Telescope Design for a Space-based Gravitational Wave Mission

Status report for the L3 Study Team

Jeff Livas
NASA Goddard Space Flight Center
23 March 2016

Outline

- **Telescope Description**
  - Functional
  - Location on the sciencecraft
  - HIgh-level requirements
- **Technology Readiness Levels (TRLs)**
  - Rough development timeline
- **Rough description of the work to be done**
- **System dependencies that affect design and development plans**

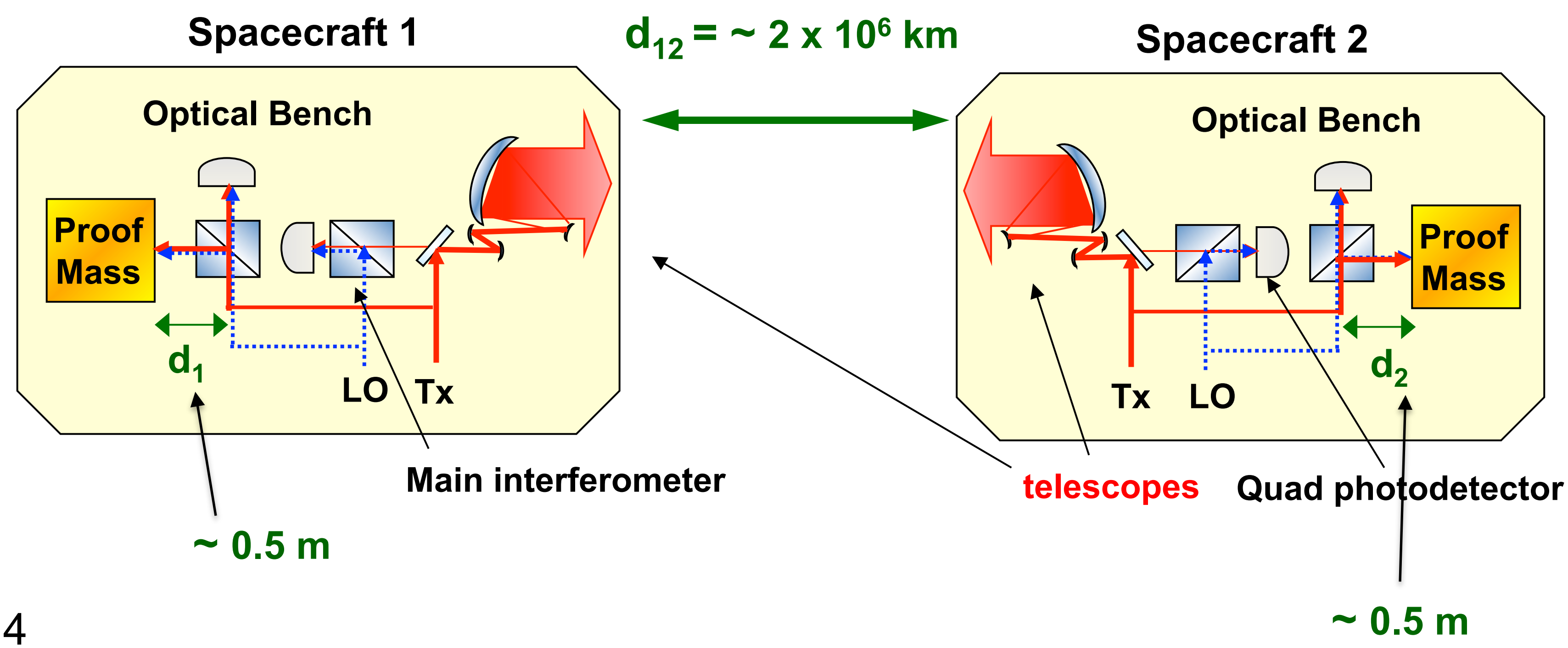
Telescope Description

- **Functional:**
  - Afocal optical beam expander
    - Classic LISA: 400 mm/5 mm = 80X
    - eLISA: 200 mm/5 mm = 40 X
  - Efficiently deliver power from one S/C to another
    - “diffraction limited” lambda/30 at 1064 nm (~ 35 nm)
    - High optical throughput
  - Smooth wavefront to minimize tilt to length coupling
    - “diffraction limited” – minimize wavefront aberrations (astigmatism is the leading term)
- **Other requirements**
  - Dimensionally stable optical pathlength
    - in series with the main measurement
  - Low scattered light (transmit and received simultaneously)

Inter-Spacecraft Distance Measurement

- Test-mass to test-mass measured in 3 parts:
  - 2 × test-mass to spacecraft measurements (short-arm: LPF tests this)
  - 1 × spacecraft to spacecraft interferometer (long-arm)

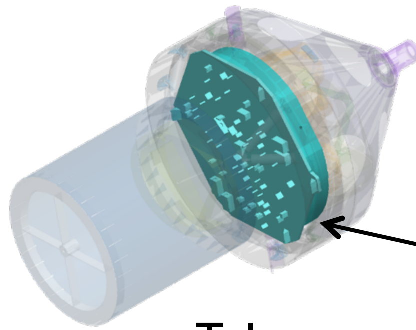
total separation = $d_1 + d_{12} + d_2$



Payload Integrated with Bus

Payload systems

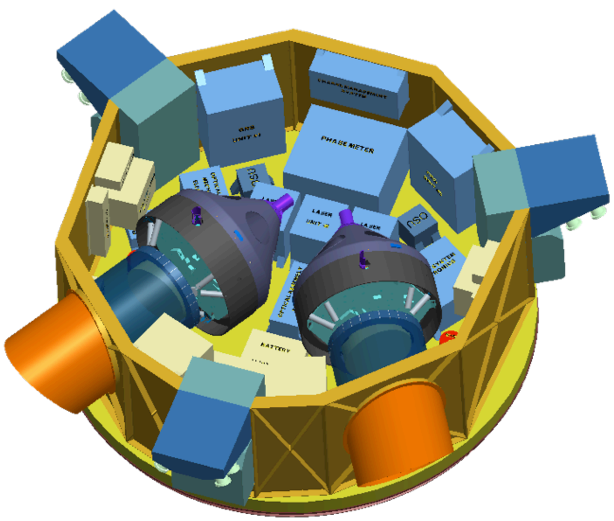
- **Interferometer Measurement System (IMS)**
  - Laser
  - Telescope
  - Optical bench
- **Disturbance Reduction System (DRS)**
  - Gravitational Reference Sensor (GRS)
  - μN thrusters
  - Control laws



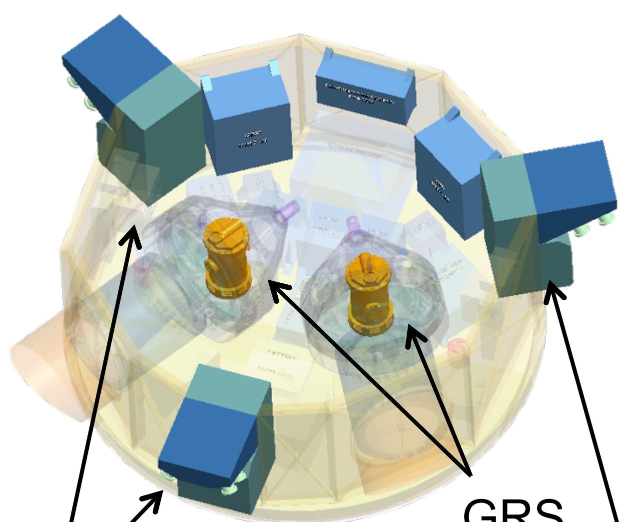
Optical bench mounted in Telescope Assembly

