Spherical Reflectors for Space Based Telescopes

Christopher K. Walket[1,4], I. Steve Smith[2], Paul F. Goldsmith[3], Stefan O'Dougherty[1], Yuzuru Takashima[1], Daewook Kim[1]

[1]University of Arizona, [2]Southwest Research Institute, [3]Jet Propulsion Laboratory, [4]FreeFall Aerospace

***Abstract*—The realization of a large, space-based 10+ meter class telescope for far-infrared/TeraHertz studies has long been a goal of NASA. Such a telescope could study the origins of stars, planets, molecular clouds, and galaxies; providing a much needed means of following-up on tantalizing results from recent successful missions such as Spitzer, Herschel, SOFIA, and, in the near future, JWST. Indeed, Herschel began its life in the US space program as the Large Deployable Reflector (LDR) – to be assembled in low Earth orbit by shuttle astronauts. Escalating costs and smaller federal budget allocations resulted in a downsizing of the mission. However, by combining break-through technologies utilizing spherical reflectors and inflatable structures, the dream of a 10+ meter class space telescope can be realized. The same telescope technology can also be used to perform sensitive, high spectral and spatial resolution limb sounding studies of the Earth's atmosphere in greenhouse gases such as CO, ClO, O3, and water, as well as serve as a high flying hub for any number of telecommunications and surveillance activities. In our paper we discuss the prospects of using inflatable, spherical reflectors to realize a ~25 meter TeraHertz Space telescope (TST).**

***Index Terms*— space telescopes, inflatable antennas, terahertz astronomy, far-infrared astronomy, deployable antennas**

I. Introduction

The TeraHertz Space Telescope (TST) utilizes breakthrough inflatable technology to create a large-aperture far-infrared observing system at a fraction of the cost of conventional space telescopes. As a follow-on to JWST, TST will revolutionize our understanding of the origin and evolution of galaxies, stars, and the interstellar medium. TST is an affordable 25m aperture FIR/THz mission concept that enables the exploration of this spectral regime in unprecedented detail and is an excellent match to NASA's Astrophysics Visionary Roadmap and the cost envelope of a Probe Class mission. Science themes include:

- Star formation through cosmic time
- Galaxy formation and evolution: from quasars, Seyferts, and starbursts to the Milky Way
- Life cycle of the interstellar medium
- Galactic ecology and astrochemistry
- Formation of solar systems: debris disks, protoplanetary evolution, Kuiper Belt objects, asteroids and comets, planetary atmospheres

A conceptual rendering of TST is shown in Figure 1. TST consists of 4 main components: 1) a 25 meter spherical mirror formed from a section of a larger inflatable structure; 2) an instrument module; 3) a spacecraft bus; and 4) an inflatable sunshade. The spherical mirror is simply a metalized portion of an otherwise transparent ~60 meter diameter sphere made of ~0.5 mil polyethylene terephthalate (PET) film, similar in size and material type to that used in the Echo Project in the early 1960's [1]. Light passes through the transparent, front hemisphere and reflects off of the metallized back hemisphere, the reflected waves coming to a focal line approximately halfway back towards the sphere's center. A spherical corrector, formed from a series of on-axis mirrors, then collapses the focal line to a focal point for the detectors. The instrument module contains the wide-field spherical corrector, metrology, fine pointing/focus, and astrophysical detection systems. It is held in position by thin dielectric support curtains that stretch across the sphere's interior orthogonal to the incoming light. The spacecraft bus provides power, telecom, and command/control. The sunshade is made using the same materials and inflation technology as the spherical primary and enables cooling of the telescope to ~50K.

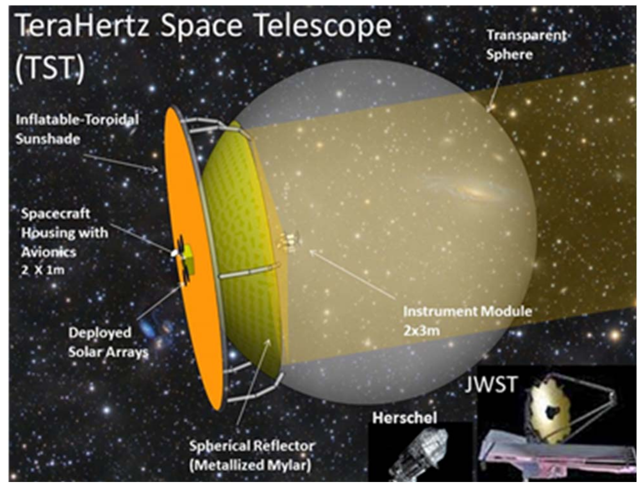

Fig. 1. The TST 25m spherical reflector is formed from the metalized portion of an otherwise transparent ~60 meter diameter sphere made of ~0.5 mil acetate film. Internal dielectric structural curtains are used to define a spherical surface figure and differential pressure control is used to maintain it throughout the mission. The instrument module is held at the nominal focal position by dielectric curtains and houses an adaptive spherical corrector, as well as coherent and incoherent imaging systems. The spacecraft bus provides power, station keeping, coarse pointing, and communications. JWST and Herschel are shown to scale.

