Cryogenic System for the Origins Space Telescope: Cooling a Large Space Telescope to 4 K with Today's Technology

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ABSTRACT

The Origins Space Telescope (OST) concept is one of four NASA Science Mission Directorate, Astrophysics Division, observatory concepts being studied for launch in the mid 2030's. OST's wavelength coverage will be from the mid-infrared to the sub-millimeter, 6-600 microns. To enable observations at the zodiacal background limit the telescope must be cooled to about 4 K. Combined with the telescope size (currently the primary is 9 m in diameter) this appears to be a daunting task. However, simple calculations and thermal modeling have shown the cooling power required is met with several currently developed cryocoolers. Further, the telescope thermal architecture is greatly simplified, allowing simpler models, more thermal margin, and higher confidence in the final performance values than previous cold observatories. We will describe design principles to simplify modeling and verification. We will argue that the OST architecture and design principles lower its integration and test time and reduce its ultimate cost.

Keywords: Cryogenics, cryocoolers, space telescopes

1. INTRODUCTION

The Origins Space Telescope (OST) concept is one of four NASA Science Mission Directorate, Astrophysics Division, observatory concepts commissioned for inclusion in the 2020 Astrophysics Decadal Survey. The Decadal Survey committee will recommend one or more of these missions to NASA for development leading to a potential launch in the mid 2030's. OST's wavelength coverage will be from the mid-infrared to the sub-millimeter, 6-600 microns. To enable observations at the zodiacal background limit the telescope must be cooled to about 4 K. The 9 m diameter primary allows faint signal collection of a factor of 100 greater than Spitzer, the largest coldest previous telescope. Combined with the telescope size (currently the primary is 9 m in diameter) this appears to be a daunting task. However, simple calculations and thermal modeling have shown the cooling power required is met with several currently developed cryocoolers. Further, the telescope thermal architecture is greatly simplified compared to the James Webb Space Telescope (JWST), allowing simpler models, more thermal margin, and higher confidence in the final performance values than previous cold observatories. We will describe design principles to simplify modeling and verification.

2. MOTIVATION

The far infrared part of the light spectrum (roughly 30-300 µm wavelength) remains a mostly underexplored wavelength region. These wavelengths are mostly blocked by the Earth's atmosphere, so only very strong emission lines are visible from the ground or airborne observatories such as SOFIA. To reach cosmic background limits the telescope must be cold. (See Figure 1.) The space missions that have operated in this wavelength region, Spitzer with a 5.5 K 0.9 m diameter primary, 6 year life and Herschel with an 80 K 3 m diameter primary and 3 year life have been flown. Both had limited life due to expendable liquid helium used for cooling. OST will use long life cryocoolers to reach telescope temperatures of 4.0 K with a 9 m diameter primary and at least a 10 year lifetime, big leaps in performance for all 3 parameters crucial to the far infrared. (See Figure 2.)

The mid-infrared wavelengths from 6 to 30 microns will also be well explored by the same telescope, taking advantage of the large cold optics and cold instrument accommodation to explore the spectral lines of exoplanets.

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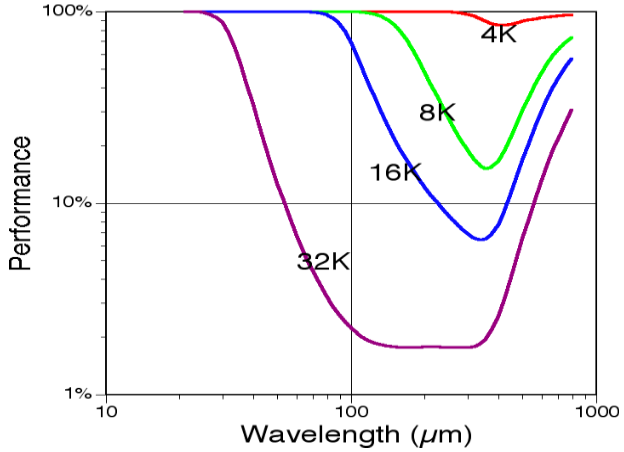

[Figure 1. Sensitivity reduction due to telescope temperature.]