Telescope Assembly

Full Spacecraft Bus

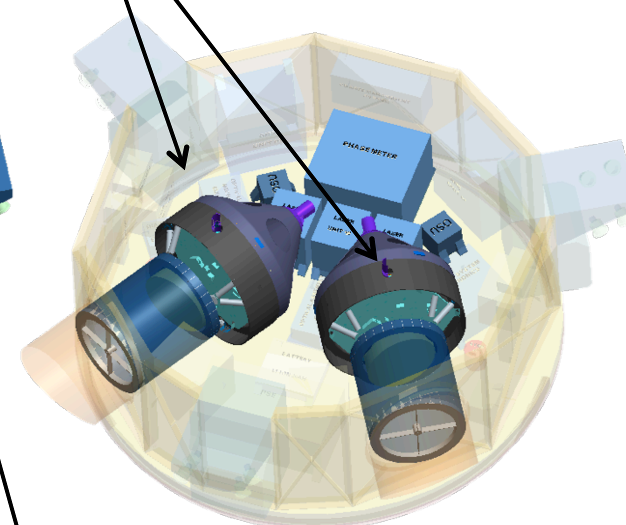


DRS Detail



GRS

IMS Detail

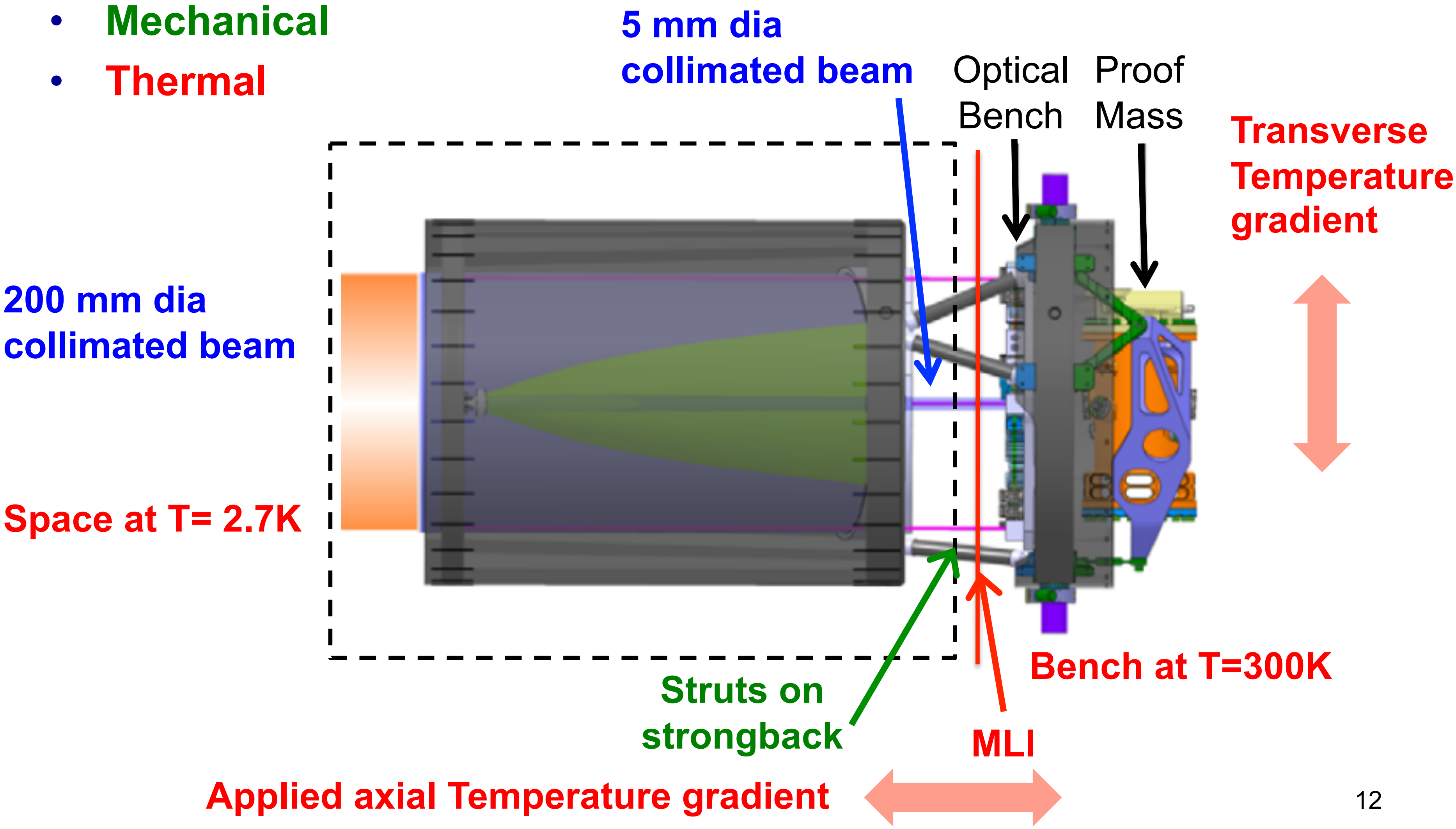


(Note: solar array not shown)

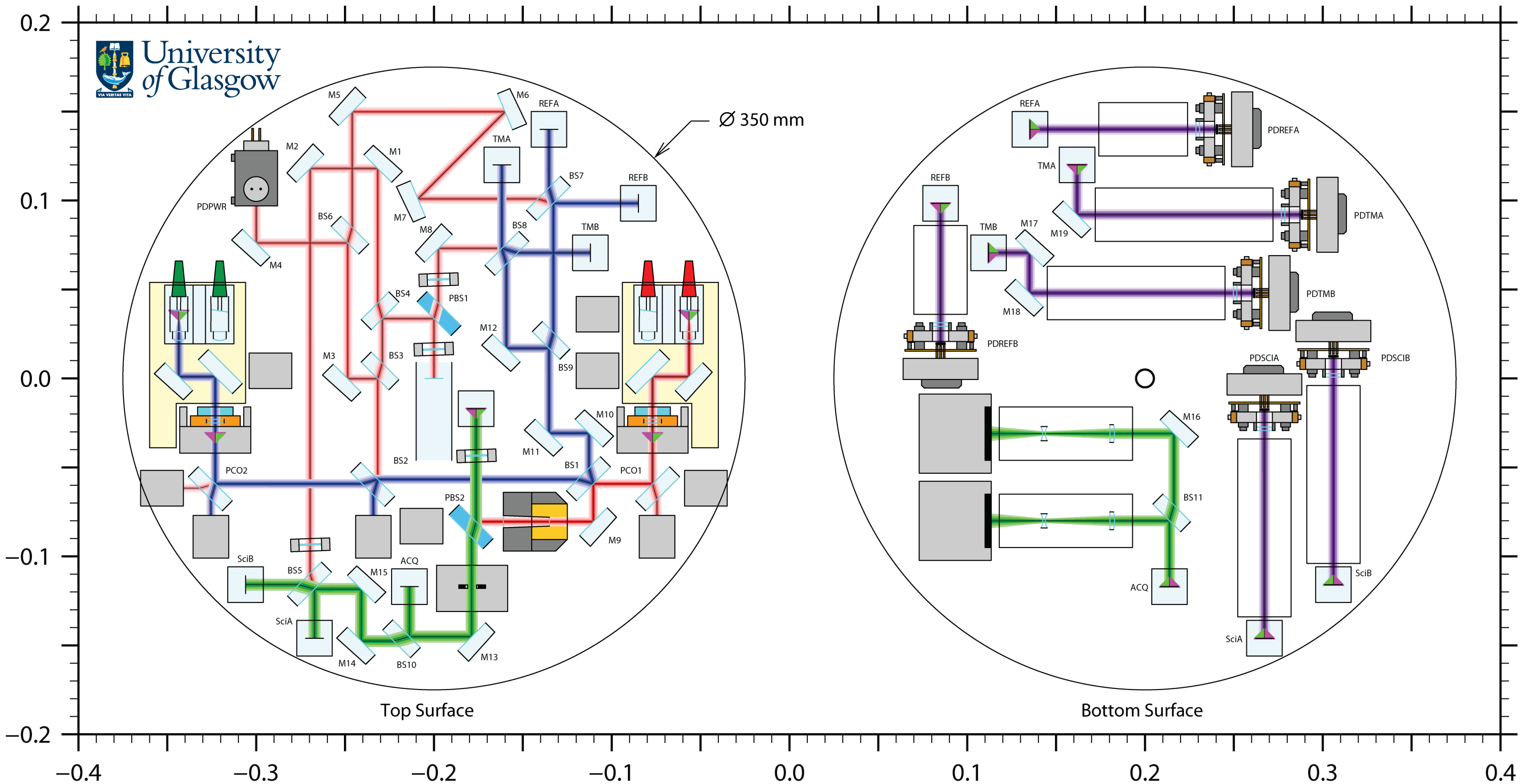
colloidal μN thrusters

Key Telescope Interfaces

- Optical
- Mechanical
- Thermal



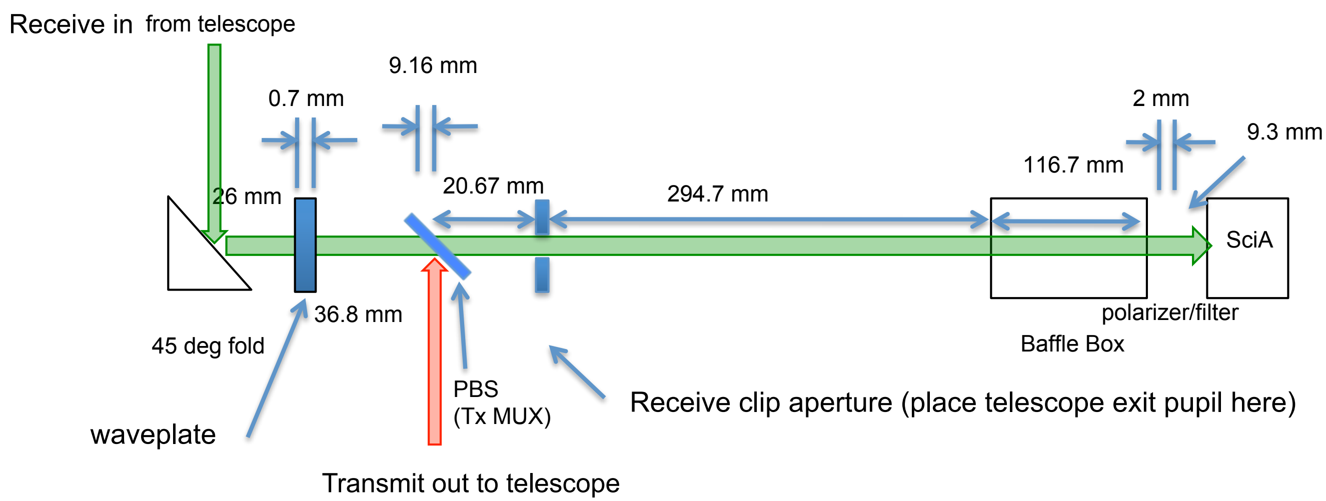
Glasgow NGO optical bench design



NGO OB Concept Layout. University of Glasgow.

