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eLISA Telescope In-field Pointing and Scattered Light Study

J Livas[1], S Sankar[1,2], G West[1], L Seals[1], J Howard[1], E Fitzsimons[3]

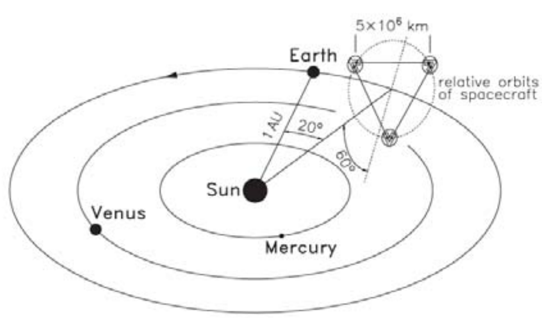
[1] NASA Goddard Space Flight Center, 8800 Greenbelt Road, Greenbelt, MD 20771, USA
[2] CRESST/USRA, Greenbelt, MD 20771 , USA
[3] UK Astronomy Technology Centre, Royal Observatory, Blackford Hill, Edinburgh EH9 3HJ

E-mail: Jeffrey.Livas-1@nasa.gov

Abstract. The orbital motion of the three spacecraft that make up the eLISA Observatory constellation causes long-arm line of sight variations of approximately ± one degree over the course of a year. The baseline solution is to package the telescope, the optical bench, and the gravitational reference sensor (GRS) into an optical assembly at each end of the measurement arm, and then to articulate the assembly. An optical phase reference is exchanged between the moving optical benches with a single mode optical fiber ("backlink" fiber). An alternative solution, referred to as in-field pointing, embeds a steering mirror into the optical design, fixing the optical benches and eliminating the backlink fiber, but requiring the additional complication of a two-stage optical design for the telescope. We examine the impact of an in-field pointing design on the scattered light performance.

1. Introduction

The LISA reference mission concept consists of a constellation of three identical spacecraft oriented in a planar equilateral triangle orbiting the sun in the same orbit as the Earth, but trailing in orbital phase by approximately 22 degrees (figure 1) [1]. The plane of the triangle is oriented at 60 degrees to the ecliptic. The triangular constellation rotates once per year about the center of the triangle, and the interior angles vary during the course of the mission. Figure 2 shows a representative variation of the angles with time for one choice of orbits [2].



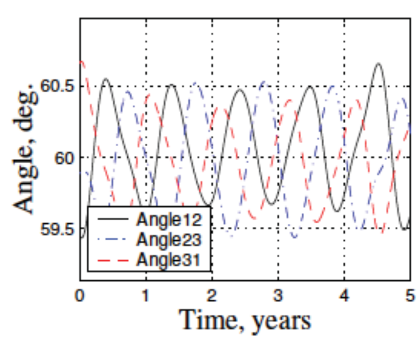


Figure 1: LISA reference mission constellation **Figure 2**: Representative interior angle variation

The variation in the internal angles of the constellation triangle means that the line of sight pointing of the telescopes will vary and must be compensated. There are two proposed solutions: telescope articulation, and in-field pointing [3,4,5]. These two solutions require different telescope designs. The articulation solution is the baseline for the LISA reference mission. Figure 3 shows the two proposed solutions. Each solution is discussed in more detail below.