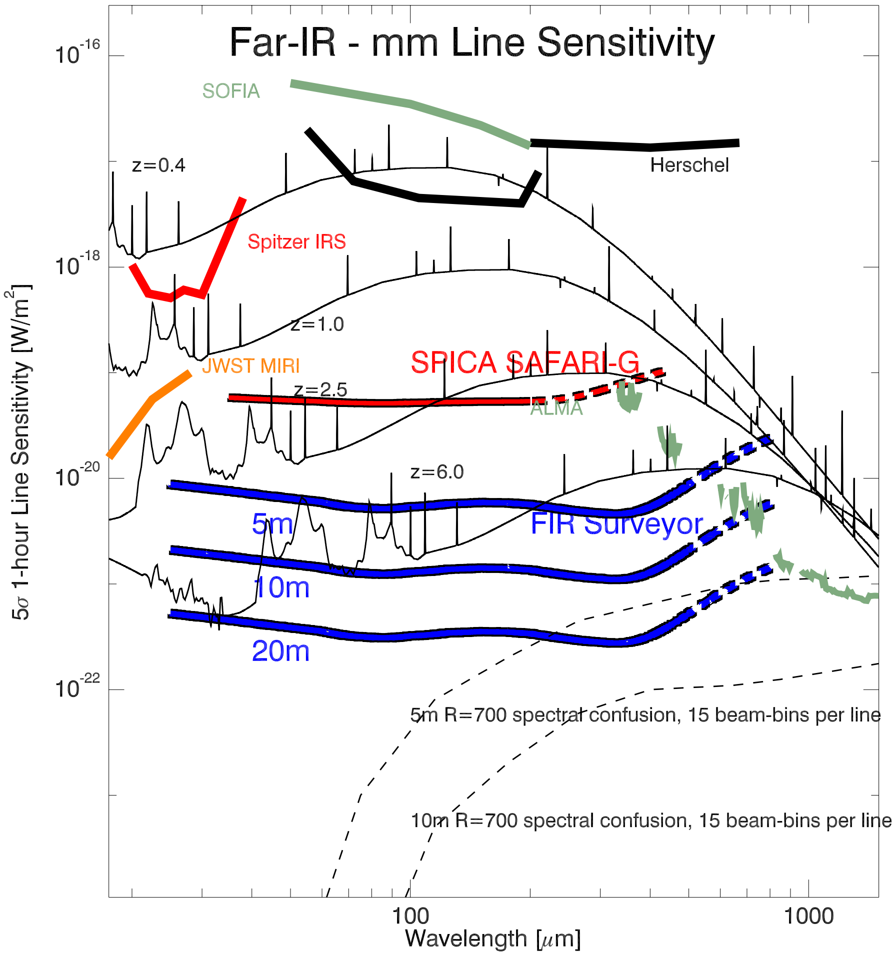

Figure 2. Line sensitivity of a 4.0 K telescope of different sizes (Labeled as Fari-IR Surveyor) for 1 hour of integration time.. OST would be close to the 10 m Far IR Surveyor indicated in blue.

3. MISSION ARCHITECTURE

An off-axis, unobscured telescope is desired to eliminate shadowing that could be an issue for exoplanet coronagraphy. The diameter of the telescope has been set by the maximum size that can be folded to fit in a 5 m diameter fairing, as exists for current rockets. This gives a 9.1 m diameter. The 1.3 m (flat-to-flat) of the 37 hexagonal segments lead to a hexagonal overall shape to the telescope (Figure 3). The low temperature requirements demand a cryo/thermal-centric design. The architecture uses passive thermal shields, mechanical cryocoolers, and sub-Kelvin coolers for the three far infrared instruments. For highest cooling efficiency, the cooling is staged: five layers of aluminized Kapton passive shields interleaved with three stages of cryocooling as shown schematically in Figure 4. Note that the sunshield must have high specularity for this scheme to work. Aluminized mylar or kapton does have a high degree (>98%) of specularity. It has been shown that providing staged cooling at the structural and wiring conductors that traverse the warm to cold regions allows the shield to achieve very low temperatures[1]. The instruments are housed in the Instrument Accommodation Module (IAM) in the 4 K zone. To prevent stray radiation from the sunshield entering the primary beam, a 4 K baffle is also provided to prevent any direct line of sight from the sunshield into the 4 K area.

The observatory will be located at the Sun-Earth Lagrange point L2 (SEL2). This location keeps the Sun, Earth, and Moon in a relatively small quadrant of the sky to enhance passive cooling.