Simplified Optical Bench Model

- **Essential Tx/Rx optics extracted from Glasgow design**



- **Main interface (for now) is the telescope pupil**
- **FRED model developed:**
  - ideal relay optics added to reduce beam from 5 mm to 1 mm detector dia
  - defines scattered light simplified model for calculation

High-Level Telescope Requirements

		Parameter	Derived From	eLISA flight telescope (for reference only)	Prototype telescope
	1	Wavelength		1064 nm	1064 nm
	2	Wave front Error [WFE] over field of view [FOV]	Pointing	≦ λ/30 RMS	≦ λ/30 RMS
	3	Field-of-Regard[1]	Orbits	+/- 20 μrad (large aperture)	+/- 20 μrad (large aperture)
	4	Field-of-View [FOV][2]	Stray light	+/- 8 μrad (large aperture)	+/- 8 μrad (large aperture)
challenging	5	Telescope subsystem OPD[4] stability under flight conditions[5]	Path length Noise/ Pointing	< 1 pm/√Hz RMS $\times\sqrt{1+\left(\frac{f_0}{f}\right)^4}$ where 0.0001 < f < 1 Hz f_0 = 0.003 Hz 1 pm = 10^{-12} m	Maintain RMS WFE (req #2) near room temp (T ~ 20 +/- 3C)
	6	Afocal magnification	short arm interferometer	200/5 = 40x	200/5 = 40x
	7	Optical throughput [transmission]	Shot noise	>0.85 at 1064 nm	>0.85 at 1064 nm
challenging	8	Scattered Light[3]	Displacement noise	< 10^{-10} of transmitted power into the receiver FOV	< 10^{-10} of transmitted power into the receiver FOV (verify by model)
	9	Stop Diameter (D) (large aperture)	Noise/ pointing	200 mm diameter	200 mm diameter
	10	Stop location (large aperture)	Pointing	Entrance of beam tube or primary mirror	Entrance of beam tube or primary mirror
	11	Exit pupil location (small aperture)	Pointing	140 mm (on axis) behind primary mirror	140 mm (on axis) behind primary mirror
	12	Exit pupil diameter (small aperture)	optical bench	5 mm	5 mm
	13	Focus adjustment	pointing	maintain WFE from room T (300K) to operating (230K) (Verify by model)	Leave provision for manual adjustment
	14	Mechanical envelope	spacecraft volume	≤ 450 mm length x 300 mm diameter (TBC)	≤ 600 mm length x 400 mm diameter or as negotiated

General Technology Readiness Levels

- ***TRL 1 Basic principles observed and reported***
- ***TRL 2 Technology concept and/or application formulated***
- ***TRL 3 Analytical and experimental critical function and/or characteristic proof-of-concept***

telescope now

- ***TRL 4 Component and/or breadboard validation in laboratory environment***

"environment" includes interfaces, not just Temp, Pressure, etc

- ***TRL 5 Component and/or breadboard validation in relevant environment***

ESA's definition is somewhere between these two

- ***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***

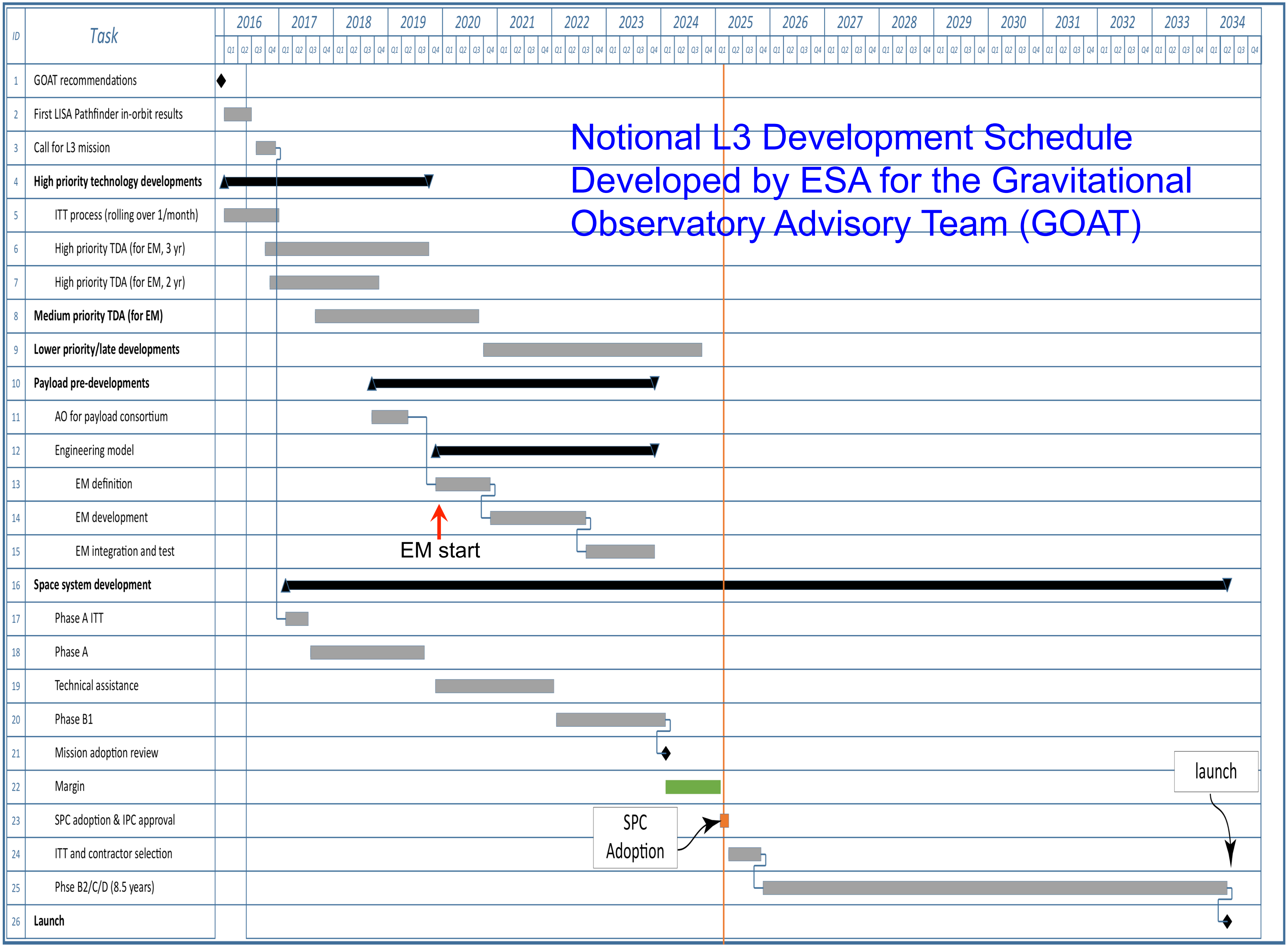
ISO TRL Comparison (for reference only)

Table 4-1: Comparison of ISO TRL scale and ESA old TRL scale

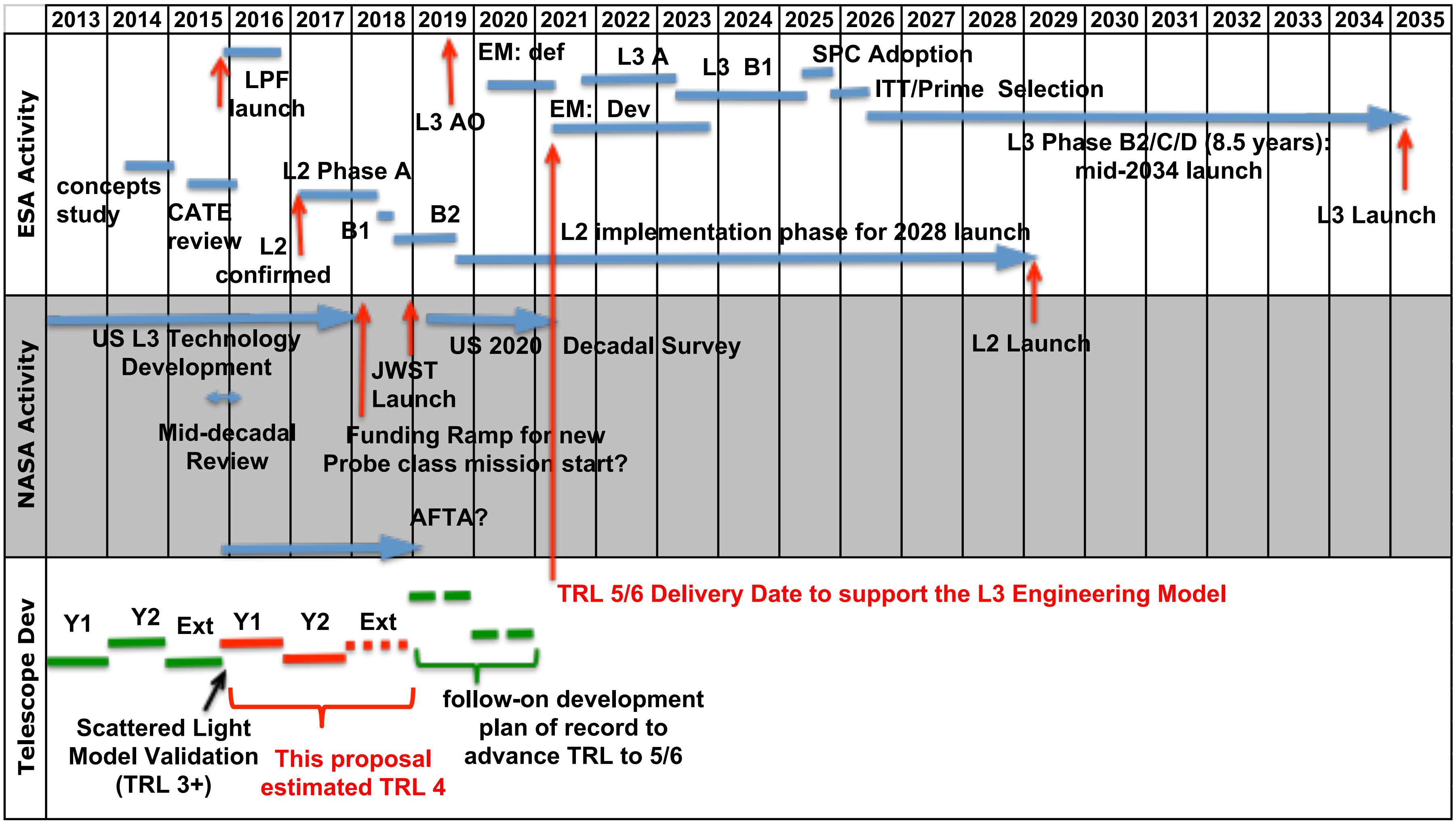
TRLs in old ESA scale		TRLs in new ISO scale	
TRLs 1 to 4		TRLs 1 to 4 are basically unchanged	
TRL 5	Critical functions verification in representative environment with representative scale breadboards	TRL 5	Same definition as TRL 5 old scale, but allowing reduced scale breadboard verification. Most useful for the development of large pieces (telescopes, structures) and for launcher developments.
		TRL 6	Same as TRL 5 old scale
TRL 6	Qualification through on ground verifications	TRL 7	Qualification level, through validation on ground or in orbit, as needed
TRL 7	Qualification through in-orbit demonstration		
TRLs 8-9		TRLs 8-9 are basically unchanged	

