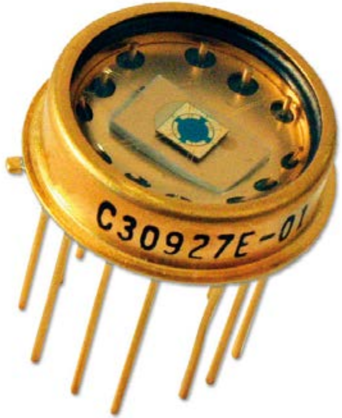
[Steinlechner, F., Gilaberte, M., Jofre, M., Scheidl, T., Torres, J. P., Pruneri, V., & Ursin, R. (2014). Efficient heralding of polarization-entangled photons from type-0 and type-II spontaneous parametric downconversion in periodically poled KTiOPO_4. J. Opt. Soc. Am.~B, 31(9), 2068. http://doi.org/10.1364/JOSAB.31.002068]

Laser terminal

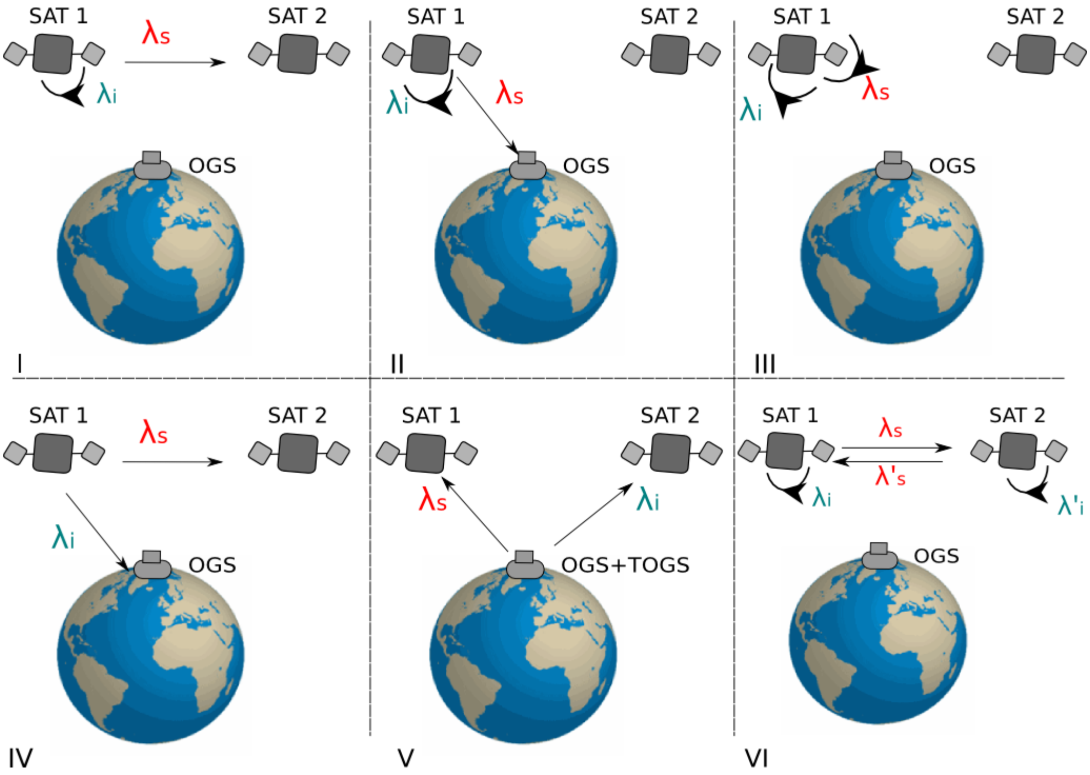
Commercial 135 mm laser terminals are used to send and receive photons in between the satellites.
-> more details in the system presentation

Single photodetector

Commercial silicon avalanche photodetector with 60% quantum efficiency cooled to -30 degC.

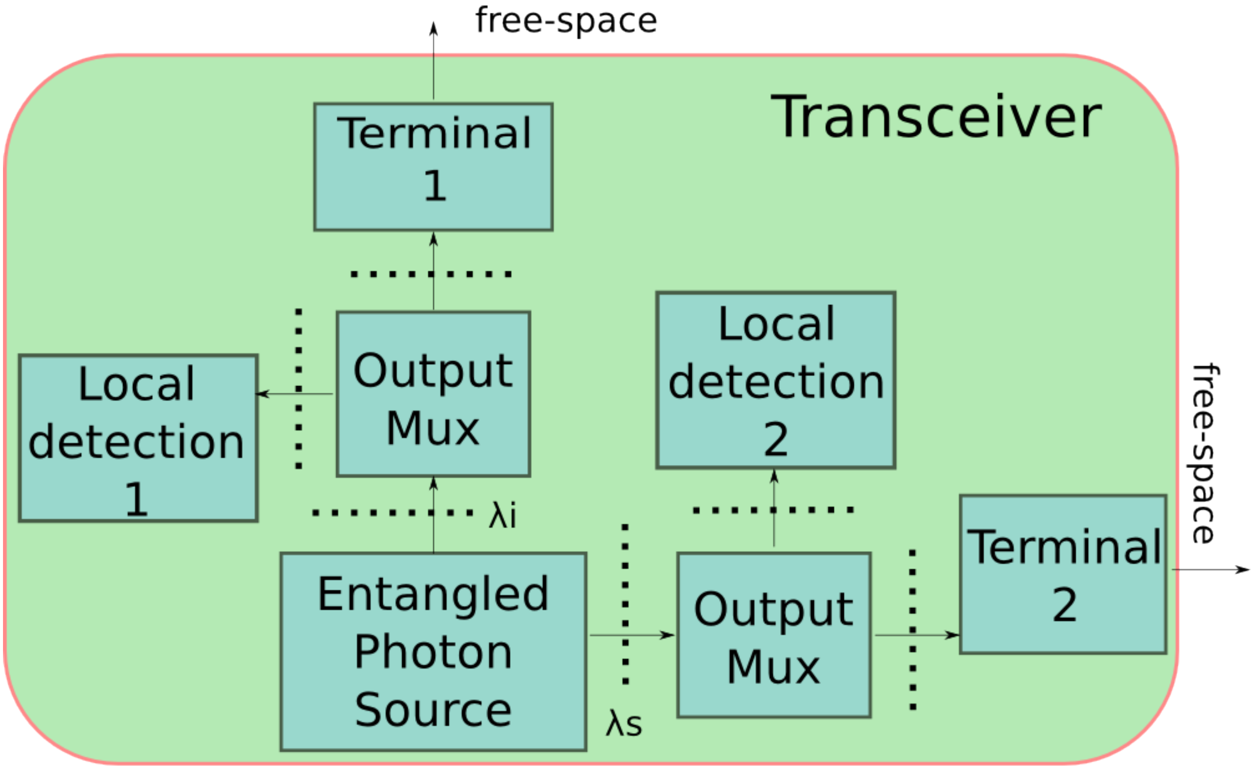


Observation Scenarios

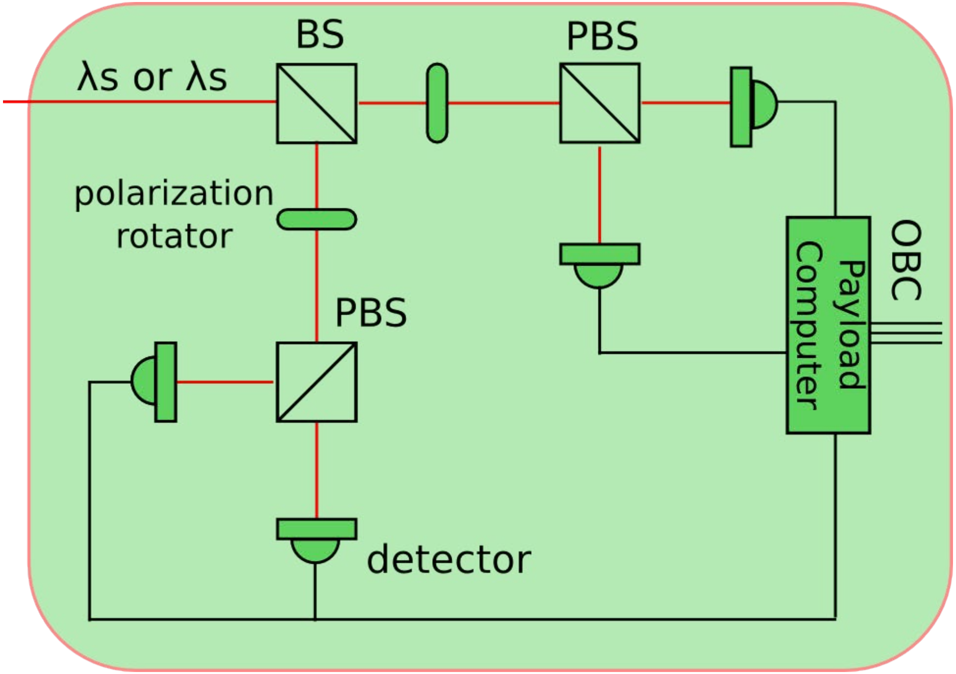


	Estimated Scenario Time
I	25 %
II	4 %
III	5 %
IV	4 %
V	2 %
VI	5 %
off	55 %

Payload layout

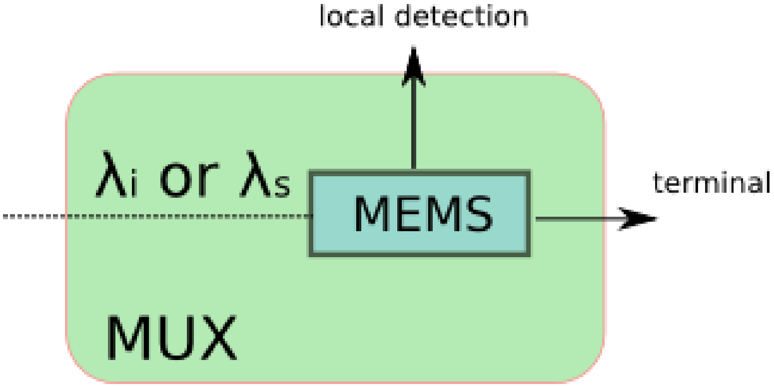


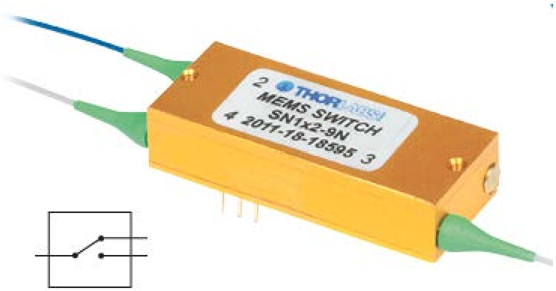
Payload: detector unit



Switching units

Micro-mechanical units for fibre switching. Commercial units not space qualified, development needed to achieve high reliability (10.000 switching cycles) and radiation hardness.





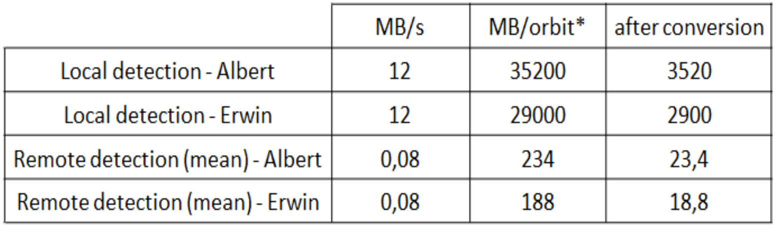
Payload key requirements

	Requirement	Payload compliance
Laser power	10 mW	compliant
Pair generation rate	10 MHz	compliant
Detection efficiency	10 M Coincidences / s	compliant
Polarization correction	Position correction + half wave-plates rotators	To be developed as part of the terminal
Coherence length	1 ps	Current performance: 100 ps 1 ps can be achieved with different EPS cavity design

Science Data Generation

Majority of the on-board data will be generated by the local detection of photons – **12 MBps**

Total amount of data depends on the experiments performed during the orbit and the orbit time, with an achievable compression rate **1:10**, the maximum amount of data **per orbit** do not exceed **4 GB** and **3,3 GB** for Albert and Erwin respectively.