The innovative use of inflatable technology makes a very large aperture telescope affordable by obviating the need for complex deployment and packaging. It also makes feasible a spherical primary mirror, as opposed to a typical parabolic mirror, providing a much larger field of view that can be electronically steered to greatly simplify operations and save precious observing time. This unique combination of aperture size, wide FOV, and cooling make TST a powerful and poten-

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tially revolutionary tool for exploring the near and distant Universe.

II. Mission and System Concept

The TST concept as presently envisioned calls for a 5 year mission duration, most likely at Sun-Earth L2. The spacecraft is 3-axis stabilized with a relative pointing capability of ~0.1 arcsec, launch mass of ~600 kg, and stowed dimensions ~2x4 m. At launch the uninflated sphere is folded around the instrument module and the whole assembly stowed within the spacecraft bus. Once the spacecraft reaches its target orbit, low pressure neon gas (~10^{-5} psi) is used to inflate the sphere, and the instrument module naturally deploys along with it. A combination of pressure sensors, strain gauges, and cameras determines when the sphere is fully deployed, and a gas reserve and pressure control system is used to maintain optimum tension and stress levels within the sphere throughout the mission. The sunshade maintains the telescope at the desired ~50 K operating temperature, and a cryocooler system further cools the detectors to ensure adequate sensitivity. Coarse pointing is achieved by reaction wheels within the spacecraft bus, and fine pointing is achieved by an adaptive mirror within the spherical corrector contained in the instrument module.

A plot comparing TST to several past, present, and proposed far-infrared missions/concepts is shown in Figure 2. TST will pick up where JWST leaves off. It is designed to operate between ~30 and 300 µm and provide angular resolutions of ~0.3 to 3 arc seconds, with 5σ sensitivities of ~$2x10^{-21}$ W/m^2 in one hour of integration. TST will carry coherent detectors for high resolution spectroscopy and incoherent detectors for low/medium resolution spectroscopy [2,3]. Significant advantages for TST over competing concepts include (1) not requiring active cooling of the telescope, (2) achieving high sensitivity irrespective of source strength, (3) ~50x lower confusion limit than *Herschel*, and (4) being much less demanding in terms of detector performance (*i.e.,* noise equivalent power (NEP)). Due to its large collecting area and ~50K operating temperature, TST can utilize detectors with ~100x higher NEP than those required for cryogenically cooled telescopes and still meet the sensitivity requirements of many of the science objectives envisioned for NASA's Far-Infrared Surveyor. This relaxed sensitivity requirement greatly eases the technical challenge of detector design and implementation.

III. Inflatable Spherical Corrector

Spherical mirrors have been used in telescopes since the time of Isaac Newton. Large modern ground based telescopes utilizing spherical reflectors include the 305 meter Arecibo telescope (radio) and the 10 meter Hobby-Eberly Telescope, HET (optical). Furthermore, inflatable spherical structures of the type and size needed for TST were deployed in space decades

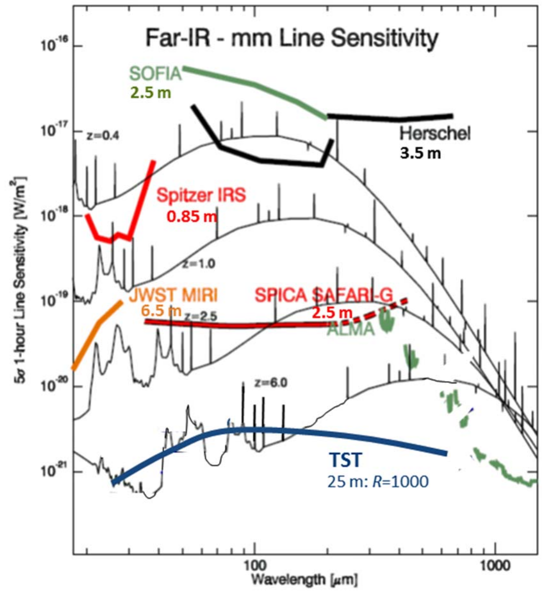

Fig. 2. TST sensitivity compared to past, present, and proposed Far-Infrared/TeraHertz missions. The large aperture of TST results in major advantages in terms of scientific performance and simplicity of implementation. (SED template from Bradford, FIR Surveyor STDF).