From "Guidelines for the use of TRLs in ESA programmes"

Prepared by	**ESA TRL Working Group**
Reference	**ESSB-HB-E-002**
Issue	**1**
Revision	**0**
Date of Issue	**21 August 2013**
Status	**Approved/Applicable**
Document Type	**Handbook**
Distribution	


Notional L3 Development Schedule Developed by ESA for the Gravitational Observatory Advisory Team (GOAT)
ID
Task
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027
2028
2029
2030
2031
2032
2033
2034
Q1 Q2 Q3 Q4
1 GOAT recommendations
2 First LISA Pathfinder in-orbit results
3 Call for L3 mission
4 High priority technology developments
5 ITT process (rolling over 1/month)
6 High priority TDA (for EM, 3 yr)
7 High priority TDA (for EM, 2 yr)
8 Medium priority TDA (for EM)
9 Lower priority/late developments
10 Payload pre-developments
11 AO for payload consortium
12 Engineering model
13 EM definition
14 EM development
15 EM integration and test
16 Space system development
17 Phase A ITT
18 Phase A
19 Technical assistance
20 Phase B1
21 Mission adoption review
22 Margin
23 SPC adoption & IPC approval
24 ITT and contractor selection
25 Phse B2/C/D (8.5 years)
26 Launch
EM start
SPC Adoption
launch

One Possible Development Timeline



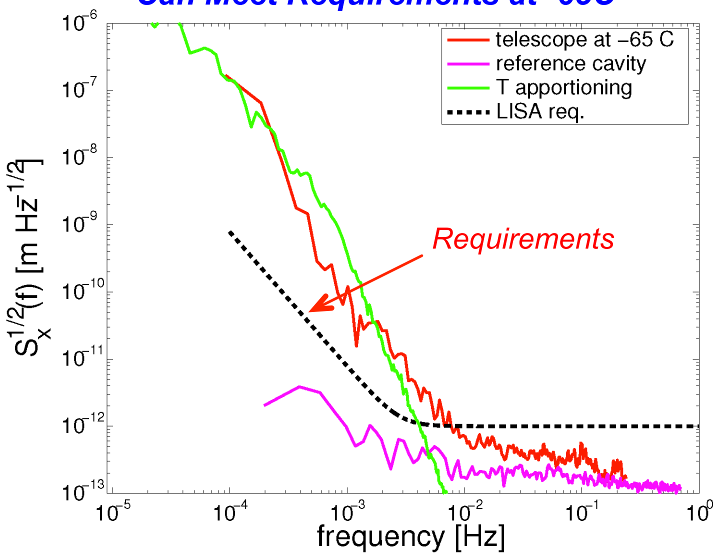
TELESCOPE STATUS AND WORK TO BE DONE

Previous Work:
SiC Spacer Dimensional Stability Demonstration

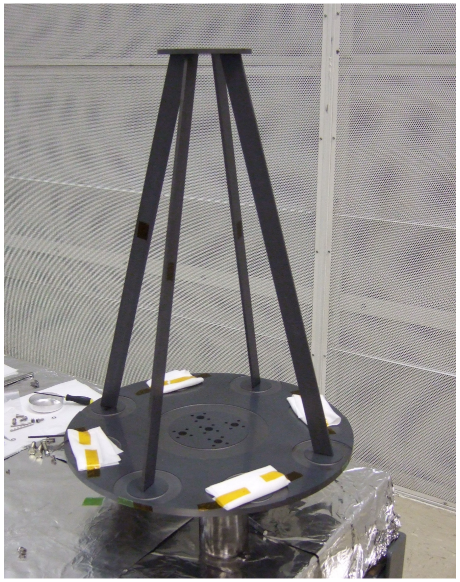
Spacer Activity Objective

- Develop and test a design for the main spacer element between the primary and secondary mirrors
- M1 - M2 spacing identified as critical by tolerance analysis
- SiC meets stability requirement
- On-axis Quadpod would not meet scattered light requirement

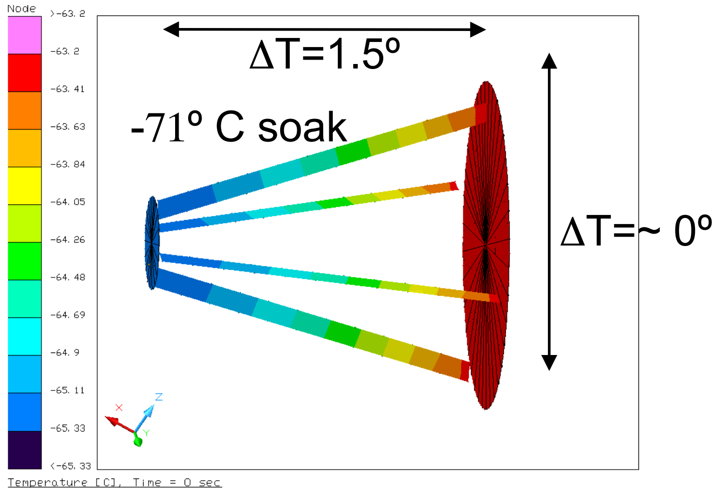
SiC Spacer Design
Can Meet Requirements at -65C



SiC Spacer Design: QuadPod



Thermal Model to Determine Test Conditions



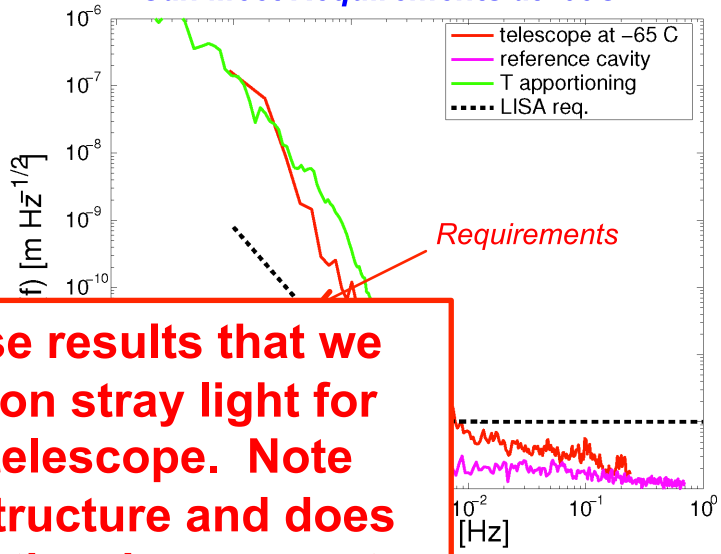
Previous Work:
SiC Spacer Dimensional Stability Demonstration

Spacer Activity Objective

- Develop and test a design for the main spacer element between the primary and secondary mirrors
- M1 - M2 spacing identified as critical by tolerance analysis
- SiC meets stability requirement
- On-axis Quad scattered ligh

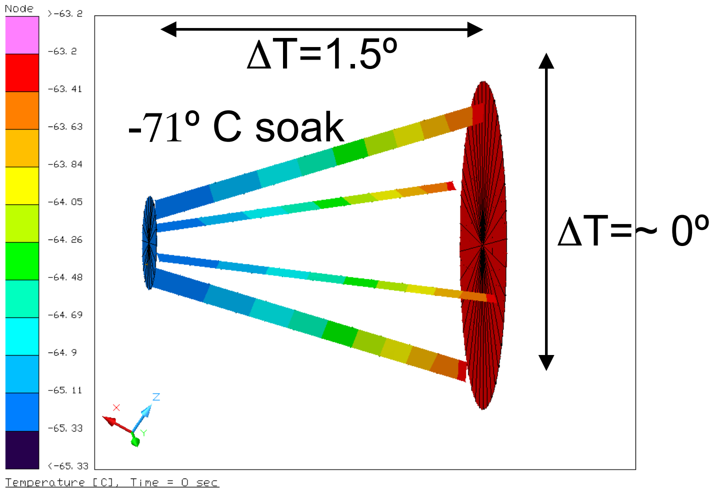
It is on the basis of these results that we decided to concentrate on stray light for the next version of the telescope. Note that this is an on-axis structure and does not include mirror realistic mirror mounts.

SiC Spacer Design
Can Meet Requirements at -65C



SiC Spacer D

Thermal Model to Determine Test Conditions



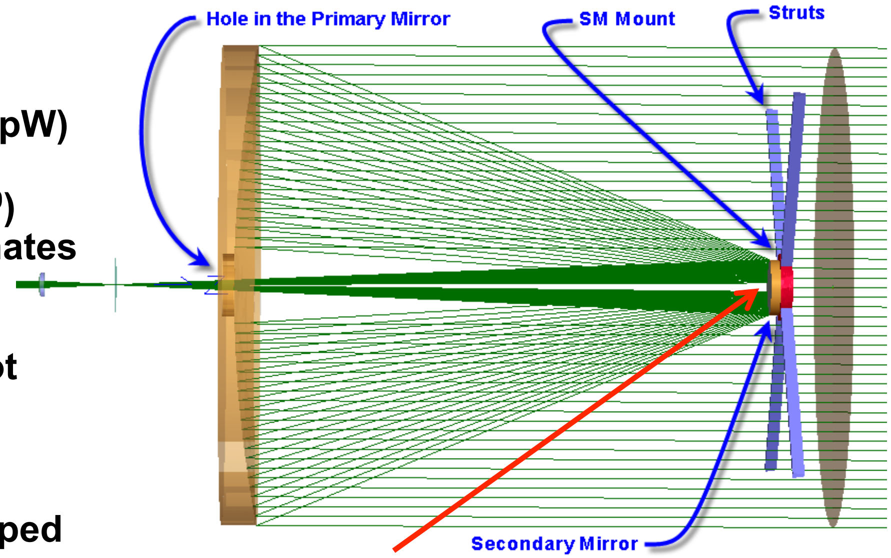
Scatter Suppression Masks

Key challenge:

- Simultaneous transmit and receive telescope operation plus an interferometric detection scheme:
  - combines extreme sensitivity (1 pW)
  - With high dynamic range of coexisting optical powers (~ 10^{10})
- On-axis (Narcissus) reflection dominates
- Hole or mask yields on-axis Poisson spot
- Petaled masks suppress on-axis spot
- Grey-scale masks do better
  - Currently limited by
    - Fabrication errors/defects
- Aaron Spector/Guido Mueller developed spiral mask shape alternative

Currently performance is not yet adequate to use an on-axis design

On-axis Telescope Model

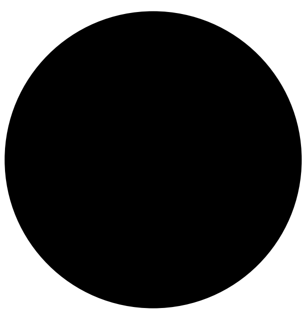


Transmit: 1W

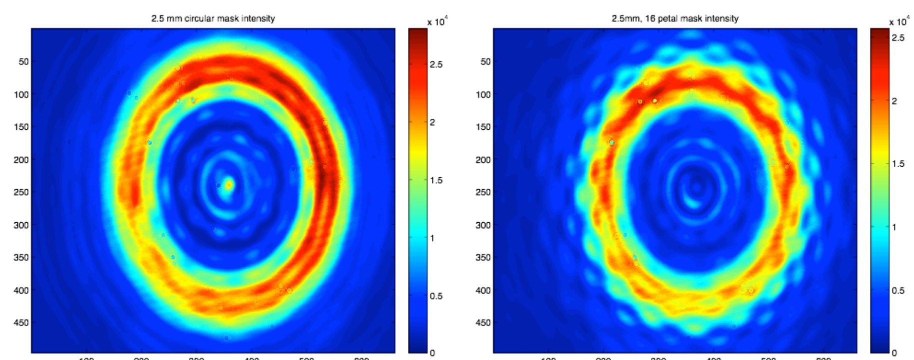
Receive: 10^{-10} W

On-axis (Narcissus) secondary reflection

Circular mask/hole

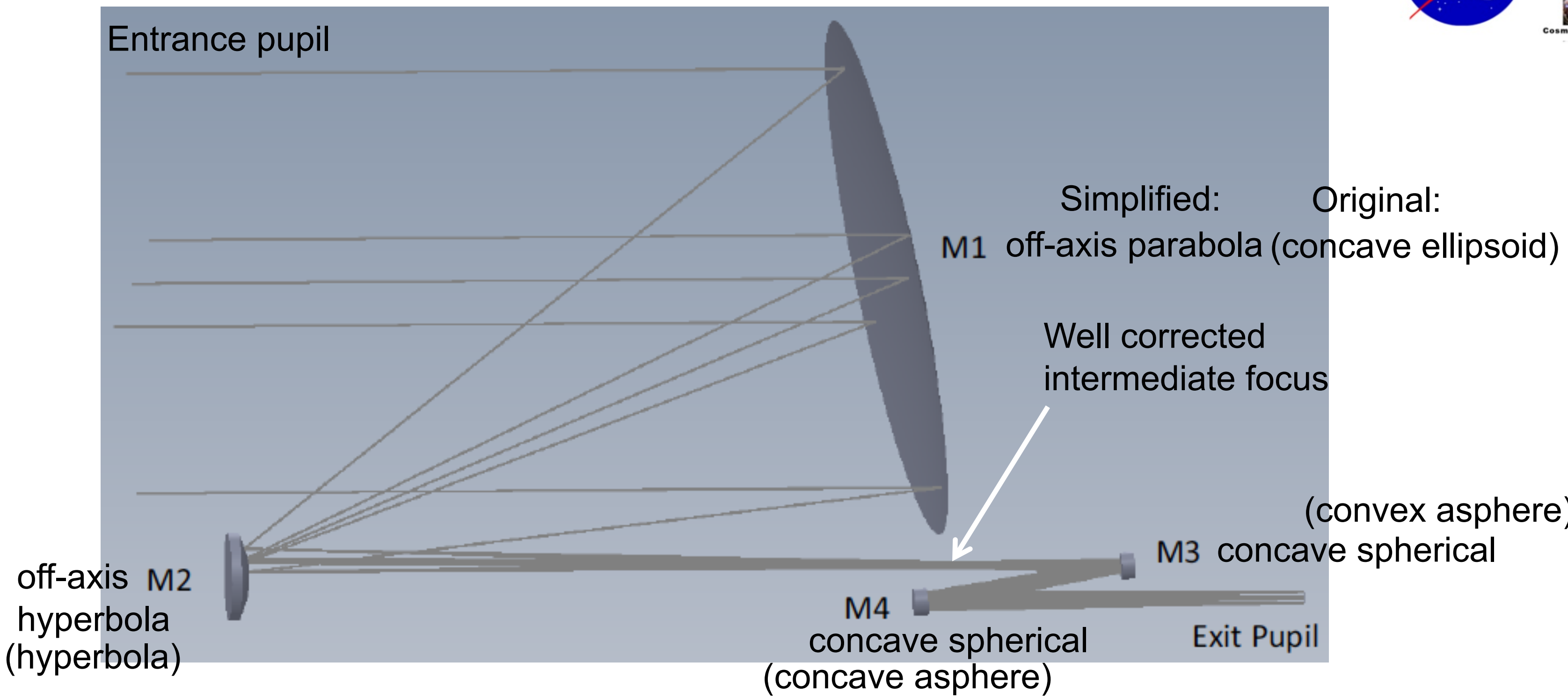


Intensity Suppression Using 16-petal Mask



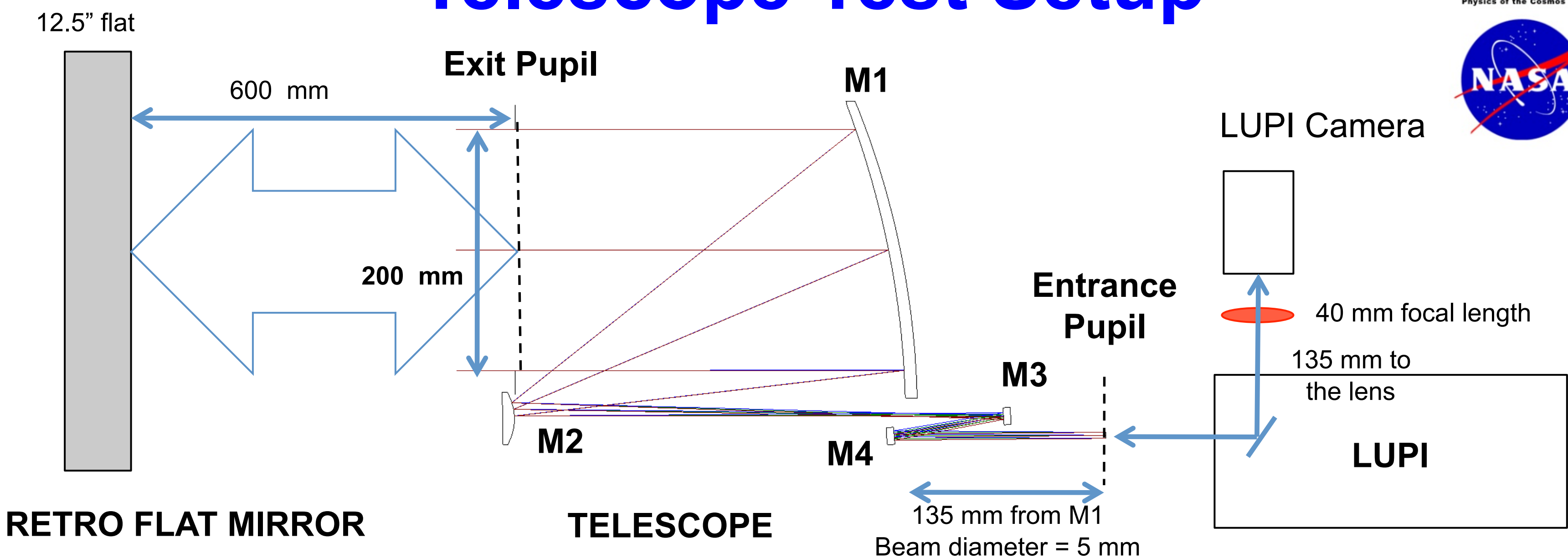
16-petal mask

Current Design:

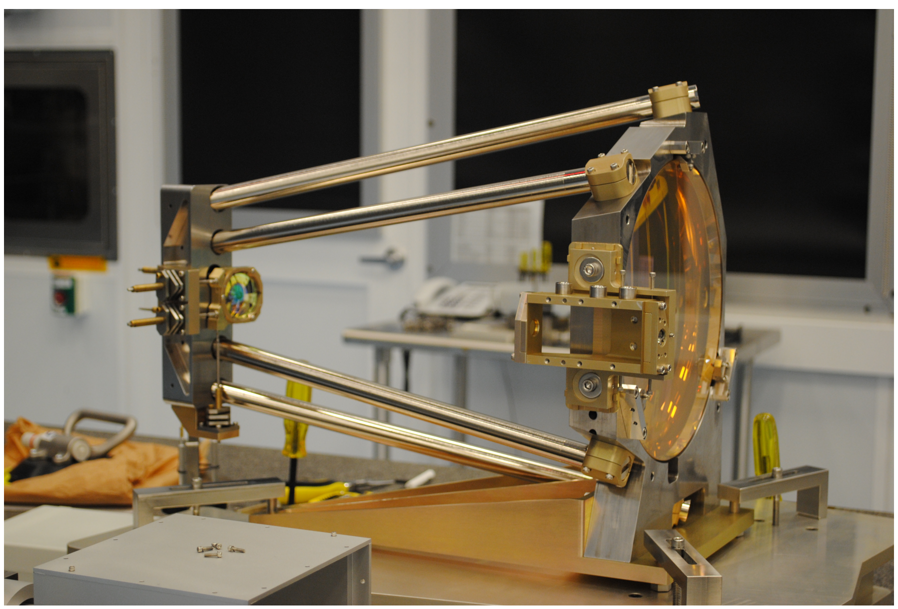


- **Off-axis Cassegrain for stray light performance**
- **Schwarzschild-style pupil extender**
- **Simplified Design to reduce mirror cost, risk**
- **Simplified construction and alignment**
- **Meets most requirements**