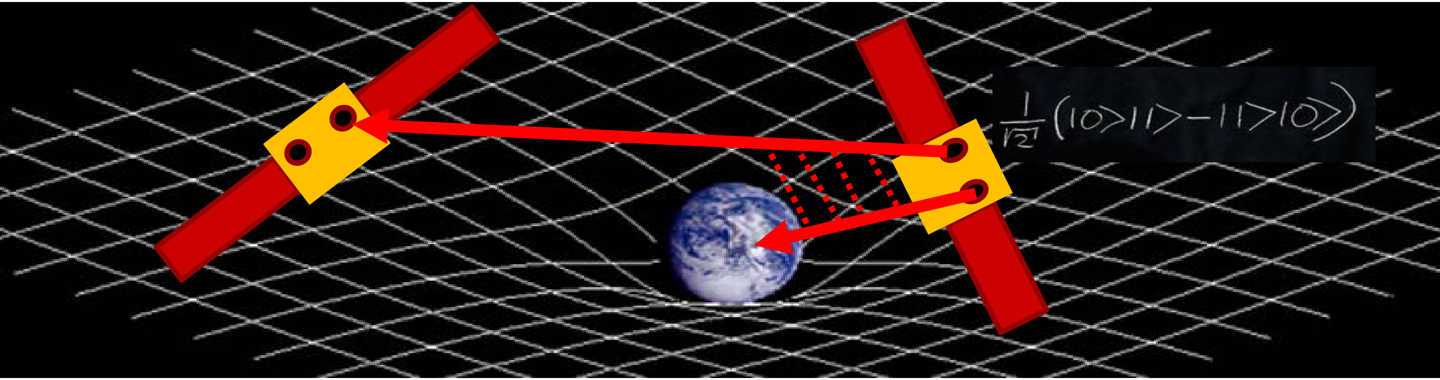


	MB/s	MB/orbit*	after conversion
Local detection - Albert	12	35200	3520
Local detection - Erwin	12	29000	2900
Remote detection (mean) - Albert	0,08	234	23,4
Remote detection (mean) - Erwin	0,08	188	18,8

Entanglement Propagation in Gravity

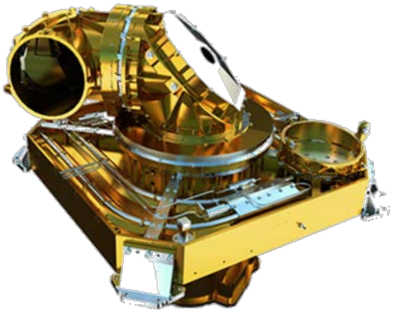
EPIG

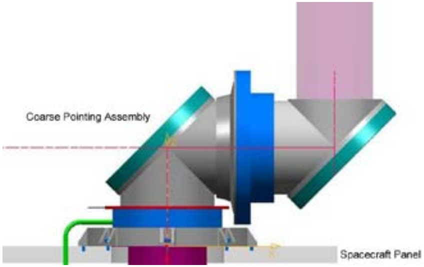
SYSTEMS



Optical link

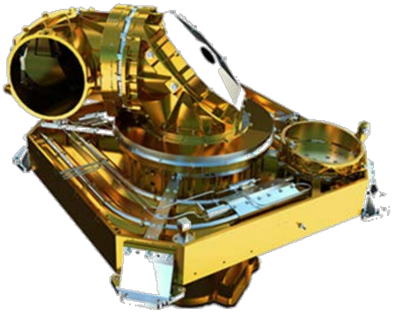
- Optical link drivers
  - 1000 photon coincidences within DU resolution 0.15 km2.s2
  - Achieving a signal to noise > 5 (based on Tenerife experiment)
  - Ensuring local detectors are not saturated
- Based on ESA OGS facility and TESAT Laser Comms Terminal
  - Modification to laser comms terminal to remove fibre optics in telescope to prevent loss of polarisation (studied within ESA)

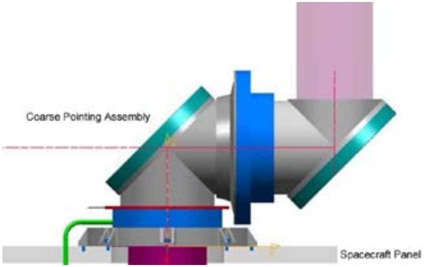




Optical link

- 10 MHz Pump (-86.1 dBm)
- Range 100 to 10000 km
- Space aperture diameter 135 mm
- Worst case atmospheric losses (HV5/7 model) -3.8 dB
- Ground aperture diameter 1016 mm

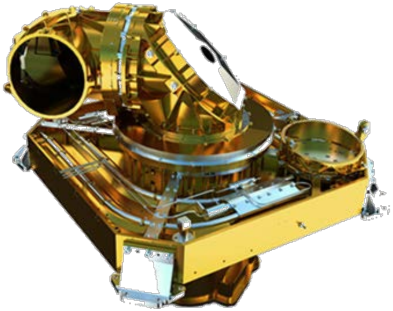


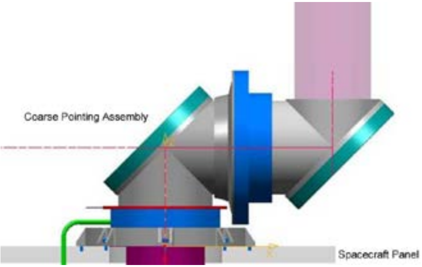


Optical link

Space-space	
Signal to noise	> 9
1000 photon observation	< 150 s
Saturation	FALSE
Space-ground	
Signal to noise	> 119
1000 photon observation	< 6 s
Saturation	FALSE

Biggest uncertainty is specular reflection from the transmitting satellite (10000 cps) to be derisked through experiment

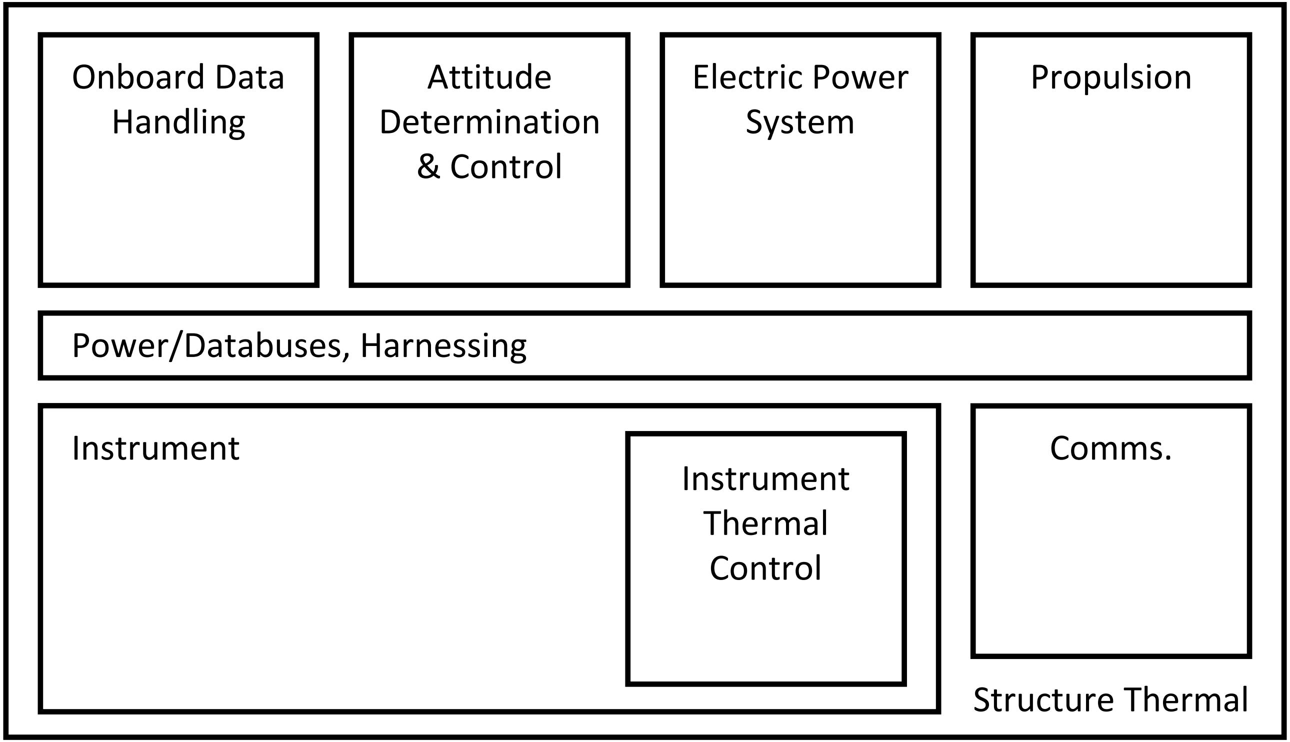




System Architecture

- There are two satellites Erwin and Albert
- Reference orbit for the mission is
  - Erwin is in a circular 700x700 km
  - Albert is in an elliptic 700x3000 km
- The ESA OGS facility is baselined for science as the ground link
- Existing ESA infrastructure is assumed for TTC + Data downlink
- A launch by Soyuz Fregat is targeted

Satellite Architecture



Onboard Data Handling

Attitude Determination & Control

Electric Power System

Propulsion

Power/Databuses, Harnessing

Instrument

Instrument Thermal Control

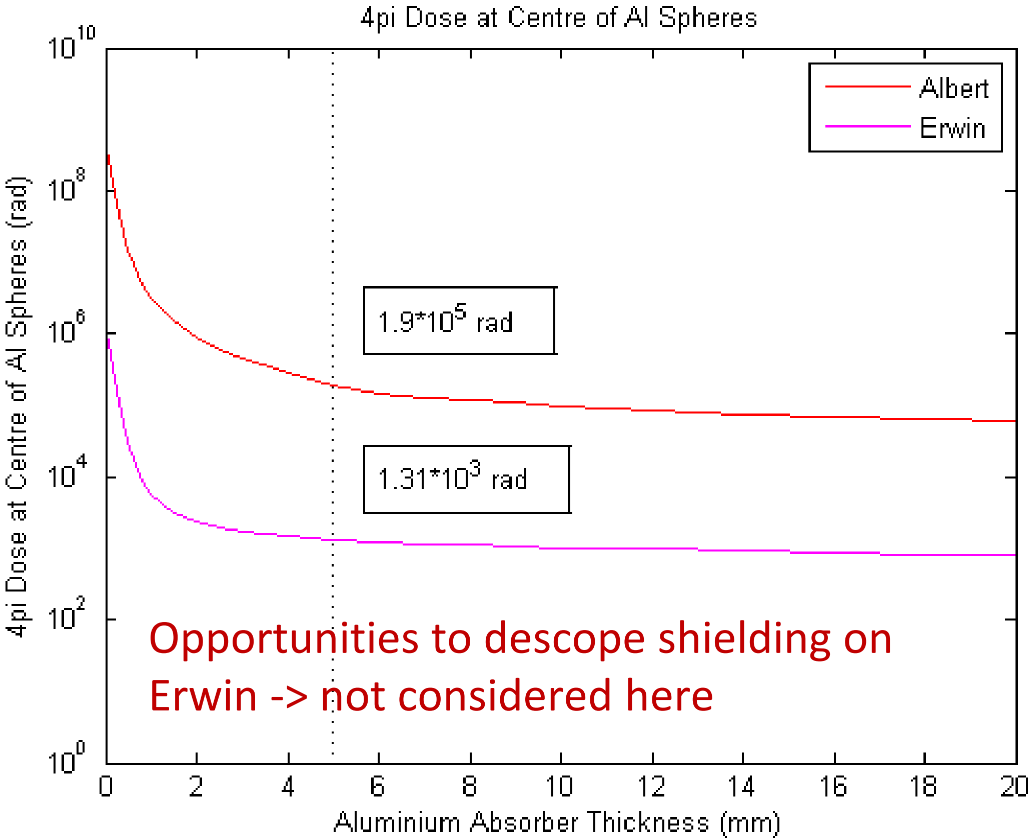
Comms.