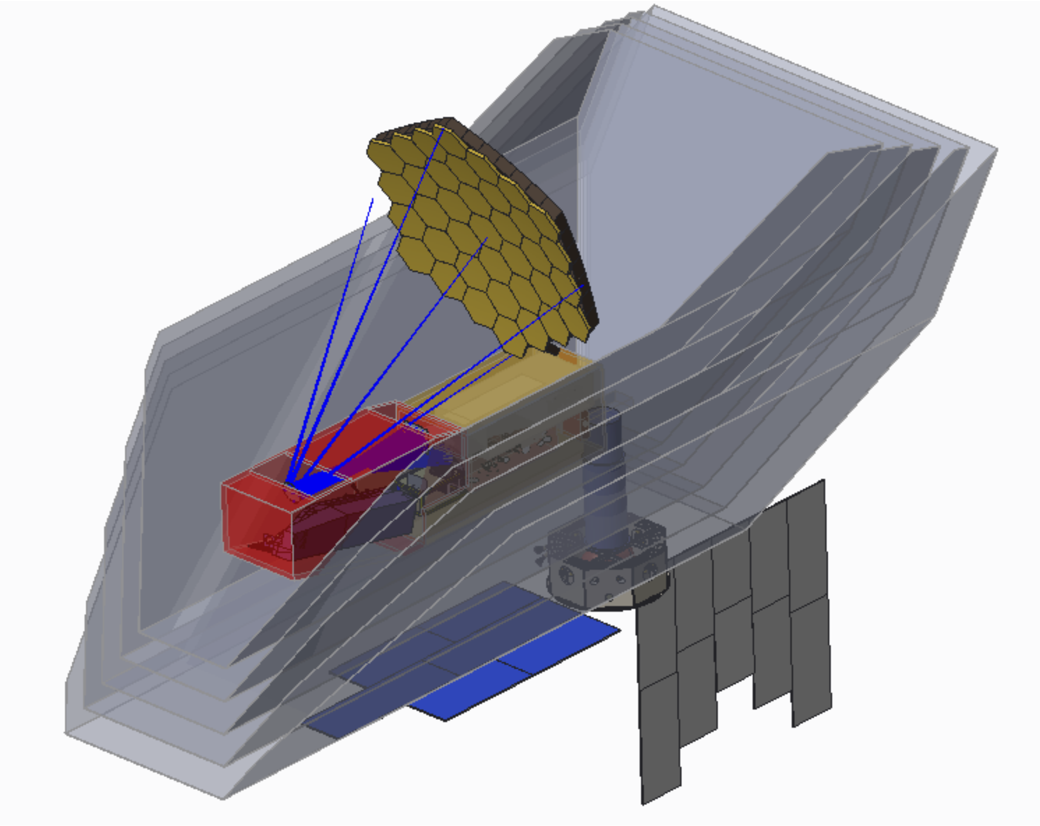

Figure 3. The Origins Space Telescope. The off-axis 9 m diameter primary is attached to the IAM which also houses the telescope secondary, the tertiary and field steering mirror as well as five instruments. The size of the outer sunshield layer is approximately 25 m x 16 m.