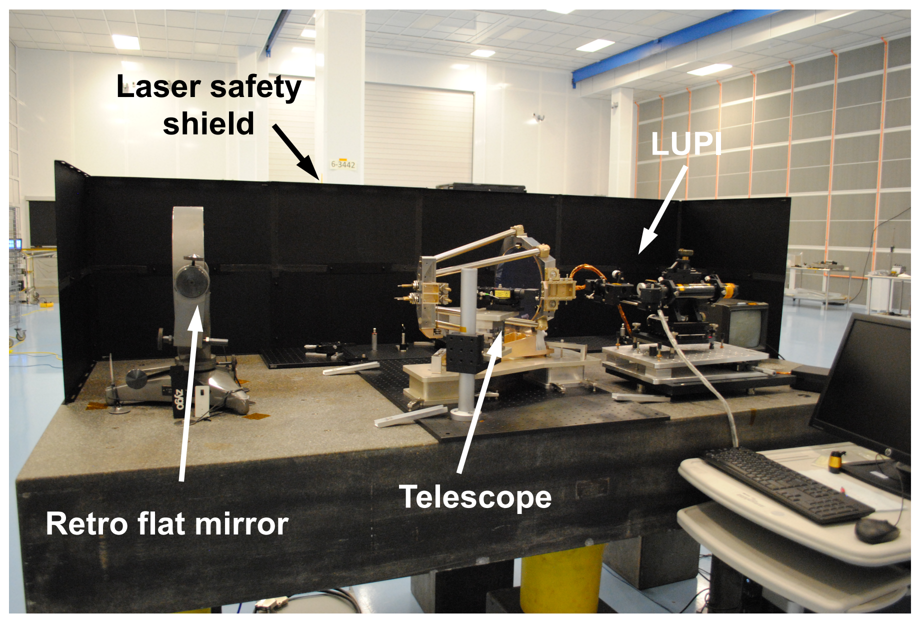
Telescope Test Setup



Prototype Telescope



Double-pass telescope test setup

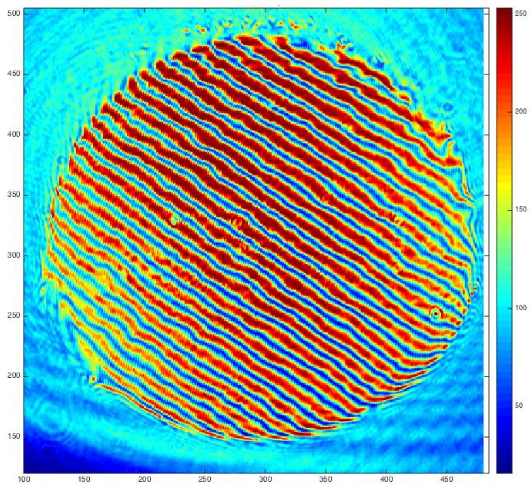


Telescope WFE at 2 wavelengths

Oct 1, 2015 data **(Spec is λ/30 at 1064 nm or 35 nm)**

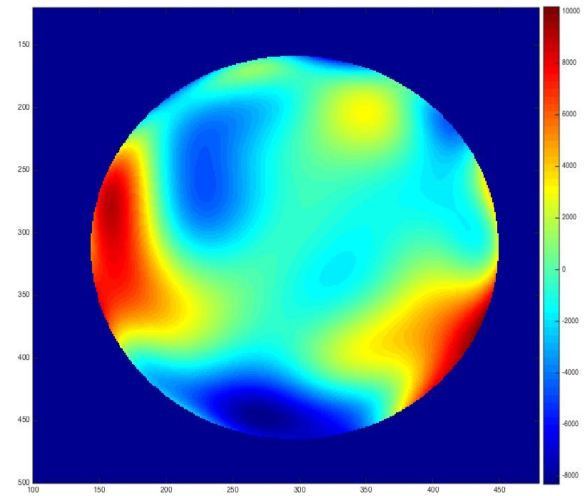
632.8 nm

Fringes



~ 5 mm

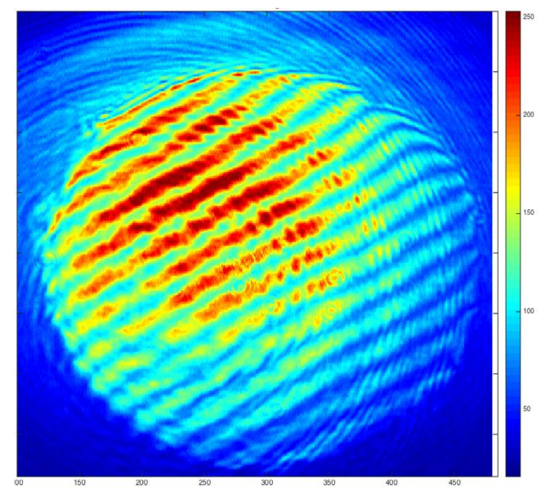
OPD (phase)



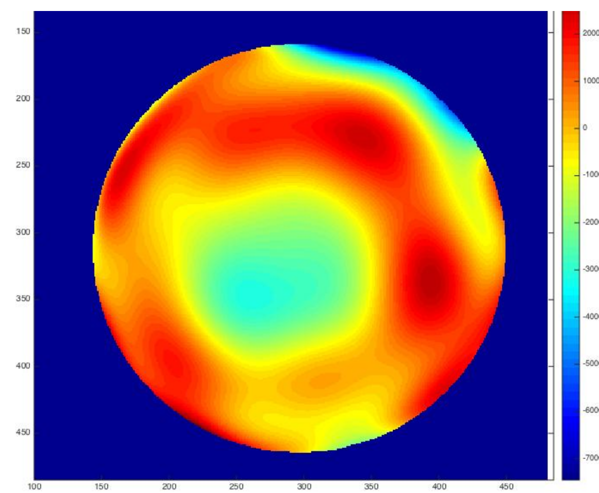
PV 167.8 nm
RMS 30.5 nm

1064 nm

Fringes



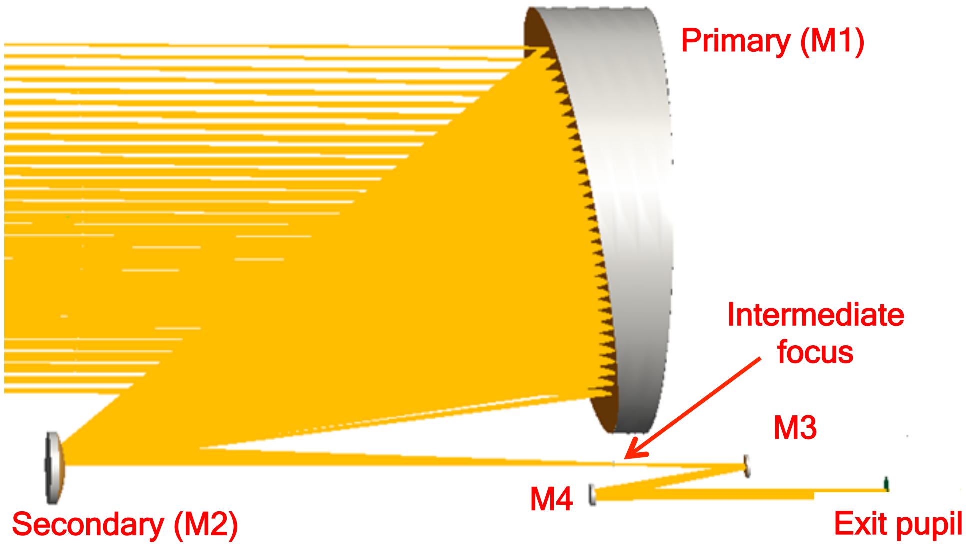
OPD (phase)



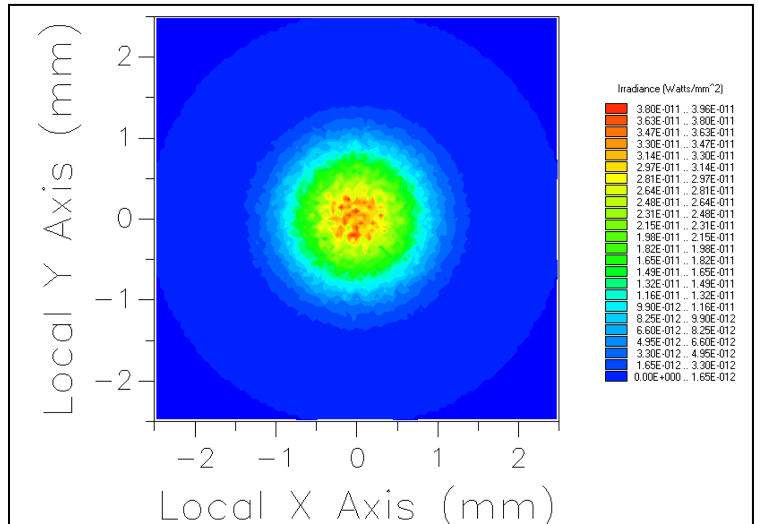
PV 96.0 nm
RMS 22.5 nm

Meets spec at both wavelengths but OPD maps are different!