Structure Thermal

Mission lifetime

- Lifetime estimation based on confidence level requirement to prove the quantum gravity theory
  - Based on core 25% availability for space-space (one-way link) for gravitational potential to 13 km2s2
  - Mission goal is 1000 photons at this 0.13 km2.s2 resolution
  - 1300 bins across the range
  - Worst case photon count is > 10 cps
  - 100 repeats of the measurement (10,000 total per data point)
- Assuming 20% margin time to complete prime objective is 2.3 years
- 3 year mission life currently specified

Radiation Environment

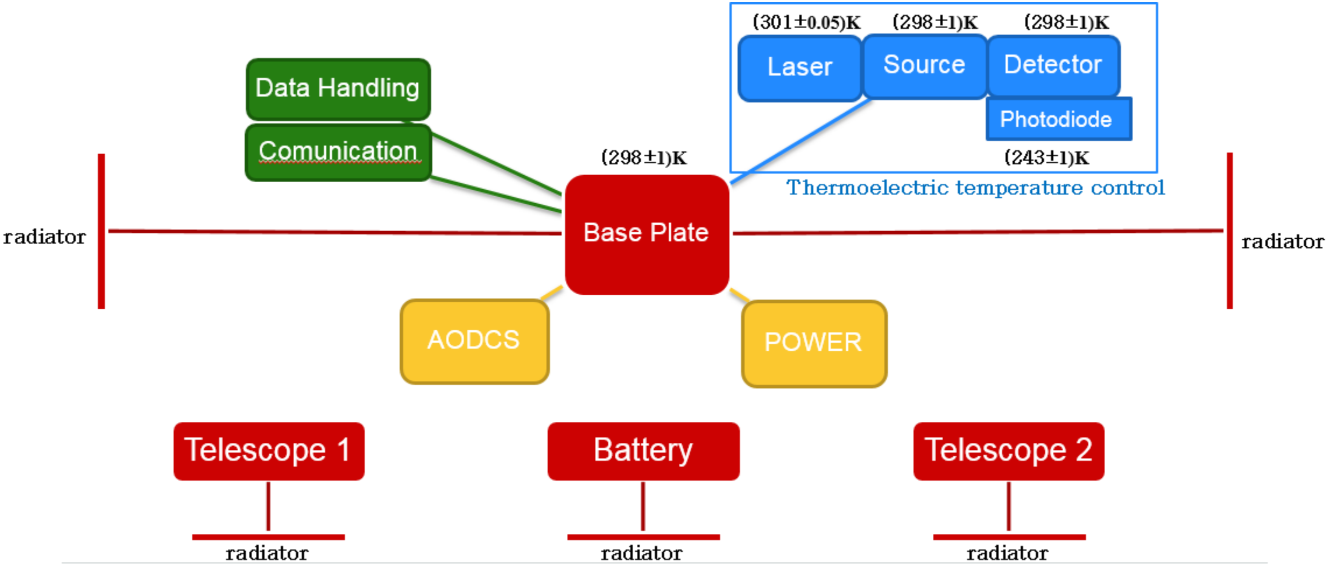


Opportunities to descope shielding on Erwin -> not considered here

Radiation Design

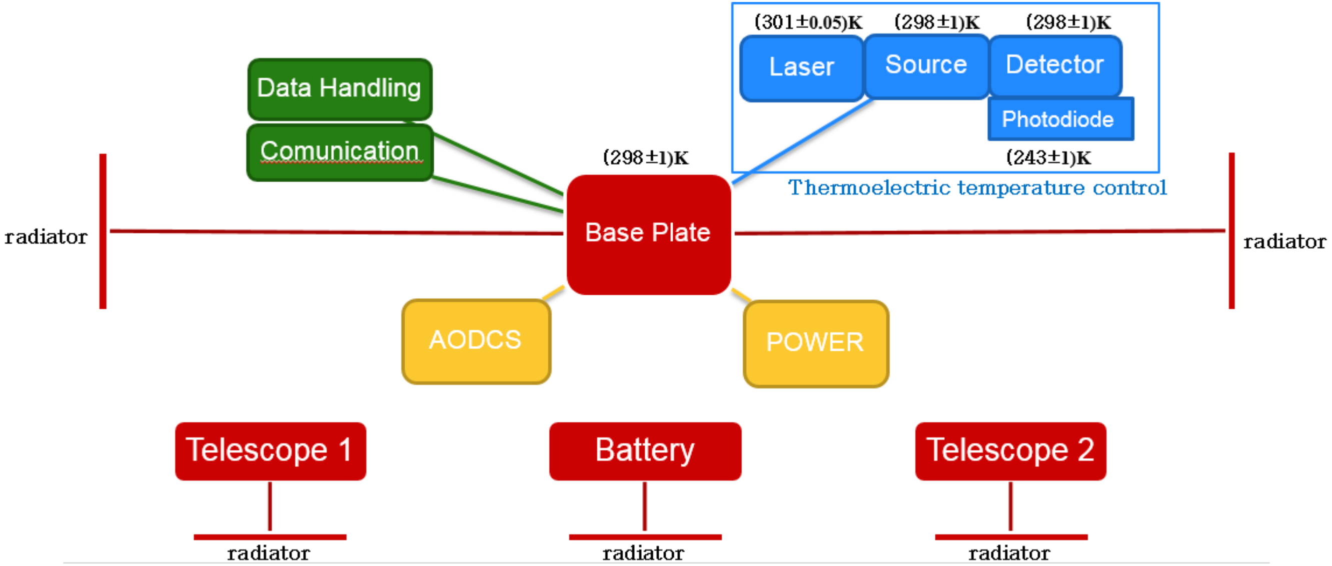
- 190 krad TID over 3 years with 5 mm Aluminium structure baseline
  - Specific at risk components identified within equipment list: Laser Comms Terminal, laser, detector
  - Laser Comms Terminal derisked by using hardened GEO version, 20% lifetime estimate (15 years GEO -> 3 years)
- Laser and detector to utilise spot shielding. Secondary effect of shielding is providing mass for thermal control
  - Radiation dose limit is 15 krad TID
  - Shielding mass is 6 kg per detector pair and laser (20 mm lead)
- Possible optimisation to shield entire optical payload (not baseline mass saving ~24 kg)
- SEE mitigated by design through FDIR and space radhard parts

System Thermal



- Thermal design philosophy is radiative with local control
  - System stability of +/- 3 degC targeted
  - Satellite designed not to overheat in hot case

System Thermal

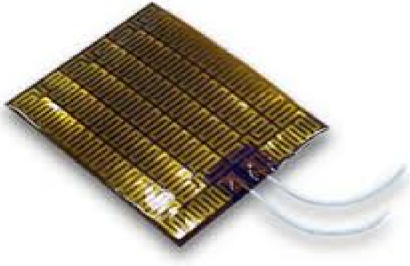


- At hot sunlit peak power case (800 W electronics) 3.2 m2 radiator required
- At cold eclipse survival mode heater required 215 W

Payload Thermal

- Approach is local thermal control of payload elements
- Thermal control of laser comms terminal handled within unit
- Local thermal control driven by sensitivity of optical elements (laser 25 +/- 2.5 deg, non-linear crystal 28 +/- 0.05 degC)
- Heat pad or Peltier dependent on sensitivity
- Total thermal control power requirement, 30 W

Peltier device



Resistive heat pad

Power

Subsystem	**Nom. (W)**	**Peak (W)**	**Remarks**
Instrument	307	397	Peak in dual LCT
Instrument Thermal Control	75	125	
Onboard Data Handling	4	8	
ADCS	139	204	
Propulsion	1	13	10% duty worst case
Power	25	63	+ 310 W conv. loss
Communications	23	116	< 40% nominal link
Harnessing	0	0	
Structure & Thermal	32	257*	Peak in survival only
Total	**0.6 kW**	**1.4 kW**	**20% margin**

Power

- Power driven by payload operations, payload thermal requirements, comms downlink capacity
- Power demand of 1.4 kW (100% operations capacity)
- Worst case eclipse of 44% (Erwin) for battery charging and overall; power system efficiency of 70%
- Solar arrays sized for 8 m2 solar panel sized for generation of 2.5 kW (EOL operations)
- Battery sized to allow full operations in eclipse with 30% depth of discharge, 45 kg mass
- Actual operations in baseline orbit 50%

Data Handling

- As fundamental science mission, raw experimental data downlinked, no onboard processing anticipated
- High speed analogue input into radhard FPGA-based payload computer at 800 MHz
- 8 MBps produced by payload after lossless compression
- Dedicated SpaceWire link (40 Mbps) between payload and TTC+Data Transceiver
- Mass memory sized at 150 GB for 3 days no link
- Dual MIL-STD 1553 databuses between main system computers 1 Mbps
- Additional computers specified for ADCS and OBC

Data Handling

Subsystem	**Data (MBps)**	**Remarks**
Instrument	8.5	Coincidence driver
Instrument Thermal Control	0.2	
Other Subsystems	< 0.1	
Total	**10.6**	**20% margin**

Data Downlink

Driven by payload data requirement of 4 GB per orbit

X-band downlink baselined is capable of 4.6 GB per orbit

TX RF Power output is 5 W
(at 20% efficiency of high power amplifier)

Maximum path length 5000 km

Receiver 12 m

Datarate 100 Mbps

Worst case link 26 dB (Eb/N0)

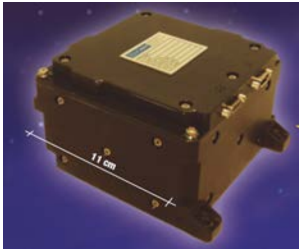
Availability requirement is 6%

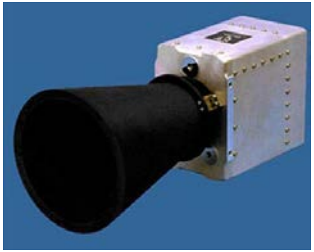
Expected to be feasible using ESTRACK network

Further trade possible for EDRS / optical links

Pointing Control

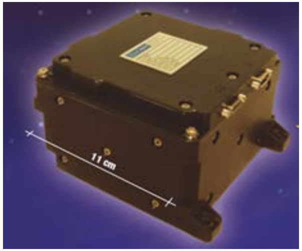
- Platform pointing requirement driven by LCT WFI acquisition of 0.16 deg
- Coarse pointing to 0.1 deg provided by platform system using reaction wheels
- Star trackers provide pointing knowledge to an accuracy to 0.001 deg
- Slow slew manoeuvre required for tracking during experiment but laser comms terminal capability > 1 deg.s-1
- Opportunities for desaturation every orbit, estimation of 7.2 N.s per day, requires DV of 20 m.s-1 over lifetime

