Optical Telescope Design Study Results

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Abstract. We report on the results of a study conducted from Nov 2012-Apr 2013 to develop a telescope design for a space-based gravitational wave detector. The telescope is needed for efficient power delivery but since it is directly in the beam path, the design is driven by the requirements for the overall displacement sensitivity of the gravitational wave observatory. Two requirements in particular, optical pathlength stability and scattered light performance, are beyond the usual specifications for good image quality encountered in traditional telescopic systems. An important element of the study was to tap industrial expertise to develop an optimized design that can be reliably manufactured. Key engineering and design trade-offs and the sometimes surprising results will be presented.

1. Introduction

Space-based gravitational wave observatories will enable the observation of astrophysical signals in the source-rich low-frequency band from 0.0001 to 0.1 Hz. All current observatory designs require the use of an optical telescope to efficiently deliver light from one spacecraft to another. Therefore the telescope is an important technology for future gravitational-wave space missions. Our goal is to continue the development work for such a telescope, using the eLISA concept [1] as a reference mission for our particular design. The work ultimately includes fabricating and testing a prototype against the requirements for a gravitational-wave observatory.

The initial approach has been to develop a telescope design that meets a set of science-based requirements and can be manufactured on a small scale, with a modest initial target of NASA Technology Readiness Level 5 by 2018. After developing a design at Goddard Space Flight Center that met all the nominal optical specifications, we commissioned a study with an industrial partner to obtain advice from a vendor with considerable practical experience in designing and building similar optical systems.

One important choice was between different implementations of the design: on-axis vs off-axis. In the eLISA application, the telescope is to be used to transmit and receive simultaneously, and the on-axis design suffers from a significant "narcissus" reflection from the secondary mirror. The outgoing beam reflects at near normal incidence from the center of the secondary, and returns an on-axis beam that appears on the detector along with the received signal. This reflection dominates the scattered light budget and makes it extremely difficult to meet the scattered light requirement without suppressing

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that reflection. An off-axis design avoids the narcissus reflection, but was thought to be more susceptible to the presence of thermal gradients on-orbit that can introduce off-axis aberrations such as coma or astigmatism. These aberrations are not easily removed by a simple focus mechanism. An important first task for the study contractor was to independently weigh such considerations and make a recommendation regarding the most suitable design form or implementation.

Two key questions were framed for the study contractor to guide the process:
(1) Does an on-axis implementation meet the requirements, in particular for scattered light and dimensional stability?
(2) Is an off-axis implementation feasible to manufacture, while still robust enough to meet the telescope specifications in an environment of axial and transverse thermal gradients?

Once a design form was chosen, the study required a number of deliverables. These included:

- complete mechanical, thermal and optical design, including scattered light analysis
- test plan for verifying and validating requirements
- manufacturing plan for building 10 identical telescopes, including a schedule
- rough order of magnitude (ROM) cost estimate and cost breakdown for 10 telescopes

2. Key Optical Requirements and Goals of the Study

The application is a precision measurement of the relative displacement of two proof masses located in widely separated spacecraft through a pair of telescopes (not for image formation). The key optical requirements for the telescope are shown in Table 1.

Table 1: Key Telescope Optical Requirements

	Parameter	Derived From	eLISA
1	Wavelength	Nominal mission design	1064 nm
2	Net Wave front quality of as built telescope subsystem over science field of view under flight-like conditions	Pointing	λ/30 RMS
3	Field-of-Regard (Acquisition)	Acquisition	+/- 200 μrad (large aperture)
4	Field-of-Regard (Science)	Orbits	+/- 20 μrad (large aperture)
5	Field-of-View (Science)	Scattered Light	+/- 8 μrad (large aperture)
6	Science boresight accuracy	FOV, pointing	+/- 1 μrad (large aperture)
7	Telescope subsystem optical path length stability under specified environment	Path length Noise/ Pointing	$1\,pm/\sqrt{Hz} \times \sqrt{\left(1+\left(\frac{0.003}{f}\right)^4\right)}$ where 0.0001 < f < 1 Hz
8	Afocal magnification	short arm interferometer	200/5 = 40x (+/- 0.4)
9	Mechanical length	spacecraft diameter	< 350 mm
10	Optical efficiency (throughput)	Shot noise	>0.85
11	Scattered Light	Displacement noise	< 10^{-10} of transmitted power into science FOV at the detector

The telescope must be nearly diffraction limited for efficient delivery of laser power over the large separation between spacecraft. The requirements for field of view and wavefront quality are not particularly challenging. Requirements 7 and 11 are the most unusual for telescope designers and thus are considered challenging. Pathlength stability (requirement 7) is required because the telescopes are in series with the displacement measurement. The required precision of the displacement measurement is 10 pm/√Hz, and the uncertainty budget allocated to the telescope is 1 pm/√Hz over the eLISA science measurement band from 0.0001 to 0.1 Hz. The contribution from the telescope enters the measurement of the one-way displacement twice, since there is a telescope at both ends of the measurement path.