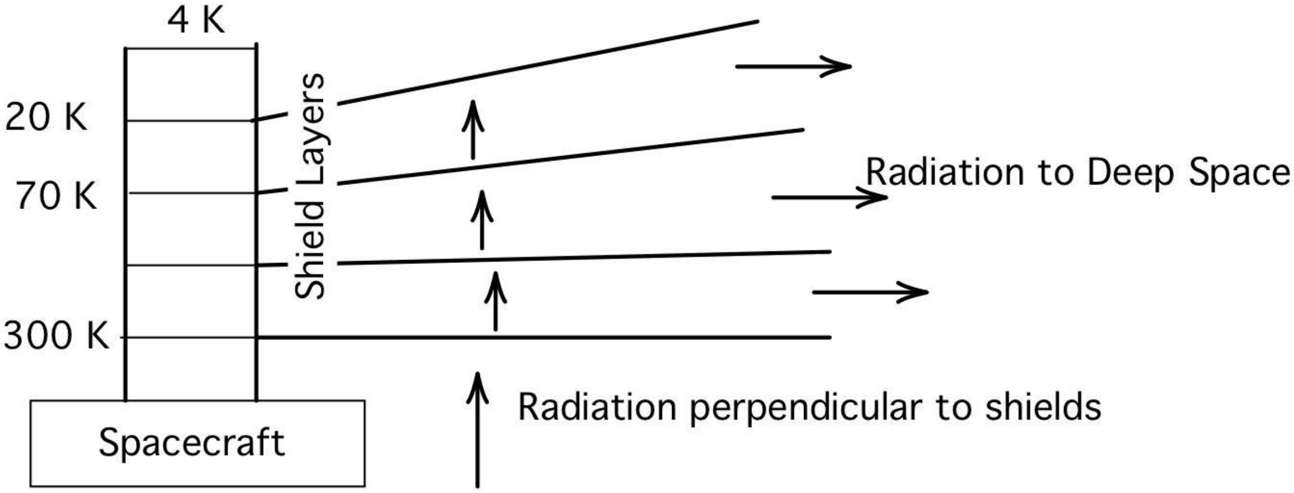

Figure 4. Cooling Schematic for OST. The sunshield is designed to reject heat flow perpendicular to the shields and radiate heat parallel to the shields.

A Thermal Desktop® model was set up for the radiative conditions of the sunshield and baffle, and the conductive heat loads were separately generated by spreadsheet calculations. The modeled sunshield is shown in Figure 3. The model predicts a radiative heat load to the telescope, instruments and 4 K baffle of 55 mW. Back of the envelope calculations result in 20 mW of conduction from structure, and 30 mW of conduction from harness traversing the warm spacecraft to the cold telescope. As a starting point, an allocation equal to the 4K telescope parasitic heat load was given to the instruments. At this concept stage of the mission, a factor of two is used as margin for the sizing of the cryocooling needed. At this preliminary stage the best estimate for heat load is ~200 mW, with cryocooling sized for double that. This requires 8 cryocoolers providing 50 mW of cooling each at 4 K for a total input power of 4 kW.

3.1 The Sunshield

The sunshield is designed to prevent radiation from penetrating from the warm to cold areas of the observatory, while radiating to deep space in the perpendicular direction Figure 4. The sunshield must shield Earth- and Moon-shine as well as Sun-shine and radiation from the warm spacecraft. At L2, depending on the orbit radius, the Earth and Moon rise up well above the Spacecraft to Sun line. Figure 5 shows this schematically. Combined with the Field of Regard (FOR) described below, the size of the sunshield is set.

The sunshield is a five-layer design with each layer separated by 0.75 m. This large separation means that wrinkles and possible thermal shorting of the layers is much less likely. It allows much more area fro radiation to deep space between layers than JWST. The current 5-layer design will be compared with 4-layer performance and with layers with slightly angled separations relative to each other. This design may then be updated.

The Field of Regard (FOR), not to be confused with the Field of View (FOV), is the instantaneous pointing angles required by the telescope out of the 4π steradians possible. Obviously pointing directly toward the Sun is not possible, but practical consideration of the sunshield make pointing much closer to the sun that 90° difficult as well. A sample calculation gives the results shown in Figure 6 for a simple flat sunshield. The telescope FOR is given by 360° in yaw, ± 5° in roll, and + 5° to -45° in pitch. The last requirement is to allowing continuous tracking of an object for 60 days. These requirements are the same as for JWST.

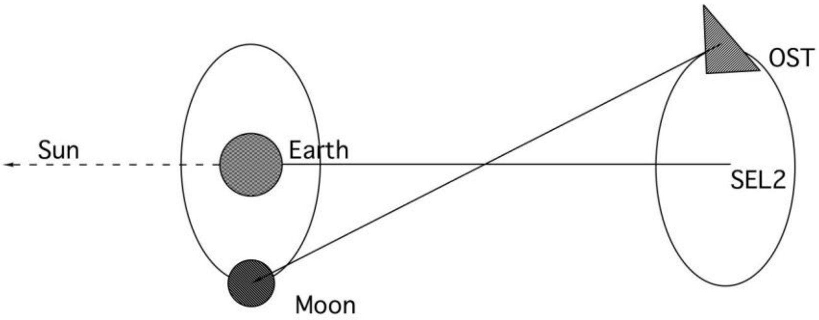

Figure 5. Schematic of SEL2 orbit illustrating the calculated keep-out angle.