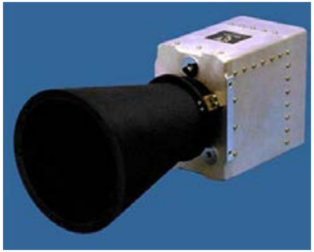




Pointing Knowledge

- Platform pointing knowledge is driven by relative angle perpendicular to photon wave between satellites
  - Requires active compensation in payload
- Resultant demand is for fine mechanical alignment of star tracker with the laser comms terminal
  - 0.2 acs alignment goal suggested to ensure that the error is within the beam divergence angle (0.3 acs)
  - Estimated mechanical alignment achievable is TBD but resolved in previous missions open issue to be addressed





Timing

- The system requires a timing signal of 0.1 s for initial synchronisation of the experiment
    - Payload provides fine counter < 1 ns
- Achievable using the 500 ns timing signal available with GPS
- Orbits always remains within GPS ring so GPS continuous availability
- Standard 10 Hz clock pulse to be distributed on satellite for onboard synchronisation of telemetries

Orbit Knowledge

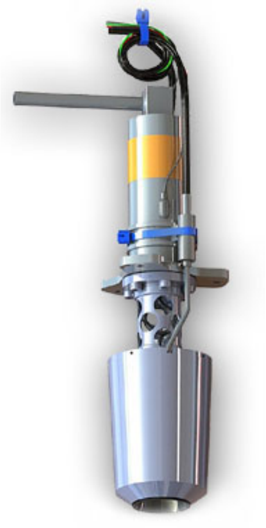
- Instantaneous and post-process orbit knowledge is required of varying accuracy
- Instantaneous measurement of 7 km driven by science requirement for uncertainty in timetagging
    - Provided by GPS with onboard propagator in ADCS computer
- Post process orbit knowledge required to 20 m for reconstruction of data
    - Achievable to 1 cm by modulating the beacon laser pulse of laser comms terminal

Jitter

- Angular jitter considered for experiment
- Jitter estimation of 3 arcsec for satellite based on
  - Solar Array Drive Mechanism
  - Reaction Wheels
  - Fuel Slosh
  - Thermal Flux
  - Comms Pointing
- Jitter requirement expected to be mitigated by the Laser Comms Terminal jitter rejection
  - Laser Comms Terminal uses feed forward active feedback compensation for jitter rejection
  - Open item but expected to be similar order of other missions

Propulsion

- No orbit maintenance requirement for science
- Albert (elliptic orbit) satellite driver in propulsion
- Selected Hydrazine with Isp 220 s
- 8 thrusters baselined, 20 N (Airbus)
- Current DV requirement is less than 70 kg
    - Wheel desaturation
    - Deorbit
    - Collision avoidance

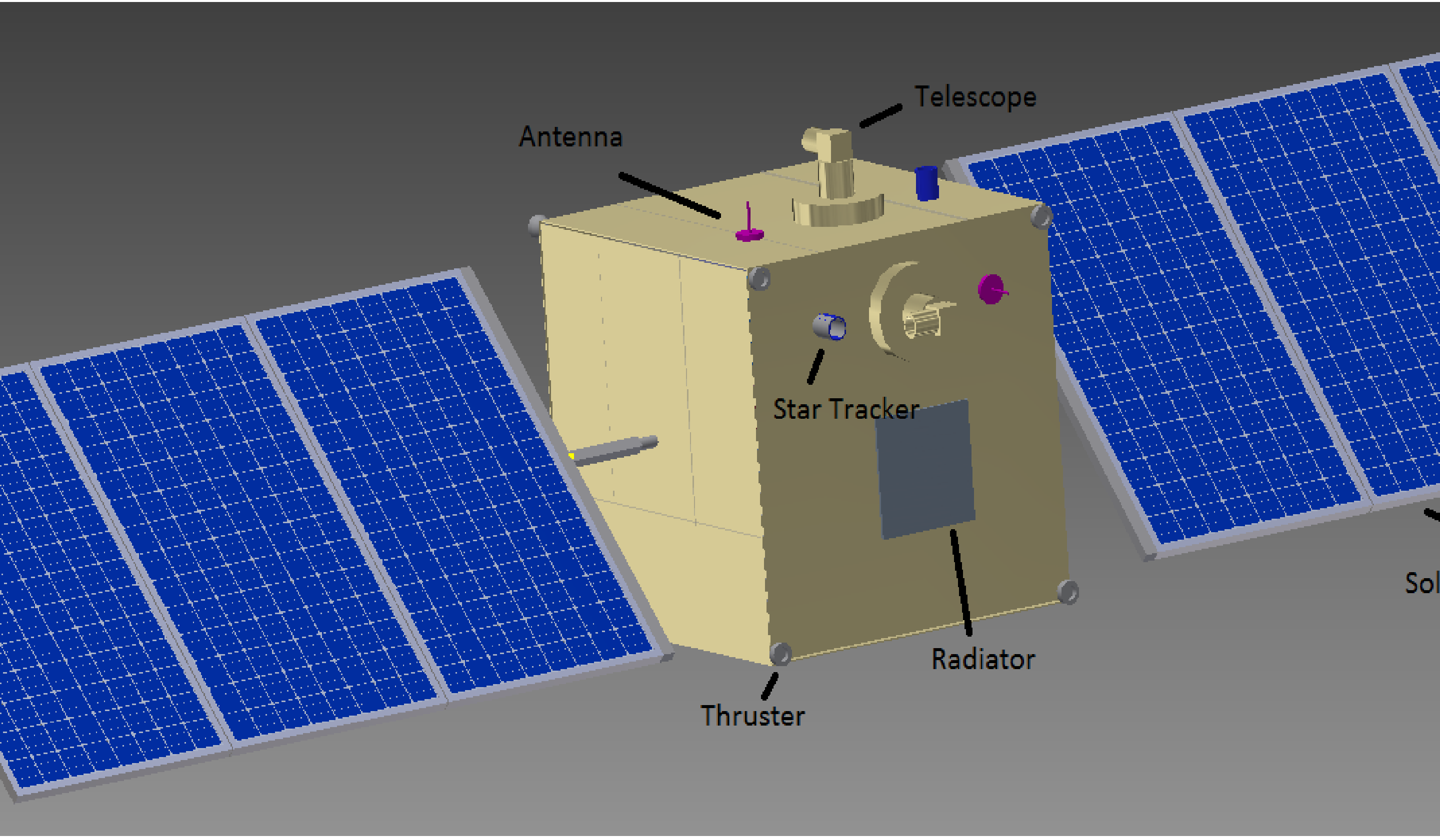


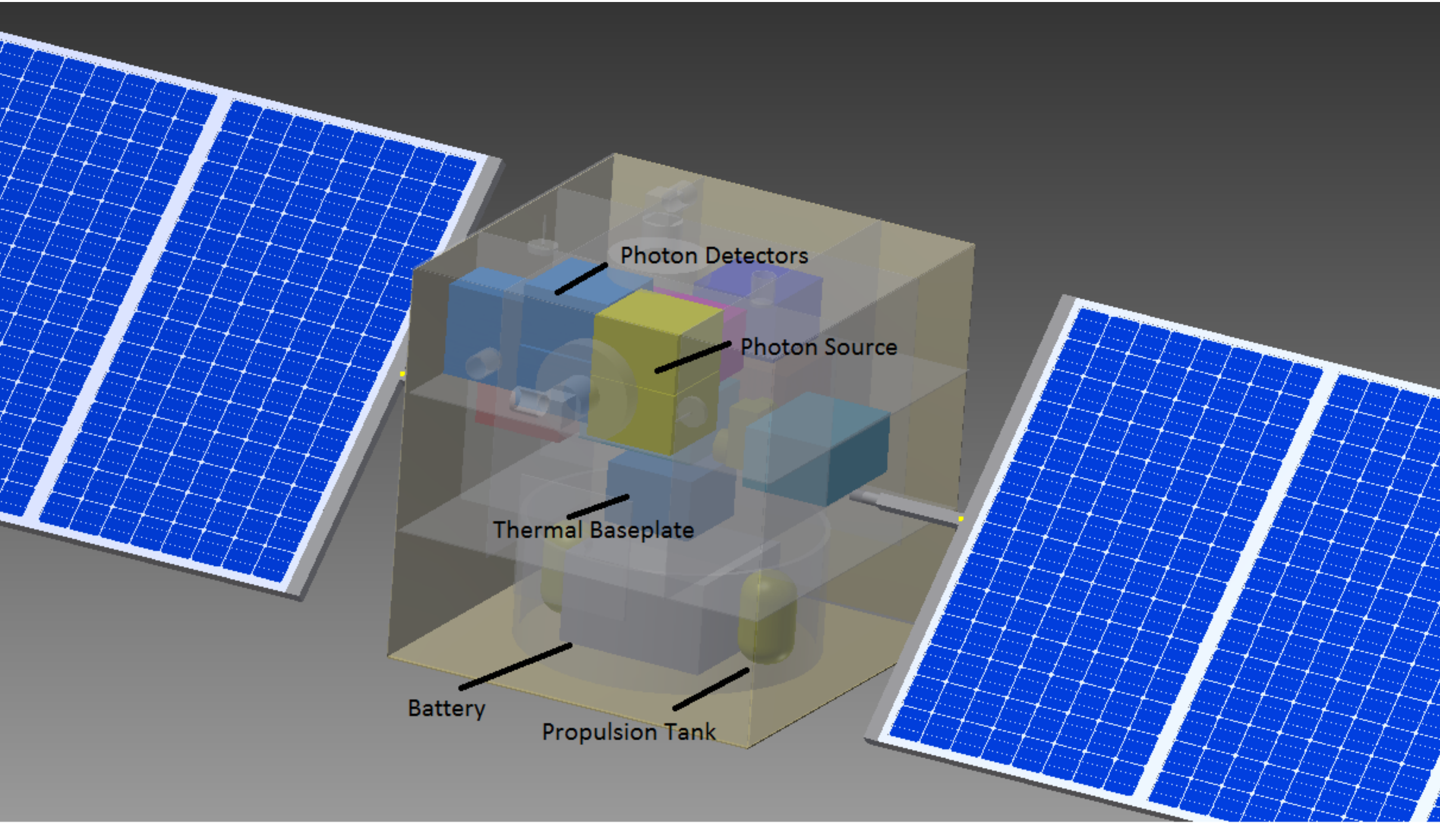
Satellite ΔV Budget

Item	**DV**	**Remarks**
Wheel desaturation	20 m.s-1	
Collision avoidance	10 m.s-1	Pcollision = 0.001
Deorbit	134 m.s-1	2 years deorbit
	164 m.s-1	
Mass of fuel	70 kg	Isp = 220 s

Configuration

- Configuration driven by
  - laser comms terminal FOV half-sky for availability
  - solar panel tracking
  - directional link antenna
  - minimising specular reflections
- Satellite total component volume 0.4 m3
- Total size 1.3 x 1.3 x 1.3 m providing suitable surface area for mounting equipment