The telescope transmits and receives optical power simultaneously. The transmitted power is 1 W from the large aperture, and the expected received power is approximately 100 pW. To avoid adding broadband noise, it is desirable for the scattered light to be stable in phase relative to the local laser against which the received light is beat to form interference fringes. Our models indicate that most of the scattered light is expected to be from the mirrors, so the dimensional stability requirement should also mean that the scattered light is phase-stable. Phase stability, in turn, impacts the maximum allowable scatter. Furthermore, the scattered light must be in the same spatial and polarization mode as the local oscillator and/or received signal beam to interfere with the observatory displacement measurement. We have approximated that condition in Table 2 by specifying that the light be scattered into the science field of view.

Finally, one other requirement that is not easily captured in Table 1 is the ease with which the telescope can be manufactured. The mission will require 6 flight telescopes, plus 1-2 spares, and several telescopes for ground testing. The telescopes must be made in a relatively short time and be interchangeable to facilitate integration and ground testing. A simple and robust design is required that can be easily manufactured to minimize the need for extensive optimization during assembly and alignment.

3. Specific Trades

Table 2 shows a summary of the major issues considered as part of the study. The grey background shading indicates the highest risk issues.

Table 2: Trade Study Summary

	Material	**Silicon / Silicon Carbide**		**Glass/Graphite Composite**	
	Design Form	**On-Axis**	**Off-Axis**	**On-Axis**	**Off-Axis**
Manufacturing	Optics	No M2 beam trap/ spot implementation	Standard practice	No M2 beam trap/ spot implementation	Standard practice
Manufacturing	Structure	Contractor heritage	Contractor heritage	Contractor heritage	Contractor heritage
Manufacturing	Alignment	Standard practice	Standard practice	Standard practice	Standard practice
Environmental Test	Thermal Vacuum	Standard practice	Standard practice	Standard practice/ Outgassing concerns	Standard practice/ Outgassing concerns
Environmental Test	Launch Loads	Heritage design and strength	Heritage design and strength	Heritage design and strength	Heritage design and strength
Recurring Cost		lower for structure/ optics/testing	lower for structure /optics/testing	Higher for structure/optics/testing	Higher for structure/optics/testing
Schedule		Optic procurement drives schedule	Optic procurement drives schedule	Structure procurement/ testing drives schedule	Structure procurement/ testing drives schedule
Stability	Thermal analysis	Can meet requirements	Can meet requirements	Can meet requirements after outgassing (long term risk)	Can meet requirements after outgassing (long term risk)
Stability	Manufacturing and material variability	Use of invar in metering path	Use of invar in metering path	Use of invar in metering path; long term outgassing effects	Use of invar in metering path; long term outgassing effects
Scattered light		No M2 beam trap/ spot implementation and native performance	Standard practice	No M2 beam trap/ spot implementation and native performance	Standard practice

Each issue was evaluated for both silicon carbide and carbon fiber/glass composite materials, and both an on-axis and an off-axis implementation of the same optical design were considered.

4. Results

The study contractor recommended an off-axis silicon carbide design as the lowest risk (Table 2) and materials cost. The composite material system is known to exhibit dimensional changes consistent with water absorption and desorption [2]. The required time for the material to stabilize by water desorption in vacuum varies unpredictably and can be a month or more. This uncertainty will add to integration and testing time, thereby adding an undesirable schedule risk. Both materials have relatively low coefficients of thermal expansion (CTE), but the composite can be tailored with some effort to a level of 0.1 ppm/K, whereas silicon carbide is approximately 4 ppm/K. However, the telescope requirement for optical pathlength stability can be met with several different CTE materials, depending on the details of the telescope design form.

An on-axis implementation (using either material) was dismissed because methods for suppression of the narcissus reflection are still in the preliminary development stage. The off-axis silicon carbide design seems to possess the least technical and schedule risk.