Scattered Light Analysis



Pupil Plane Scatter Irradiance



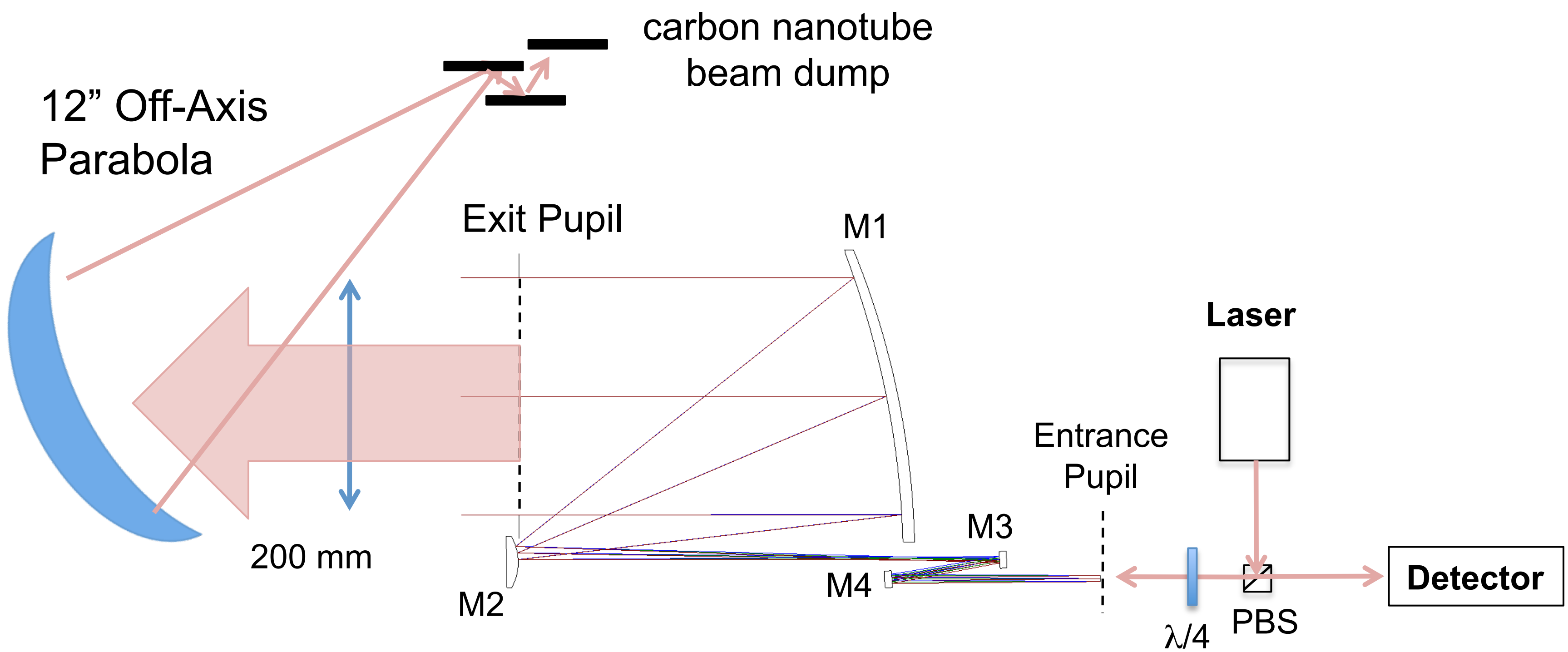
Mirror	RMS surface roughness (Å)	MIL-STD 1246D CL
M1	15	300
M2	15	200
M3	5	200
M4	5	200

Conflicting accounts of on-orbit levels

- Source power = 1W
- Total power on the detector = 6.6×10^{-11} W → (barely) meets specification of less than 10^{-10}

	Path#	# Rays	Power %	Power	1st scatter surface
3	7	2291695	74.947	4.9421e-11	.20140417_elisa_baseline.M3.Front
4	3	2711030	23.053	1.5201e-11	.20140417_elisa_baseline.M4.Front
2	11	2565386	1.9733	1.3012e-12	.20140417_elisa_baseline.M2.Front
1	14	1399213	0.026184	1.7266e-14	.20140417_elisa_baseline.M1.Front
Totals		8967324	100	6.5941e-11	

Scattered Light Test Setup

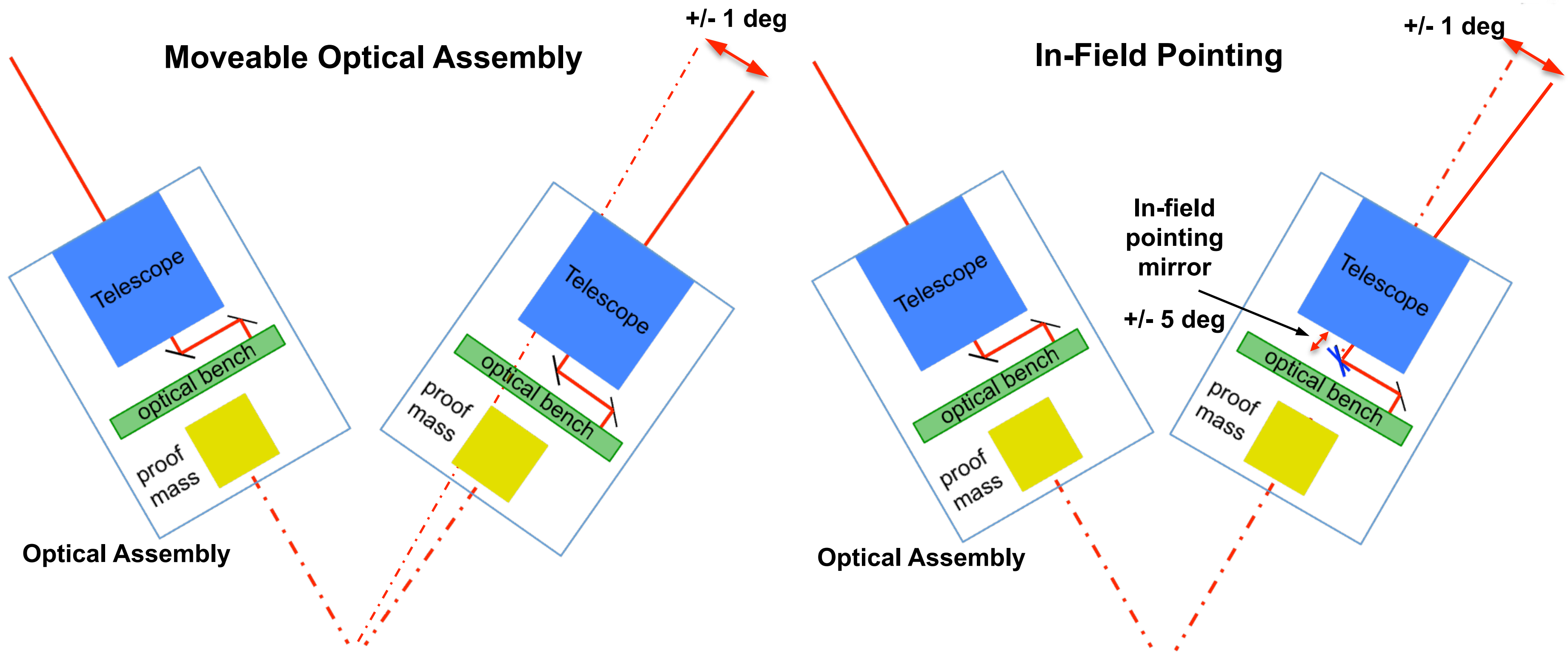


- Simplified Scattered Light Setup
  - Polarization optics separates input from output beam
  - Modulated laser allows synchronous detection for better noise rejection

Rough idea of work to be done

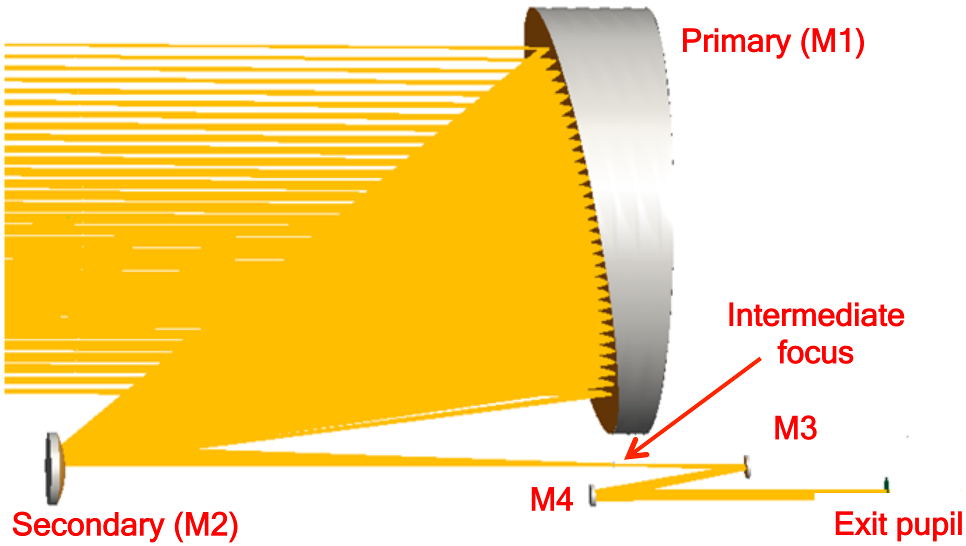
- **Validate scattered light model**
  - Surface roughness vs particulate contamination
    - What is achievable on-orbit is not known
  - Realistic baffling and stop/aperture design
- **Demonstrate stability and scattered light simultaneously**
  - Materials choice plus good mirror mount design
  - Not worrying about light-weighting mirrors, etc
- **Develop interface specifications**
  - Interface with optical bench
    - Optical: relay optics to GRS, detectors; scattered light/reflection, point ahead
    - Thermal: bench is at ~ 300K, telescope is ~ 230K if SiC
    - Mechanical: stability, etc
  - Transmit/receive beams
- **System level study**
- **Investigate In-field guiding**
  - scattered light specification may be incompatible
- **Other scattered light suppression approaches?**
  - Petaled masks
  - Modulation or digital interferometry