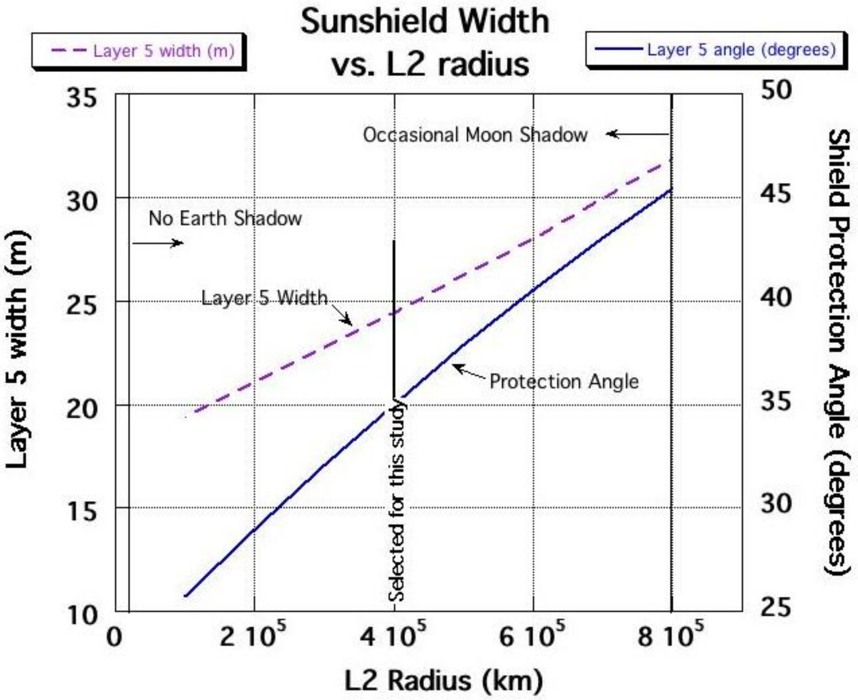

Figure 6. notional sunshield size vs. radius of SEL2 orbit. The SEL2 orbit radius selected for this study is 4 x 10^5 km, resulting in a protection angle of 35° and a coldest layer nominal dimension of 24 m.

Another important consideration is the torque on the spacecraft caused by solar pressure. This torque arises when there is an offset between the location of the observatory center of gravity (cg) and the center of pressure (cp). An accumulation of solar torque over time must be accomplished using propulsion or some active solar balancing. For a reflective surface perpendicular to the Sun line at SEL2, the solar pressure is 9 µPa. Figure 7 shows the magnitude of the solar torque for two different sunshield shapes. The first sunshield design used a flat geometry with the aft end canted upward to allow the pitch to rotate to -45°. The second design wrapped the shield layers around the telescope to achieve a lower projected area. Large portions of the shield had a more obtuse angle to the Sun vector, which also decreases the angle momentum. Note that the sunshield is highly specular. Further decreases in solar torque are possible, but in the end OST may require either a fixed solar trim tab, like JWST, or a moveable one to minimize the solar torque offloading.