Our industrial partner provided a cost estimate and schedule as part of a confidential bidding process so we cannot disclose the details. However, we can say generally that the recurring engineering costs are consistent with earlier NASA estimates from the LISA Project, but we also emphasize the contracted industrial partner arrived at their estimates independently and without prior knowledge of these LISA Project estimates. The cost estimate includes non-recurring engineering as well as creation of testing facilities for subsystem verification both of which were significant portions of the total cost. The schedule assessment provided by the industrial partner was somewhat longer than NASA estimates, but included time for procurement of the silicon carbide components, which is in series with the rest of the telescope manufacturing and not included in the NASA estimates. They recommended performing parallel fabrication/testing of multiple copies of the telescope, utilizing three teams of personnel with team members periodically rotating from team to team.

5. Lessons Learned

The process of working with a technically capable industrial partner has been worthwhile. The exercise forced us to work on converting the mission level specifications into lower level requirements, which could then be more easily assimilated by the contracted vendor into a design form and model. We have gained a great deal of insight by collaboration - in particular we have a better appreciation for the parts of the system that are considered difficult in the industry. We have also learned some of the capabilities of this contractor regarding both manufacture and modelling. This knowledge has allowed us the chance to address many issues from the point of view of the telescope engineer, instead of the scientist's viewpoint.

An example of this collaboration can be found in the thermal design. The thermal specifications were difficult for the vendor, and we found that an interface specification to the spacecraft was necessary, but not sufficient. We eventually provided the study contractor with a full spacecraft thermal design from our prior observatory-level work at NASA. Furthermore, we simplified the design compliance criteria to check only the lowest frequency point in the specifications to make the problem tractable for the industrial engineering team. This example of interchange and collaboration was one of many and enabled the project to proceed more smoothly.

We found that the scattered light specifications and, in particular the coupling mechanism to the observatory sensitivity, were also very unusual and thus challenging for the industrial partner. Approximations were made to facilitate more rapid optimization and communication with the study team. An example of such an approximation was the specification of a science field-of-view at the detector, instead of the full mode-overlap calculation often computed by a science team. The pathlength stability criterion is also unusual for the industry and, though the study engineering team ultimately determined that it was feasible, it does impact cost and schedule to have the industrial partner perform the verification of this requirement for the telescope subsystem. Indeed, the metrology apparatus for testing to this level of displacement sensitivity does not exist at the facility of our study contractor. Much of the quoted cost of the telescope subsystem goes towards establishing the testing facilities and purchasing the necessary equipment.

6. Summary and Outlook

Our partnership with the industrial study team was fruitful and produced several interesting results. For example, the reluctance of the engineers to recommend carbon composite materials (due mainly to technical and schedule risk) drove the choice of a light weighted silicon-carbide structure to meet the stability and thermal requirements. Integrated thermal, mechanical, and optical modelling enabled the study contractor to conclude that the off-axis design would be acceptable in the expected on-orbit environment. Another interesting conclusion was that fabrication and testing of an off-axis telescope is no more difficult than an on-axis version, especially for the higher end optical companies likely to bid on a flight-model, but the back-scattered light is expected to be a significant challenge for an on-axis design.

This study was an important first step in our communication with industry regarding the telescope subsystem. We anticipate continued collaboration with industry partners as we endeavour to push the telescope towards higher technical readiness levels. We have also begun efforts to procure and test a prototype telescope as part of these ongoing efforts at both model validation and technology maturation.

We are aware of a similar effort in Europe [3] and that approach is complementary. Both investigations have converged to an off-axis optical design, although the design approach and material choices are very different. The European study is focused on testing the telescope system level CTE at low temperatures, while this study seeks to investigate the trade-offs involved in ultimately achieving low noise contributions from back-scattered light. Our laboratory demonstration will concentrate on scattered light model validation since earlier work has indicated dimensional stability with a silicon carbide metering structure [4]. We continue to work towards the ultimate goal of a robust telescope design for space-based gravitational wave observatories.

Acknowledgements

The authors would like to acknowledge the help of the Goddard Space Flight Center eLISA Telescope team, including Petar Arsenovic, Peter Blake, John Crow, Joseph Howard, Lenward Seals, Ron Shiri, Justin Ward, and Garrett West. The work described here was supported by grant 11-SAT11-0027 awarded by NASA Strategic Astrophysics Technology program. S. Sankar acknowledges support by NASA grant NNX12AE97G.

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