Telescope
Antenna
Star Tracker
Sol
Radiator
Thruster


Photon Detectors
Photon Source
Thermal Baseplate
Battery
Propulsion Tank

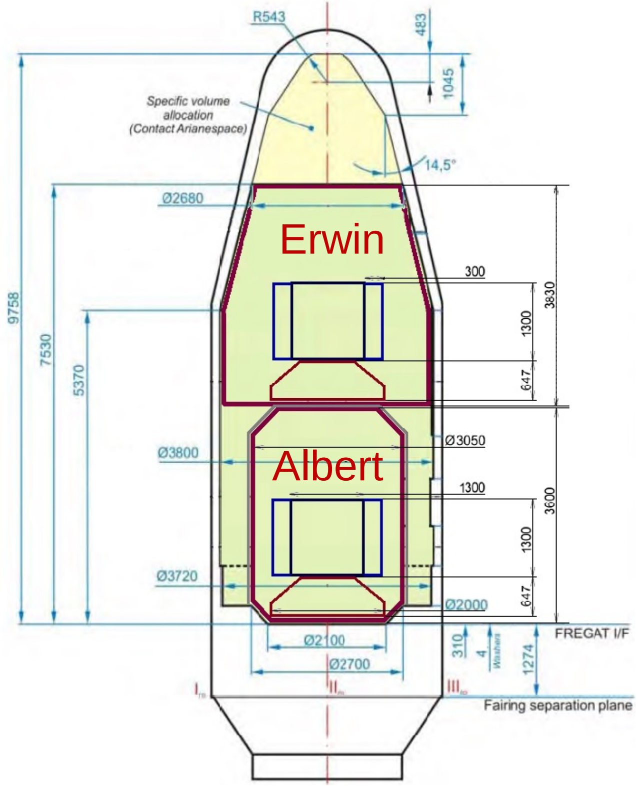
Mass budget

Subsystem	**Mass (kg)**	**Remarks**
Instrument	177	
Instrument Thermal Control	39	
Onboard Data Handling	6	
ADCS	39	4 x 5 kg wheels
Propulsion	95	70 kg Hydrazine
Power	129	
Communications	72	
Harnessing	37	
Structure & Thermal	155	Peak in survival only
Total	**903 kg**	**20% margin**

Erwin (deployed 1st)

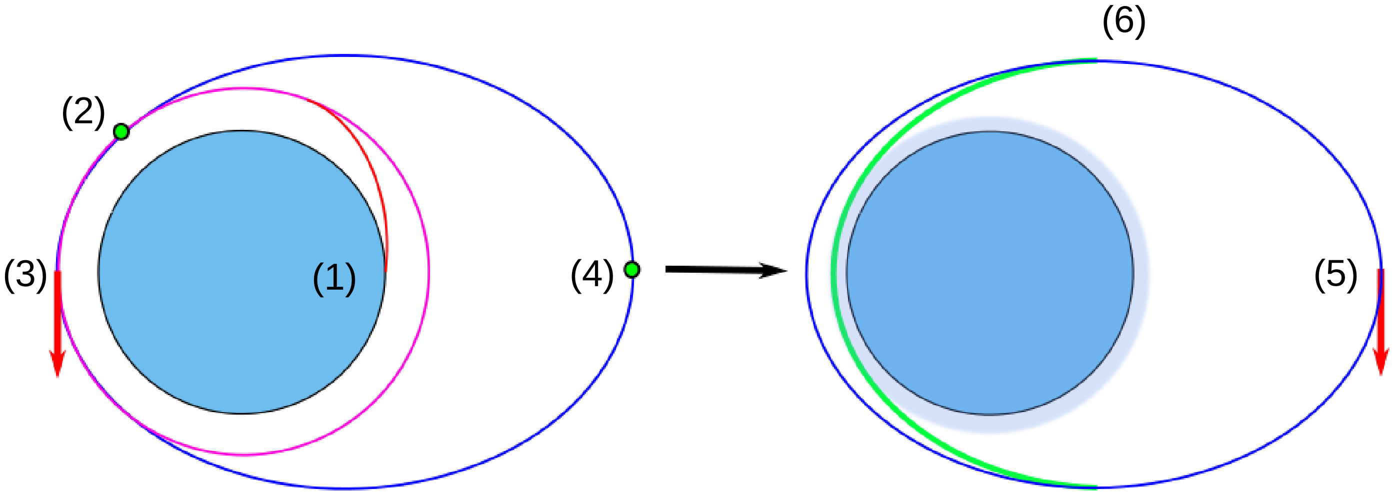
Launch Accomodation

- Total satellite wet mass 900 kg with all margins
  - Mass of SYLDA-S dual ride adaptor for Soyuz Fregat 220 kg
  - Adaptor with clamp-band (MAS), 115 kg
- Total launch mass to 700 km is 2600 kg
- Both satellites and adaptors fit within Soyuz Fregat 2.1b



Fregat Deployment

- Soyuz Fregat can deliver 4.2 tons to 700 km (1.6 tn margin)
- 822 kg required for Fregat manoeuvres (26%)



Ground Segment

RF

Optics

ESTRACK Network

Optical Ground Station

TTC

Science

Mission Operations Centre

Science Operations Centre

Science Plan

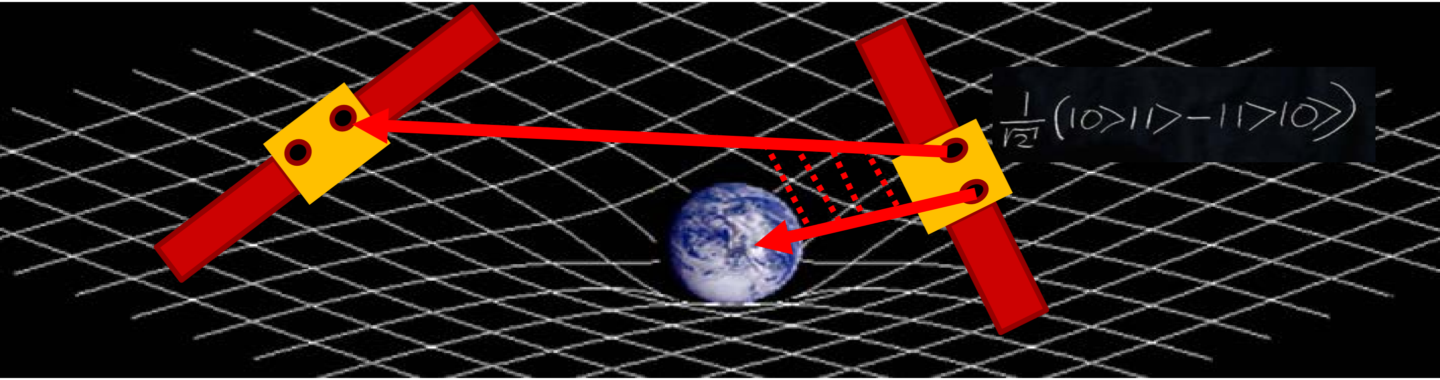
Data Archive

Science Community

Entanglement Propagation in Gravity

EPIG

PROGRAMMATICS



Cost estimation

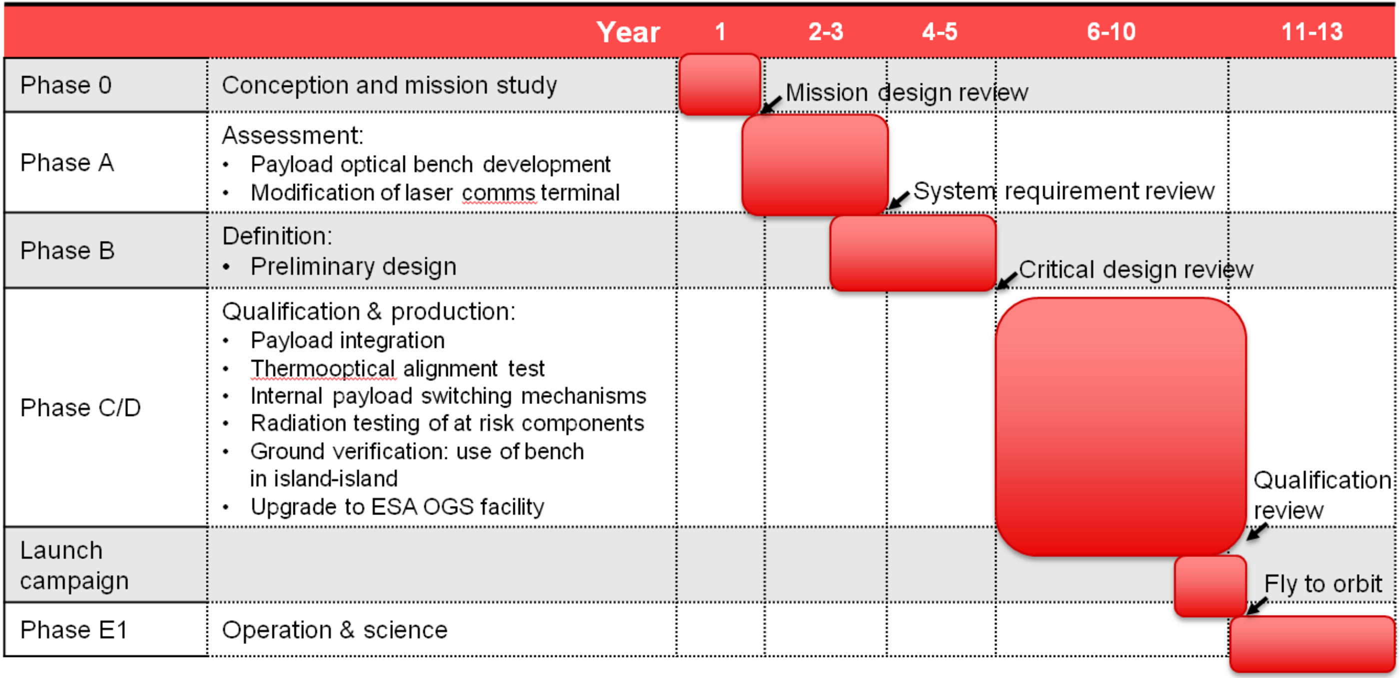
COST AREA	MEUR	Who	Notes
Launch	75	ESA	
Laser communication terminal	80	ESA	Includes laser, not required for mission
Modification to LCT	5	Member	
Development of source	10	Member	
Development of detector pairs	5	Member	Inc. polarisation compensation in local detector
Detector pair FM	20	Member	
Source	40	Member	
Platform	120	ESA	Cost of GIOVE-A to ESA 28 MEUR inc. MAIT
TTC operations	50	ESA	
Science operations	50	ESA	
MAIT	50	ESA	
Science ground segment	50	Member	If OGS is used may be reduced / ESA
EM / ground verification	15	Member	
Total	570	MEUR	
Member contribution	145	MEUR	
ESA contribution	425	MEUR	
ESA overhead	20%		
COST TO ESA	**510**	**MEUR**	

COST TO ESA : 510 MEUR Suitable for M Class

Low TRL equipment

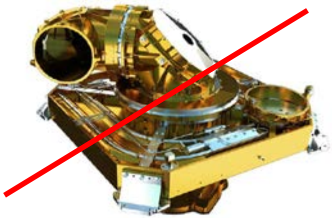
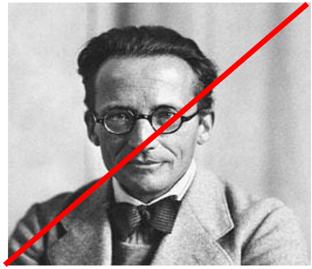
- Targeting 2025 launch therefore high TRL requirements
- Only payload subsystems have < 6 TRL levels
- Component and system margins applied according to TRL estimations
- Subsystem components with a low TRL are:
  - Entangled photon source and detectors (TRL 4)
  - Polarisation compensation unit detectors(TRL 4)
  - Laser control terminal (TRL 5, modification to telescope)

Development plan



Phase 0	Conception and mission study
Phase A	Assessment: • Payload optical bench development • Modification of laser comms terminal
Phase B	Definition: • Preliminary design
Phase C/D	Qualification & production: • Payload integration • Thermooptical alignment test • Internal payload switching mechanisms • Radiation testing of at risk components • Ground verification: use of bench in island-island • Upgrade to ESA OGS facility
Launch campaign	
Phase E1	Operation & science