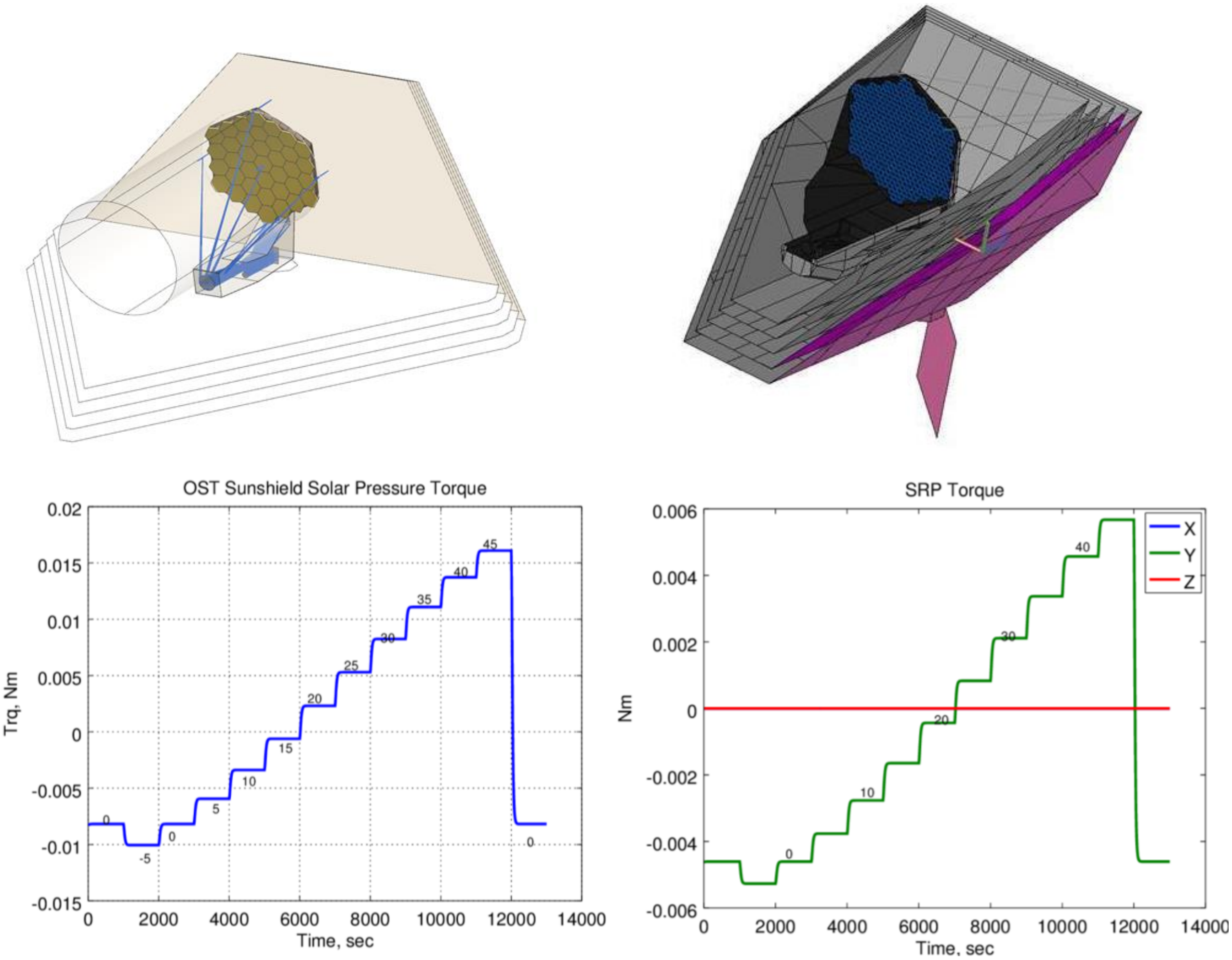

Figure 7. Solar torque estimates for two different sunshield shapes.

3.2 4 K Cryocoolers

The single biggest recent technology advance that enables OST are 4 K class cryocoolers. It started with the Advanced Cryocooler Technology Development Program (ACTDP) by NASA in the early 2000’s[ref Ross], bringing Northrop-Grumman’s, Ball Aerospace’s, and Lockheed Martin’s cryocoolers to TRL5.Further, the MIRI cryocooler was matured by JWST and Northrop to TRL 7. Other advances by Ball Aerospace, Lockheed Martin, Creare, Raytheon, and the flight of the JEM/SMILES and Hitomi 4.5 K cryocoolers by Sumitomo Heavy Industries have made these cryocoolers selectable for long duration missions. At temperatures below 40 K, mechanical cryocoolers have a tremendous cooling capability advantage over passive cooling, and allow designs to be achieved with less performance uncertainty. At this point OST is baselining multiple high TRL cryocoolers with 50 mW of cooling at 4 K, rather than expecting development of a higher power cryocooler. This also offers redundancy. The reliability of space cryocoolers is so high that in a survey conducted by Ron Ross, Jr.[3], no US-made mechanical cryocoolers, and only 2 Japanese-made cryocoolers have failed before the overall mission was ended. It is therefore expected that while there is mechanical redundancy in the present design, only the electronics powering the cryocoolers will be required to be redundant based on reliability studies.

3.3 Instrument Accommodations

In the current concept of OST there are 5 instruments covering the wavelengths of 6 to 600 µm both for imaging and for spectroscopy. Each of the instruments requires 4 K cooling in some way, and three of the instruments require sub-Kelvin cooling of the detectors. The 5 instruments are contained in the Instrument Accommodations Module (IAM), shown in Figure 8. A separate set of cryocoolers, similar to those used to cool the telescope, will be used to remove heat from these instruments.