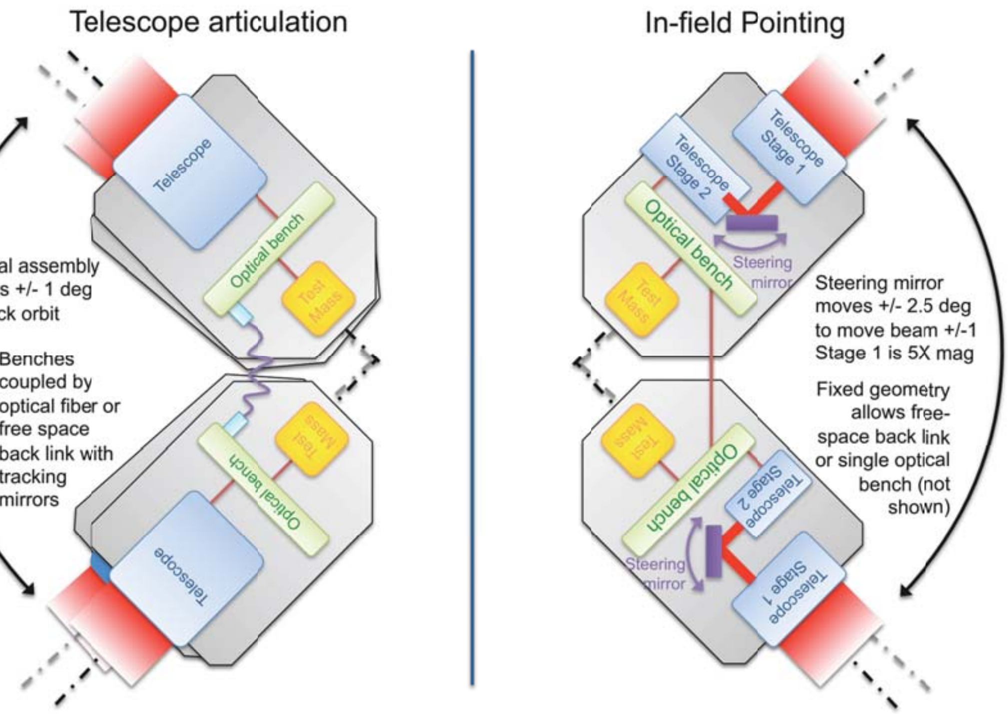


Figure 3: Proposed telescope pointing compensation solutions. Left: telescope articulation. Each telescope is mounted together with an optical bench and a gravitational reference sensor in an assembly that can be rotated as a unit to track the angular variations. Right: The in-field pointing alternative design has a steering mirror embedded into the telescope design so that the telescopes are mounted rigidly to the spacecraft. Specific values shown in the figure are representative of a TNO mirror design and assumed for the purposes of this study.

Both solutions perform the same function for the mission: they enable a continuous length measurement between widely separated proof masses and therefore operate with a transmitter and receiver simultaneously. An important requirement to accomplish this function is low coherent backscatter. This means that very little light from the transmitter must scatter back into the receiver. Since the transmitter is frequency stabilized and phase locked to the laser in the far spacecraft, any scattered light is coherent with the received light and with the local oscillator. Scattered light can therefore interfere with those beams and add noise to the main measurement.

The purpose of this report is to present the results of a preliminary study of the coherent backscatter performance of several representative in-field pointing designs. The study was motivated by concern over the stray light performance of the fixed mirror telescope designs. As will be shown below, the mirrors closest to the detector that collect the light and direct it onto the detector dominate the scattered light budget. An in-field pointing design will require a different optical design due to the practical limitations of the moveable mirror, and will typically have more of these small mirrors. If the scattered light performance scales with the number of mirrors, it may be difficult to meet the scattered light performance. We note that there are a number of other considerations that go into the design of these in-field pointing telescope systems [3,4,5,11].

2. Scattered Light Modeling

The scattered light modelling was done with FRED [6], a non-sequential ray tracing program. For the purposes of this study, two surface properties were considered for the modelling: surface roughness, and particulate contamination.

Surface roughness is specified with a Harvey-Shack model, and we considered two levels of roughness: 5 or 15 Angstroms rms. To some extent the achievable surface roughness depends on the material, the shape of the mirror, and the fabrication technique. State of the art for a flat mirror is < 1 Angstrom rms, so these specifications are not particularly challenging.

Particulate contamination is specified according to MILSTD-1246c [7], and two levels were considered: cleanliness level (CL) 200 or 300. Generally, the scattered light modelling results indicate that surface roughness can usually be made low enough that particulate contamination is the major contribution to the total backscatter.

The real requirement for the scattered light performance of either telescope is that the light that reaches the detector must not add noise to the measurement [8,9]. Since the scattered light is coherent with the transmitter, the local oscillator, and the received signal from the far spacecraft, the complete requirement must specify both the magnitude and the phase stability of the scattered light. To simplify the calculation for purposes of this study, we adopted the simplified specification that any light scattered by the transmitter into the solid angle subtended by the detector at the small beam exit pupils of the telescope would be counted toward the stray light. The solid angle is the instantaneous science field of view multiplied by the angular magnification, or approximately 8 μrad x 90 = 720 μrad. We required this scattered light to be $< 10^{-10}$ of the transmitter power, or about 100 pW for a 1 W transmitter. This amplitude is consistent with other results [9], and should be considered to be a conservative specification.