Descope options

	Option	Impact	Cost Saving
	Lose 1 LCT per satellite	50% less correlation count loss, loss of redundancy	-40 MEUR (470 MEUR)
	Use GIOVE-A like OTS platform	Higher perceived mission risk, radiation risk	-85 MEUR (425 MEUR)
	Single satellite only	Robustness of QG hypothesis, 80% reduction in availability	-205 MEUR (305 MEUR)

Risks specific to EPIG

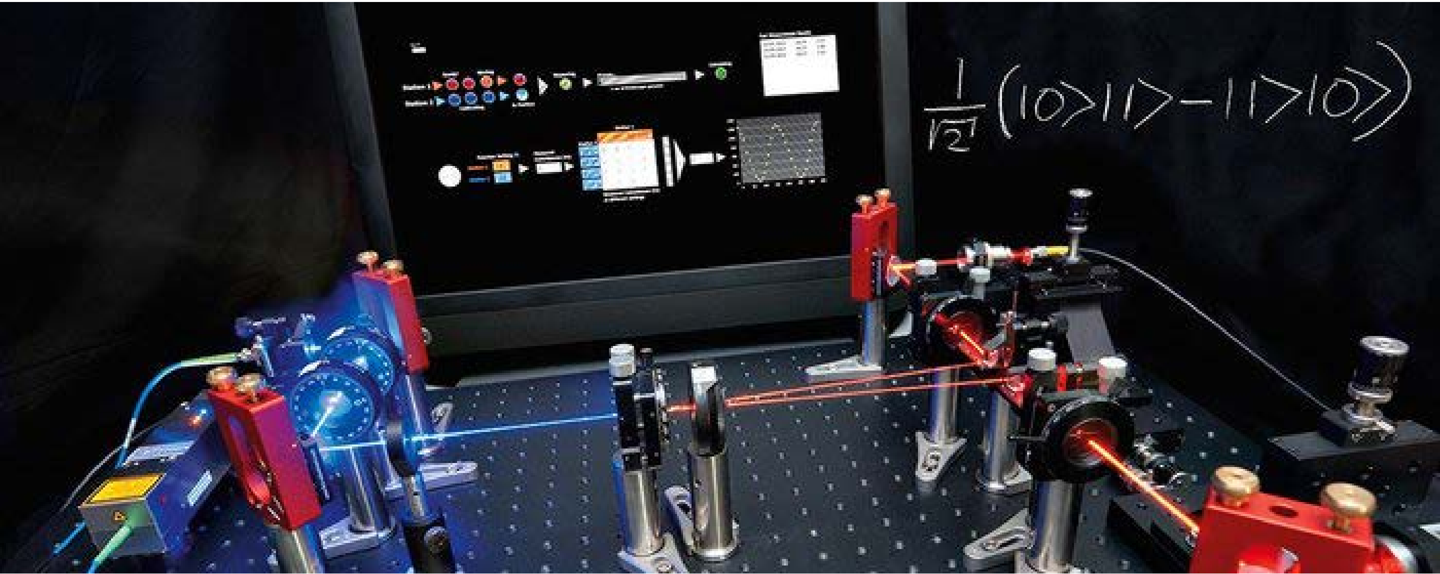
Risk evaluation	Risk (A-E)	Severity (1-5)	Comment
Low TRL subsystems not ready in time (entangled photon source, TESAT terminal modification)	D	2	Schedule delay or reduced science performance
Failure of payload subsystem	D	2	No single point failure, but link availability reduced, could be recovered with longer mission duration
Radiation shielding not sufficient for photo diodes, crystals or fibres	C	3	Mitigatable by proper test programme; reduced performance loss would lead to lower accuracy

Risks specific to EPIG

Risk evaluation	Risk (A-E)	Severity (1-5)	Comment
Underestimation of straylight in particular specular reflection from the satellite or stars in field of view	C	3	Mitigatable by proper simulations and experimental test programme; larger avoidance angles would lead to lower counts/orbit. Possible to include low specular reflective material.
Failure of optical switching mechanisms	D	3	Using a high reliability models, optimising operations for low switch cycles. Failure will lead to reduced link availability

Education & Outreach

- Building on the popularity of Einstein and Schroedinger, educational material about GR and QM for different school levels should be provided
- Demonstrator experiments for entangled photons and gravity potentials for science museums or for road shows
- Regular social media updates for measurement progresses and specific missions events (eg. ground station links with VIPs)



Thanks

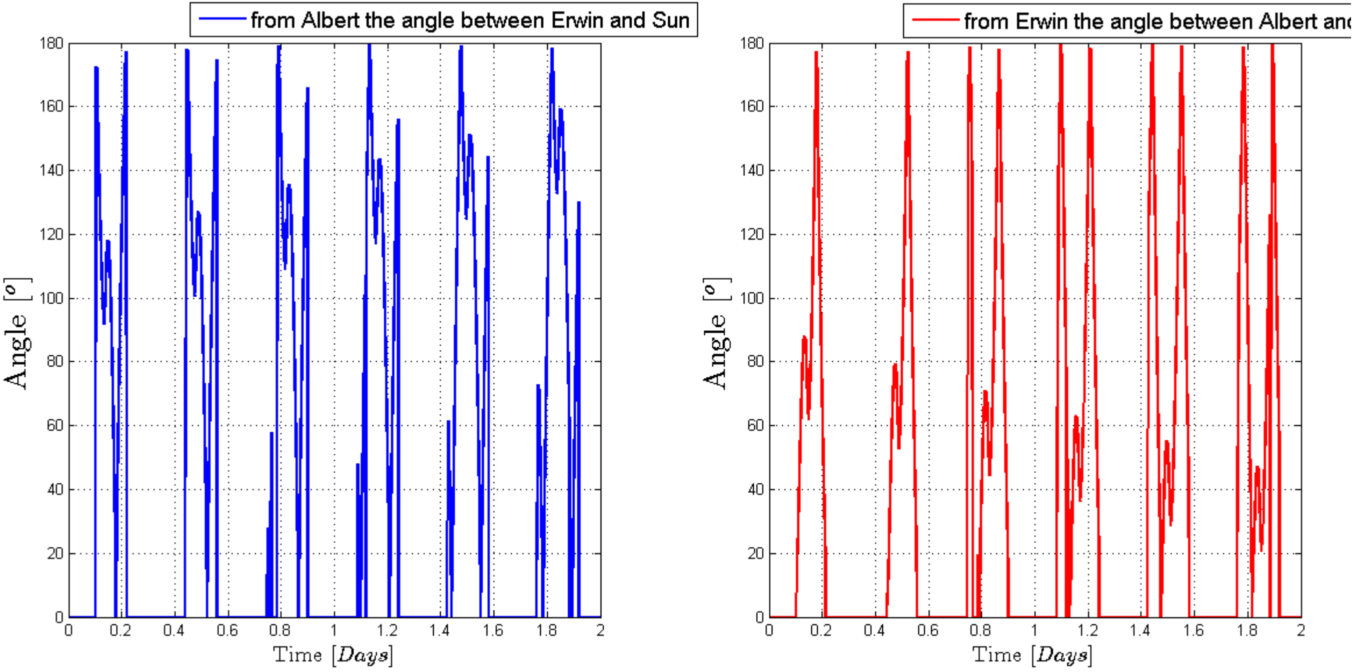
Questions

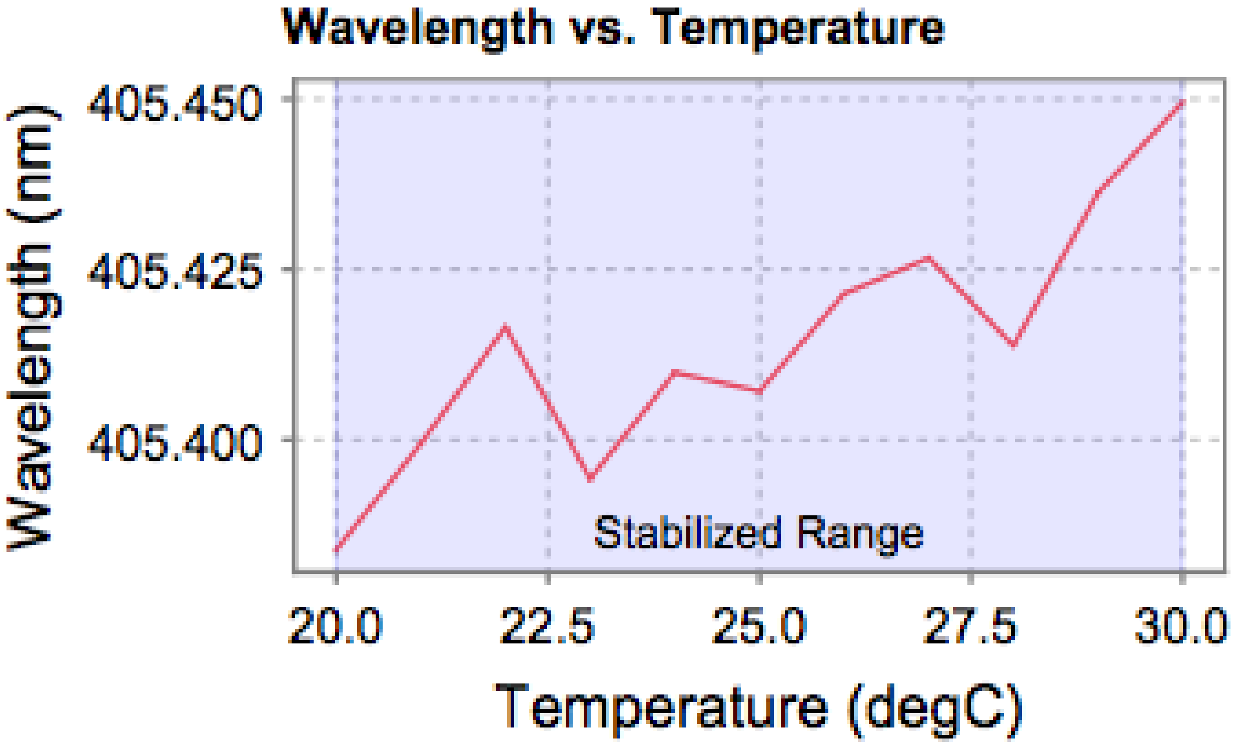
International collaboration opportunities

Element	Impact
Additional optical ground stations	More ground-space link availability
One entangled photon source	Development risk reduction, complementary EPS properties (τ)
Critical opto-electronic components	405 nm laser currently only available from Japan; better models may be available from US/Japan for photo diodes and crystals

Final Orbit

15° Sun angle with transmission link:




Wavelength vs. Temperature
Wavelength (nm)
405.450
405.425
405.400
Stabilized Range
20.0
22.5
25.0
27.5
30.0
Temperature (degC)

Payload: Data Generation

Internal Bell‘s inequalities test (A)

Performed by payload computer – only N_C/s is used – cca 4MB

Asymmetrical measurement (B)

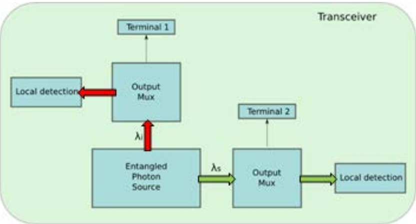
Each photon detection event is time-stamped, polarization of the detected photon is saved. Time-stamp bit size varies for `internal´ and `external´ (in case of bidirectional link) detection due to the detection rate

	detection/second	bits/detection	bits/second	MB/s
internal detection	10000000	10	100000000	12
external detection (mean)	57	66	3762	0,0005

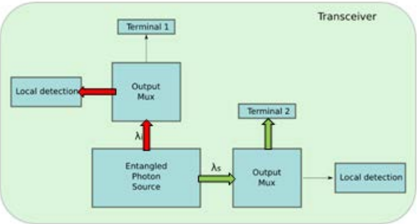
Symmetrical measurement (C)