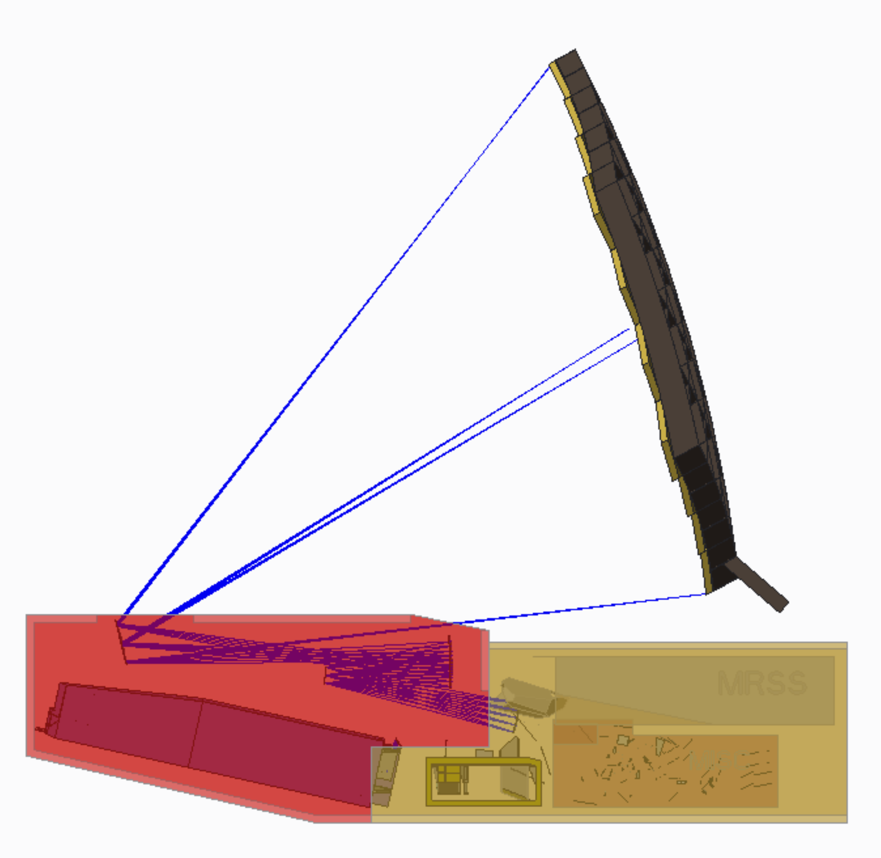

Figure 8. Instrument Accommodation Module. (IAM).The instruments are housed in the same structure containing the telescope secondary, tertiary, and field steering mirror.

To obtain high sensitivity in the far infrared, direct detectors are used. These commonly take the form of superconducting Transition Edges Sensors (TES), Microwave Kinetic Inductance Devices (MKID), or Quantum Capacitive Detectors (QCDs). All require cooling to below 100 mK to obtain their ultimate sensitivity; most require 50 mK. Adiabatic Demagnetization Refrigerators (ADR), flown on Hitomi[4] provide a high TRL method to achieve those temperatures. Enhanced cooling power with reduced mass is achieved by continuous ADR (CADR) demonstrated to TRL 4 in the early 2000s[5] cooling to 35 mK from a heat sink at up to 5 K. A team lead by Jim Tuttle is advancing this design to TRL6 within the next few years[œ] while also extending the upper end heat sink to 10 K. This machine will provide 6 µW of cooling at 50 mK compared to <1µW at 50 mK done for Hitomi. A CAD drawing of a possible OST CADR is shown in Figure 9.