3. Baseline Solution: Telescope Articulation

A telescope design with fixed mirrors that is representative of a possible solution for the baseline articulated telescope solutions is presented in the next subsection, along with a scattered light analysis, as a point of comparison for the in-field pointing designs.

3.1. Articulated Telescope Basic Design

The design for the baseline articulated telescope solution is a four mirror design with an off-axis Cassegrain/Gregorian primary and secondary, and a Schwarzschild-style pupil extender. An off-axis design is required for either telescope solution to avoid the “narcissus” reflection from the secondary mirror. A complete discussion of the design [10] is outside the scope of this report, but Table 1 shows the basic design assumptions and parameters.

Table 1: Telescope design assumptions.

Parameter	value	Comments
Primary	200 mm	NGO design
Small beam pupil	2.24 mm	real pupil
magnification	~ 90 X	calculated for information only
Instantaneous field of view	± 8 μradian	for science operations
Angular line of sight variation	± 1 degree	Assumed; may not be the final

3.2. Articulated telescope scattered light performance

The basic design described in the previous section along with the scattered light performance is shown in Figure 4. The design meets the simplified scattered light specification of < 100 pW, although with little margin, and of interest for this report is that most of the light comes from the M3/M4 mirror pair.

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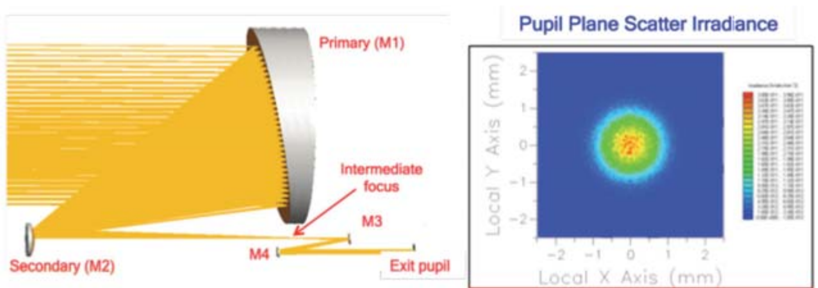


Mirror	RMS surface roughness (Å)	MIL-STD 1246D CL
M1	15	300
M2	15	200
M3	5	200
M4	5	200

- 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

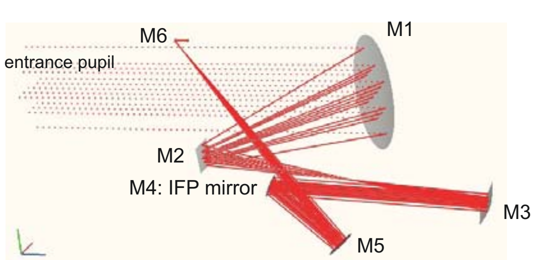
Figure 4. An example of scattered light modeling for a particular design for the articulated telescope assembly concept.

4. In-field Pointing Solution

For the purposes of this study, we assumed the performance of an in-field pointing (IFP) mirror similar to what has been demonstrated by TNO [12]. Specifically we assumed a mirror with a ± 2.5 degree angular rotation about one degree of freedom (giving ± 5 degree local beam angle change), designed for a 22.5 degree angle of incidence.

If we assume that the required line of sight variation is ± 1 degree at the output of the telescope, then the in-field pointing mirror must be placed inside the telescope where the maximum magnification is five, to accommodate the maximum angular deviation of the beam by reflection from the IFP mirror. This forces a 2 stage design for the telescope into a magnification five stage before the IFP mirror, and a stage with magnification 90/5 = ~ 18 after the IFP mirror.

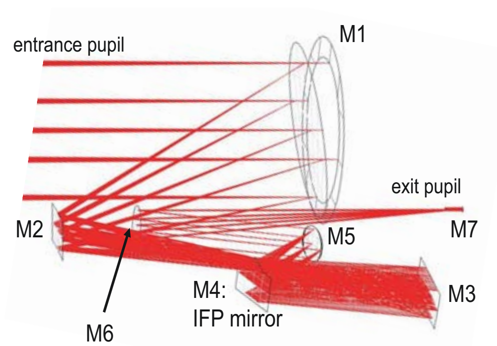
Three representative designs were analyzed for their stray light performance. Figure 5 shows a design with the minimum mirror count (six) we could use to achieve the full magnification and get exit beam moving in the correct direction. The placement of the exit pupil is probably not practical, but the scattered light performance meets requirements with all mirrors at 5 angstroms rms surface roughness and CL300. The model indicates most of the light scattered into the reference solid angle is scattered from the final mirror.