No experiment data is stored on board of the source satellite

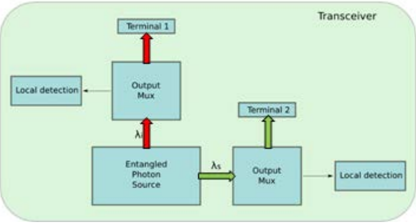
(A)



(B)

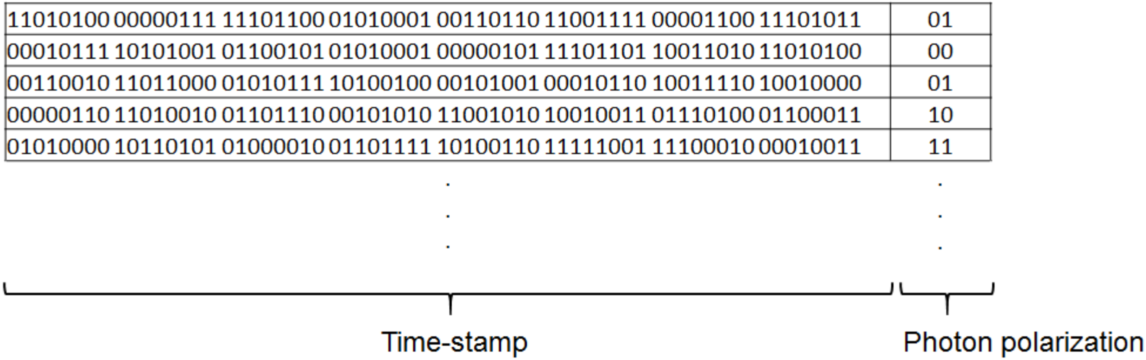


(C)



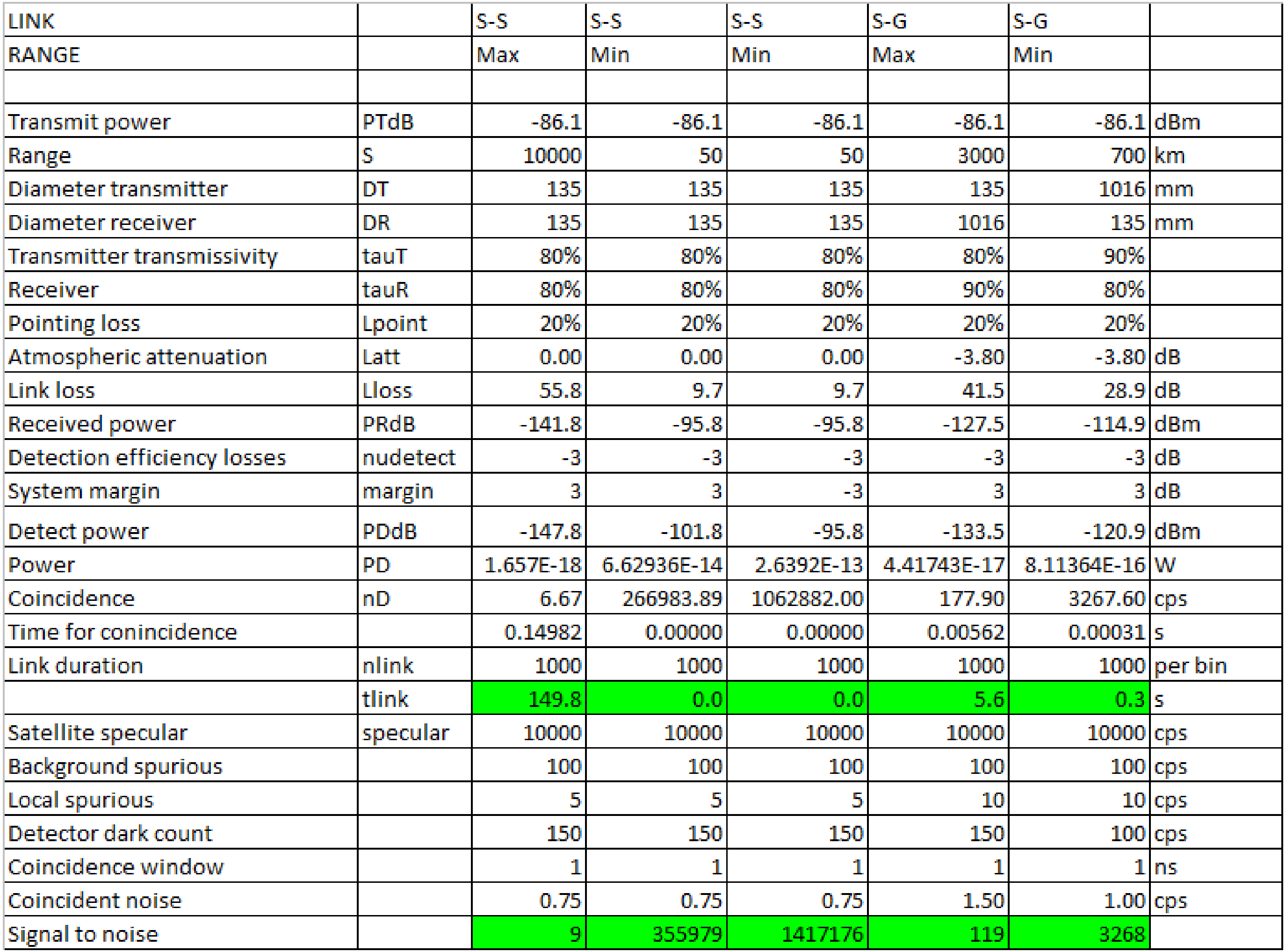
Payload: Data Generation

Example of the acquired experimental data:



11010100 00000111 11101100 01010001 00110110 11001111 00001100 11101011	01
00010111 10101001 01100101 01010001 00000101 11101101 10011010 11010100	00
00110010 11011000 01010111 10100100 00101001 00010110 10011110 10010000	01
00000110 11010010 01101110 00101010 11001010 10010011 01110100 01100011	10
01010000 10110101 01000010 01101111 10100110 11111001 11100010 00010011	11
.	.
.	.
.	.

For local detection the time-stamp bit size can be reduced to 8-bit due to the high detection rate of 10MHz



LINK		S-S	S-S	S-S	S-G	S-G	
RANGE		Max	Min	Min	Max	Min	
Transmit power	PTdB	-86.1	-86.1	-86.1	-86.1	-86.1	dBm
Range	S	10000	50	50	3000	700	km
Diameter transmitter	DT	135	135	135	135	1016	mm
Diameter receiver	DR	135	135	135	1016	135	mm
Transmitter transmissivity	tauT	80%	80%	80%	80%	90%	
Receiver	tauR	80%	80%	80%	90%	80%	
Pointing loss	Lpoint	20%	20%	20%	20%	20%	
Atmospheric attenuation	Latt	0.00	0.00	0.00	-3.80	-3.80	dB
Link loss	Lloss	55.8	9.7	9.7	41.5	28.9	dB
Received power	PRdB	-141.8	-95.8	-95.8	-127.5	-114.9	dBm
Detection efficiency losses	nudetect	-3	-3	-3	-3	-3	dB
System margin	margin	3	3	-3	3	3	dB
Detect power	PDdB	-147.8	-101.8	-95.8	-133.5	-120.9	dBm
Power	PD	1.657E-18	6.62936E-14	2.6392E-13	4.41743E-17	8.11364E-16	W
Coincidence	nD	6.67	266983.89	1062882.00	177.90	3267.60	cps
Time for conincidence		0.14982	0.00000	0.00000	0.00562	0.00031	s
Link duration	nlink	1000	1000	1000	1000	1000	per bin
	tlink	149.8	0.0	0.0	5.6	0.3	s
Satellite specular	specular	10000	10000	10000	10000	10000	cps
Background spurious		100	100	100	100	100	cps
Local spurious		5	5	5	10	10	cps
Detector dark count		150	150	150	150	100	cps
Coincidence window		1	1	1	1	1	ns
Coincident noise		0.75	0.75	0.75	1.50	1.00	cps
Signal to noise		9	355979	1417176	119	3268	

Jitter

			Estimate			
Reaction wheels			4,8	µrad	0,990071	arcsec
Solar panels			5,4	µrad	1,11383	arcsec
Thermal fluctuations			0,5	µrad	0,103132	arcsec
Propellant movement			1	µrad	0,206265	arcsec
Comms pointing			1	µrad	0,206265	arcsec
Total:			12,7	µrad	2,619563	arcsec

Reaction wheel estimate found, solar panel estimated from that number (by comparing angular momentums, and assuming that the proportionality betw. ang.mom. and jitter are the same). The rest are found or estimated from similar setups

Why no results yet?

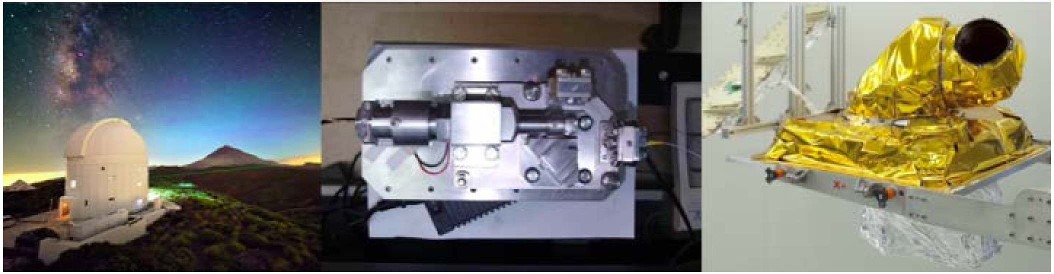
Enabling technologies only recently available/demonstrated

(2007) 144 km free-space distribution of entangled photons

(2015) TRL 4-5 of space suitable laser sources for entangled photons

(2015) Operational demonstration of COTS laser space terminals for EDRS

And: Ralph Pienaar theoretical model only published **last year**



Subsystem: Thermal Control

The temperature requirements:

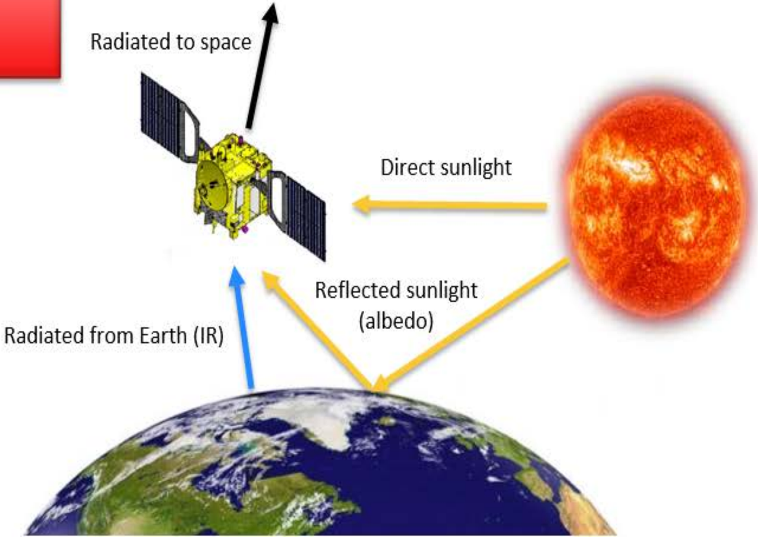
- payload optics (laser, crystal): 298 K +/- 0.05 K
- detector: 243 K +/- 1 K