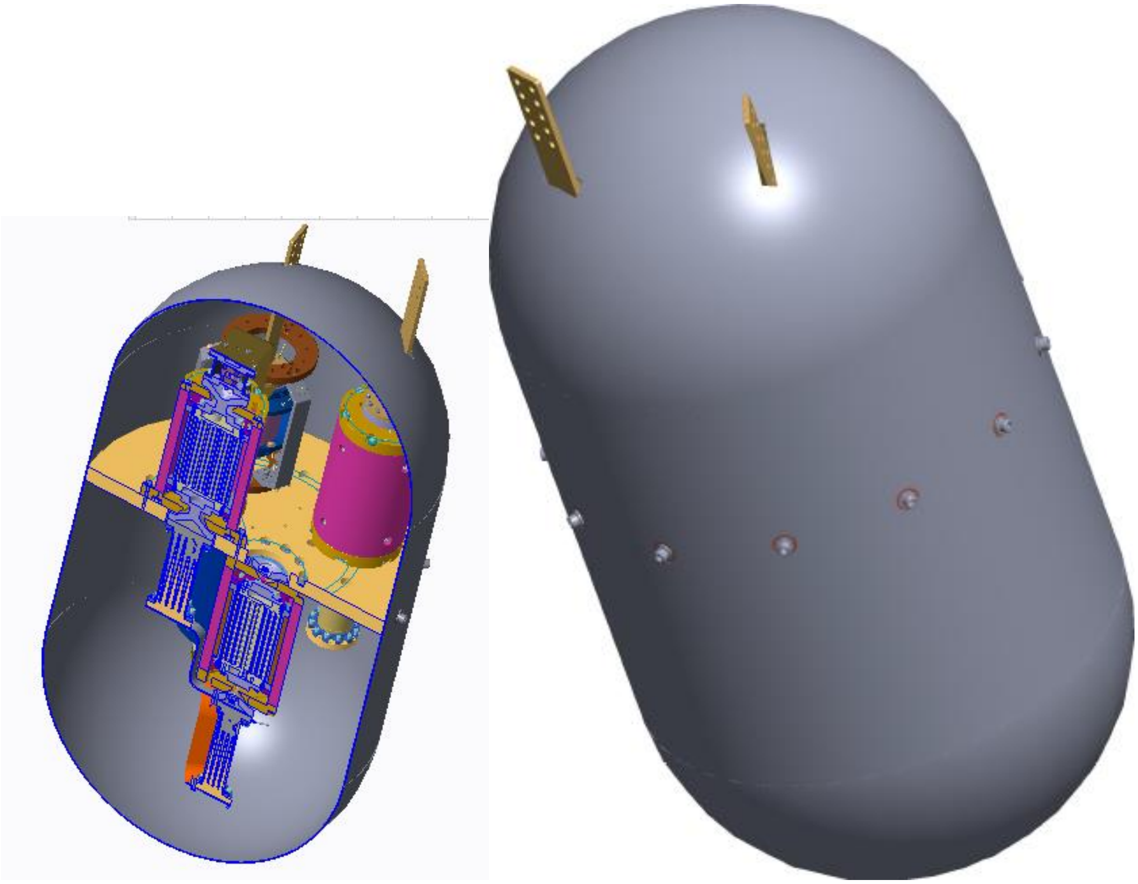

Figure 9. CAD drawing of a high cooling power sub-Kelvin cooler using the CADR concept. The basic dimensions are 44 cm long x 23 cm wide. The location of the component shown in the cutaway is flexible and may be reconfigured as needed.

3.4 The 4 K Baffle

Between the primary mirror and the IAM there will be a 4 K baffle. This baffle will be designed to keep radiation from the inner sunshield layer from striking any surface inside the IAM or primary, or the inside of this 4 K baffle. The baffle may be made of a simple sandwich of aluminum foil between two layers of Kapton. The outer Kapton surface will be aluminized and the inner surface will use black Kapton.

4. INTEGRATION AND TEST (I&T)

There is a high correlation of cost and duration of the ground development. The most expensive part of this development is the I&T phase. Shortening the I&T phase of OST is therefore a key component of cost savings.

Since the OST telescope will operate at 4 K, its optics must be figured to perform at this temperature. The normal process is to perform a figure polishing using the expected thermal contraction between room temperature and 4 K, then test, then repolish to take out the non-uniformities of the thermal contraction. For OST we plan to use materials that do not need this cryo-figuring step and thus save time and money in the fabrication process. Part of the reason that this is possible is that the diffraction limit is 40 µm rather than the 2 µm of JWST.

Aside from individual segments, the entire telescope must be brought into alignment such that its wavefront error is less than 1 µm. This cannot easily be accomplished on the ground due to 1-g sag of the mirror. Instead, each segment will have a large range of adjustment such that true focus can be achieved on orbit using a strategy of segment adjustment being pioneered by JWST. This lowers the test time and cost of this step in ground I&T.

5. OTHER MISSION CHALLENGES

This paper has concentrated on the cryogenic system: sunshield, cryocoolers, and sub-Kelvin coolers necessary for OST. There are taller poles in the design at this point. To make use of the large, cold telescope, large (~1-5x10^4 pixels), low background noise, far infrared detectors are required. The goal for the overall size and mass is that it fit in and existing rocket fairing and rocket launch mass to L2. Future large missions such as OST must be serviceable, so sunshield, IAM, and spacecraft must be designed to accommodate replacement, refueling, or refurbishment. The deployments must be reliable.

6. SUMMARY

The Origins Space Telescope has an exciting science case, with potential for discoveries over 2 decades of wavelength and allowing background-limited detection of faint signals. When combined with very sensitive far IR pixels in large arrays, it has many orders of magnitude higher mapping speeds at better sensitivities than the best far IR telescopes yet flown. The OST design presented here is derived extensively from lessons learned from previous space missions. OST has a cryogenic-centric design that utilizes key principles of cryogenic design, so that the cryogenic system is reliable, robust, and easy to verify.

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