Scatterers	Rays	Power (W in 720 μrad)	RMS surf rough (Å)	CL
All	3004	2.0e-11	5	200
All	3004	1.0e-10	5	300
M5	3081	9.0e-11	5	300

Figure 5: Minimum mirror count (6 mirrors) in-field pointing design. This design meets the specification that the power scattered in the field of view of the detector is $\leq 10^{-10}$.

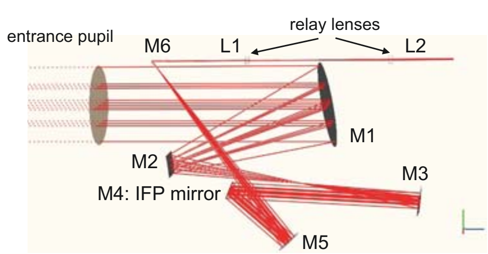
Figure 6 shows another design with better packaging and one additional mirror. The exit beam is going in the same direction as the beam coming off the primary mirror, which may make it difficult to use in a practical implementation. The scattered light performance is dominated by the final optical element. In this design, however, the scattered light from all of the mirrors is much higher in the minimal mirror design of Figure 5 with the addition of only one mirror. This result indicates that the details of the design and layout are important, not just the mirror count.



Scatterers	Rays	Power (W in 720 μrad)	RMS surf rough (Å)	CL
All	10046	1.6e-9	5	200
All except final mirror	23	1.5e-12	5	200

Figure 6: Repackaged in-field pointing design with 7 mirrors. This design meets the scattered light requirement only if there is no scattering from the final mirror.

The final design considered here, shown in Figure 7, includes some further repackaging plus a pair of relay lenses to try to push the exit pupil back toward the optical bench in a more realistic manner. The scattered light performance of the lenses is more complicated because in addition to scattering at the surface there is then generation of ghost beams from the reflections at the anti-reflection-coated interfaces. We found this design could meet the requirements only with unphysical near-perfect anti-reflective (AR) coatings and an unphysical non-scattering final lens. Further work would include a design with just mirrors, however it would be expected that those mirrors would contribute to the scatter given the proximity to the exit pupil.



Scatterers	Rays	Power (W in 720 μrad)	RMS surf rough (Å)	CL
All, 10^{-4} AR	38,633	6.8e-7	5	200
All, perfect AR	1,084,665	1.2e-7	5	200
All, perfect AR, no L2	3004	2.0e-11	5	200

Figure 7: In-field pointing design with 6 mirrors plus a relay lens pair. This design meets requirements only if there is no scattering from the final lens.

5. Summary and Next Steps

The results are summarized below:

- Minimum mirror count (6) (but poor packaging)
    - Meets the requirement with 5Å rms surface roughness and CL 200
- Minimum mirror count plus one (7) (better packaging, but unrealistic ray paths and clearances)
    - Does not meet the requirement with 5Å rms surface roughness and CL 200
    - Meets the requirement with no scattering from the final mirror
- With 6 mirrors plus 2 relay lenses
    - Does not meet the requirement with realistic parameters

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- Does not meet the requirements with perfect AR lens coatings
- Meets the requirement with perfect AR coatings and no-scatter lenses

Based on these results it does not seem that the scattered light increases in a simple way with the number of small mirrors in the back end of the design. It does suggest that the final optical elements tend to drive the scattered light budget. There has been no attempt to optimize the designs considered here, and that we have only shown that some simple in-field pointing designs do not meet the (simplified) scattered light requirements; we have not shown that it is impossible to do so. The results suggest that is important to consider the scattered light performance as part of the design process.

For the immediate next steps, it may be useful to extend the design with relay lenses to an all-reflective surfaces design to avoid the complication of AR coatings and ghost beams. Scattered light analysis of more realistic and optimized telescope designs than those considered here should be undertaken as well. It would also be useful to have a more realistic calculation for the stray light performance than the simplified metric considered for this study. Longer term, the modelling should be extended to include realistic light baffling and the telescope structure, as well as a better model of the receiver optics. Finally, we have neglected the contribution of thin films to the scattered light budget, such as those that might be formed from non-volatile residue in a space environment. We may need to consider this additional contribution to any scattered light analysis.

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