Orbital Motion Compensation Concepts

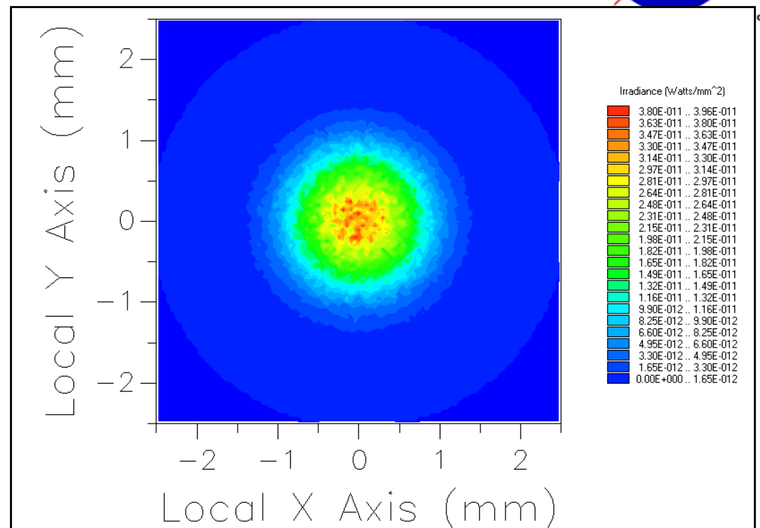


	Moveable Optical Assembly	In-Field Pointing
Telescope	Narrow (+/- 200 μrad) field of view Moveable optical assembly +/- 1 deg Beam path fixed through telescope	Wide (+/- 1 deg) field of view Fixed optical assembly; beam moves Small scanning mirror (no piston)
Inter-bench	Back-link fiber	Fixed free-space beam
Issues	Actuator concept demonstrated	Mechanism; Scattered light

Scattered Light Analysis



Pupil Plane Scatter Irradiance



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2	11	2565386	1.9733	1.3012e-12	.20140417_elisa_baseline.M2.Front
1	14	1399213	0.026184	1.7266e-14	.20140417_elisa_baseline.M1.Front
Totals		8967324	100	6.5941e-11	

aft optics contributes most of the scattered light: in-field pointing needs more

SYSTEM DEPENDENCIES

System Dependencies

- **Telescope Aperture and Laser Power trade**
  - Key metric is SNR at the detector ($D^4 \times P_{Tx}$ = constant)
  - Lower laser power may reduce risk
  - Space telescope cost scales with area
- **Arm length/Orbits**
  - Telescope area scales with length (D^4/L^2 = constant)
  - Point ahead angles depend on L
    - Definitely need a point ahead actuator at 5×10^6 km
    - Probably do not at 1×10^6 km
  - Telescope pointing: moveable optical assembly vs in-field guiding
    - Changes the optical design and/or the field of view specification
- **Science targets**
  - Influence overall noise budget balance
    - high frequency (0.1-1 Hz) performance?
    - low frequency (0.0001-0.001)
    - both

Simplified expression for the received power[1]:

$$P_{Rx} = P_{Tx}\left(\frac{D_{Tx}^{\,2} D_{Rx}^{\,2}}{C \bullet L^2 \lambda^2}\right)$$

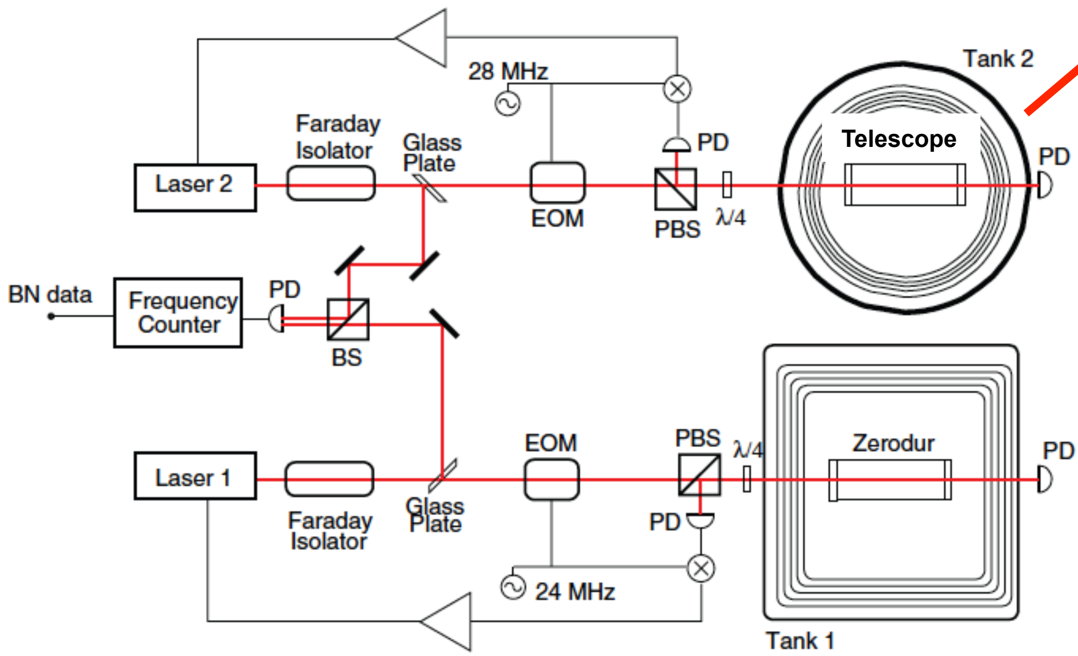
[1]C is a constant that depends on the beam shape
Tx = transmitter, Rx = receiver, L is the arm length, and λ is the laser wavelength, D is the beam diameter

BACKGROUND MATERIAL

Resources

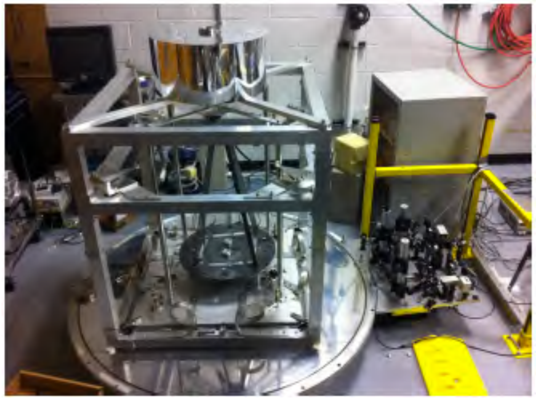
Key Facilities

- **University of Florida/Gainesville**
  - Dimensional stability measurement
    - Large, instrumented vacuum tank used for spacer stability demonstration
    - Vibration and thermal isolation
    - Frequency stabilized laser
  - Need a lead person (postdoc/grad student)



UF Test Chamber

Internal fixtures and vibration isolation



ESA Telescope Work

LISA Telescope Assembly Optical Stability Characterization for ESA

Adrianus L. Verlaan[a], Harmen Hogenhuis[a], Joep Pijnenburg[a], Martin Lemmen[a], Stefano Lucarelli[b], Dietmar Scheulen[b], David Ende[c]

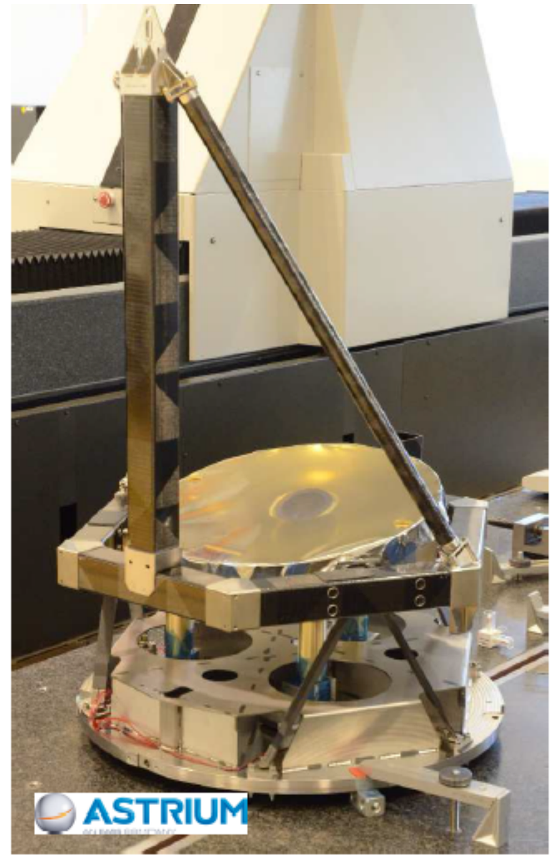
a. TNO, Stieltjesweg 1, Postbus 155 2600AD Delft, The Netherlands
b. EADS ASTRIUM, 88039 Friedrichshafen, Germany
c. xperion AEROSPACE GmbH, Claude-Dornier-Str., 88090 Immenstaad Germany,

ABSTRACT

The LISA Optical Stability Characterization project is part of the LISA CTP activities to achieve the required Technonlogy Readiness Level (TRL) for all of the LISA technologies used. This activity aims demonstration of the Telescope Assembly (TA), with a structure based on CFRP technology, that a CTE of 10^{-7} 1/K can be achieved with measures to tune the CTE to this level. In addition the demonstration is required to prove that the structure exhibits highly predictable mechanical distortion characteristics when cooling down to -90°C, during outgassing in space and when going from 1g environment to 0g.

This paper describes the test facilities as well as the first test results. A dedicated test setup is designed and realized to allow monitoring dimensional variations of the TA using three interferometers, while varying the temperature in a thermal vacuum chamber. Critical parameters of the verification setup are the length metrology accuracy in thermal vacuum and the thermal vacuum flexibility and stability. The test programme includes Telescope Assembly CTE measurements and thermal gradient characterization.

Keywords: LISA, NGO, telescope, characterization



- **Off-axis design**
  - **Optically more complicated, mechanically less**
- **Composite (water outgassing issues)**
  - **Supports 18 K temperature gradient**
- **Low CTE goal (10^{-7}/K)**
  - **But – need to demonstrate optical path length stability**

Performance Verification of In-Field Pointing for eLISA

An Experiment to test In-Field Pointing for eLISA

ICSO 2014, Tenerife, Canary Islands, Spain

Christina Brugger[1], Bernhard Broll[1], Ewan Fitzsimons[1], Ulrich Johann[1], Wouter Jonke[2], Stefano Lucarelli[1], Susanne Nikolov[1], Martijn Voert[2], Dennis Weise[1] and Gert Witvoet[2]

[1] Airbus DS GmbH, 88039 Friedrichshafen, Germany

[2] TNO Opto Mechatronics, 2600 AD Delft, Netherlands

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More recent results may be available

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