Thermal balance

$$Q_{ELECTRONIC} + Q_{ENVIRONMENT} = A\varepsilon\sigma T^4$$

$$\downarrow$$

$$Q_{SUN} + Q_{ABSORBED\ FROM\ EARTH} + Q_{ALBEDO}$$



Subsystem: Thermal Control

The worst-case solar heating / operation mode

$Q_{elecrtonic}$ = 800 W, $Q_{environment}$ = 182 W/m^2

Surface area of the radiators: 3.2 m^2 (5mil silvered Teflon)

Temperature: 293 K

Heater (52 W)

Temperature 298 K

- Sensors, thermo-electrical heaters, monitoring and controlling
- Radiator on the both side of the spacecraft
- Structure of the spacecraft covered by MLI

Subsystem: Thermal Control

The cold-case / no operation mode

$Q_{elecrtonic}$ = 100 W, $Q_{environment}$ = 35 W/m^2

Surface area of the radiators: 3.2 m^2

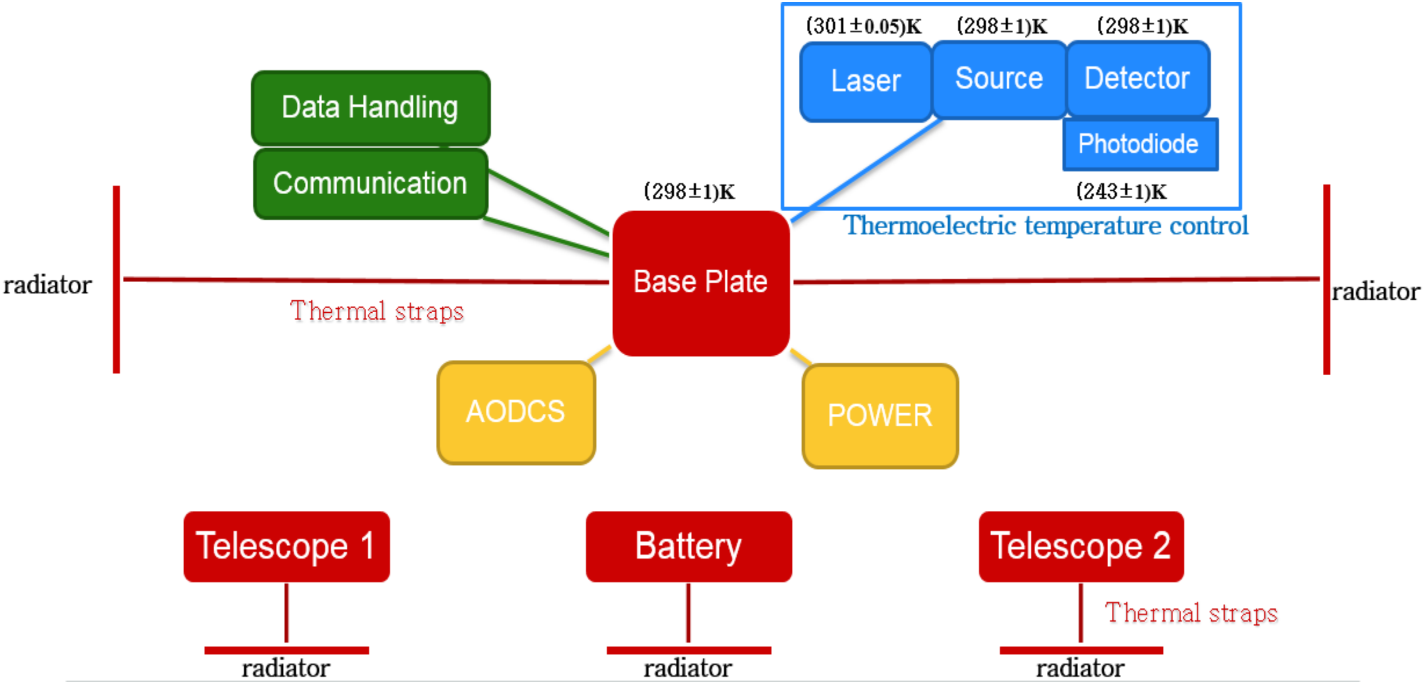
Temperature: 284 K

Heater (215 W)

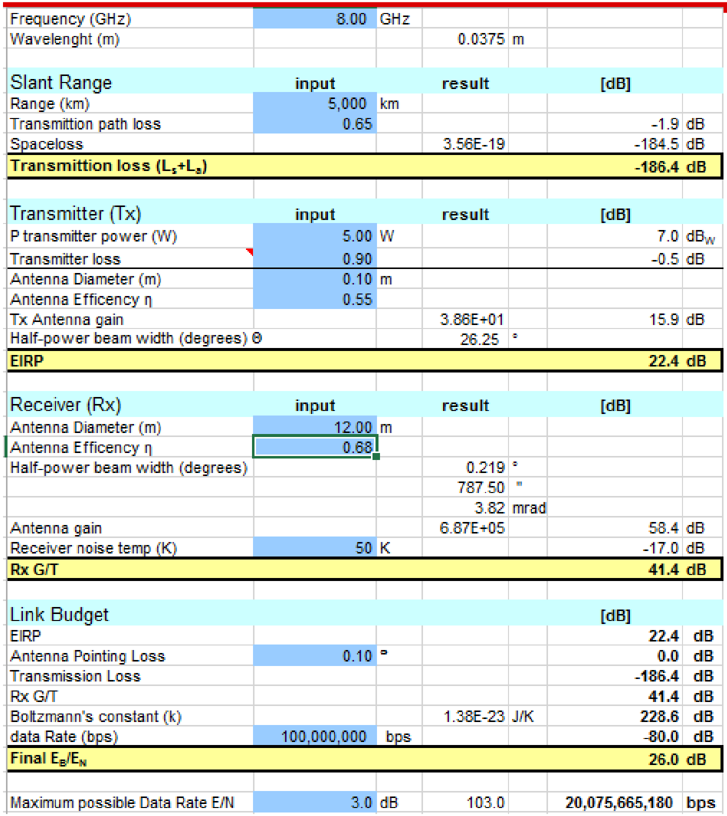
Temperature 298 K

- Bus stability +/- 3 K
- Payload inside the thermal shielding with active temperature control
- Detector will be cooled with thermos-electrical elements (Peltier elements)

Subsystem: Thermal Control

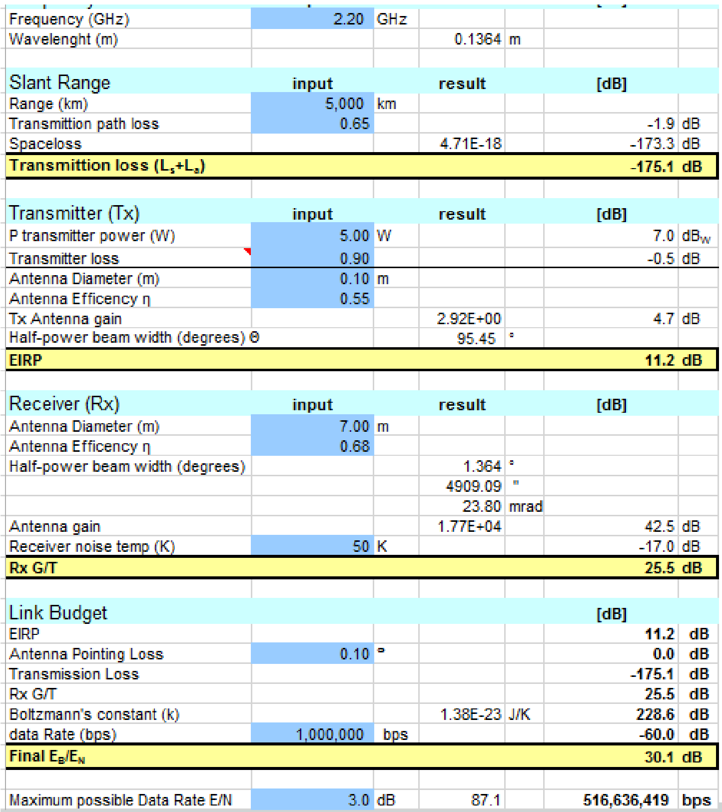


RF Link X-band



Frequency (GHz)	8.00	GHz				
Wavelenght (m)			0.0375	m		
Slant Range	input		result		[dB]	
Range (km)	5,000	km				
Transmittion path loss	0.65				-1.9	dB
Spaceloss			3.56E-19		-184.5	dB
Transmittion loss (L_s+L_a)					**-186.4**	**dB**
Transmitter (Tx)	input		result		[dB]	
P transmitter power (W)	5.00	W			7.0	dB_W
Transmitter loss	0.90				-0.5	dB
Antenna Diameter (m)	0.10	m				
Antenna Efficency η	0.55					
Tx Antenna gain			3.86E+01		15.9	dB
Half-power beam width (degrees) Θ			26.25	°		
EIRP					**22.4**	**dB**
Receiver (Rx)	input		result		[dB]	
Antenna Diameter (m)	12.00	m				
Antenna Efficency η	0.68					
Half-power beam width (degrees)			0.219	°		
			787.50	"		
			3.82	mrad		
Antenna gain			6.87E+05		58.4	dB
Receiver noise temp (K)	50	K			-17.0	dB
Rx G/T					**41.4**	**dB**
Link Budget					[dB]	
EIRP					**22.4**	**dB**
Antenna Pointing Loss	0.10	°			**0.0**	**dB**
Transmission Loss					**-186.4**	**dB**
Rx G/T					**41.4**	**dB**
Boltzmann's constant (k)			1.38E-23	J/K	**228.6**	**dB**
data Rate (bps)	100,000,000	bps			**-80.0**	**dB**
Final E_B/E_N					**26.0**	**dB**
Maximum possible Data Rate E/N	3.0	dB	103.0		**20,075,665,180**	**bps**

RF Link S-band



Frequency (GHz)	2.20	GHz				
Wavelenght (m)			0.1364	m		
Slant Range	**input**		**result**		**[dB]**	
Range (km)	5,000	km				
Transmittion path loss	0.65				-1.9	dB
Spaceloss			4.71E-18		-173.3	dB
Transmittion loss (L_s+L_a)					**-175.1**	**dB**
Transmitter (Tx)	**input**		**result**		**[dB]**	
P transmitter power (W)	5.00	W			7.0	dB_W
Transmitter loss	0.90				-0.5	dB
Antenna Diameter (m)	0.10	m				
Antenna Efficency η	0.55					
Tx Antenna gain			2.92E+00		4.7	dB
Half-power beam width (degrees) Θ			95.45	°		
EIRP					**11.2**	**dB**
Receiver (Rx)	**input**		**result**		**[dB]**	
Antenna Diameter (m)	7.00	m				
Antenna Efficency η	0.68					
Half-power beam width (degrees)			1.364	°		
			4909.09	"		
			23.80	mrad		
Antenna gain			1.77E+04		42.5	dB
Receiver noise temp (K)	50	K			-17.0	dB
Rx G/T					**25.5**	**dB**
Link Budget					**[dB]**	
EIRP					**11.2**	**dB**
Antenna Pointing Loss	0.10	°			**0.0**	**dB**
Transmission Loss					**-175.1**	**dB**
Rx G/T					**25.5**	**dB**
Boltzmann's constant (k)			1.38E-23	J/K	**228.6**	**dB**
data Rate (bps)	1,000,000	bps			**-60.0**	**dB**
Final E_B/E_N					**30.1**	**dB**
Maximum possible Data Rate E/N	3.0	dB	87.1		**516,636,419**	**bps**

Development actions

- Payload optical bench development
- Modifications of laser comms terminal
- Optical bench and laser comms terminal integration
- Thermooptomechanical alignment test
- Testing of internal payload switching mechanisms
- Radiation testing of at risk components
- Ground verification: use of bench in island-island
- Upgrade to ESA OGS facility