ago, including the 30.5 m Echo 1 in 1960 (Clemmons 1964), the 41 m Echo 2 in 1964 (Staugaitis and Kobren 1966), and the 30.5 m PAGEOS in 1974 (Zerbini 1980). The metallized Mylar film spheres worked as passive reflectors, bouncing terrestrial signals off their surfaces back down to receiving stations on the ground. These two development tracks merged for the first time in our NIAC work to design low-cost, high performance spherical reflectors for THz observations from suborbital and space-based platforms. Over a ~3 year period our team designed, built, and tested 3- and 5-meter scale models of inflatable spherical reflectors. Together with more recent work, this shows that a wide-field, high performance ~25 meter THz space-based telescope can be achieved utilizing a ~60 meter diameter inflatable sphere and a ~2 meter spherical corrector. The inflatable sphere should be made from low-loss dielectric material with a high degree of sphericity. For acceptable aperture efficiency (~0.8 Strehl ratio), the sphere must hold its figure to a "peak-to-valley" (P-V) of ≤ λ/8 of the wavelength of interest. The surface roughness should be ≤ λ/30; thus at its shortest operating wavelength (~30 µm) the

Fig. 3. Dielectric film as an optical element. Saran wrap deformed by a partial vacuum reimages the NASA logo

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TST sphere surface roughness needs to be ~1 μm and its spherical figure held to ~4 μm. The required surface roughness is known to be achievable for dielectric films under pressure (see Figure 3). Recent FTS measurements performed by our team show that thin, ~0.2 and 0.5 mil films of CP1® (for example) are ~98% to 80% transparent through the FIR/THz spectrum. During the TST concept study we will further explore and test materials and fabrication techniques to arrive at an optimum design. Rigidizable materials, as used on Echo 2, are also being investigated; these materials stiffen after inflation and enable the balloon to maintain its shape without a constant internal pressure, making it relatively immune to the effects of micrometeroids. Even without rigidization, preliminary analyses indicate the lifetime of a 40 meter sphere to be > 5 years in the relatively benign environment of L2 [4] with gas replenishment.

IV. Lightweight Adaptive Spherical Corrector

A spherical corrector is an integral element of all spherical reflectors, required to collapse the reflector's focal line to a focal point and take advantage of the wide FOV intrinsic to the reflector. At Arecibo the spherical corrector consists of two off- axis mirrors with an intermediate focus between them, referred to as a "Gregorian corrector" [5]. In the case of the HET, the spherical corrector consists of 4 on-axis mirrors [6]. Preliminary analyses performed under the NASA Innovative Advanced Concept (NIAC) indicate that distortions are expected to be large-scale (over ≥1 meter) and slowly varying (over minutes to hours). The corrector should be able to operate at temperatures ≤50K, have sufficient FOV to make efficient use of the reflector surface, and have focus and fine pointing control capabilities. The Arecibo off-axis system has the advantage of requiring only two mirrors, but suffers from a limited FOV (~1 arcmin). The HET corrector (see Figure 4) requires twice as many mirrors but has the advantage of a ~0.5° FOV from 30 to 300 μm. Preliminary designs indicate the corrector can support medium and high resolution arrays of ≥10^4 pixels.

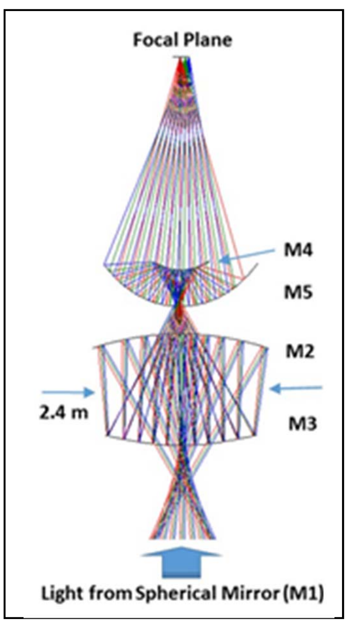

Fig. 4. TST wide-field Spherical Corrector, based on the successful design for HET, provides FOV ~0.5°.

V. Surface Metrology and Figure Control

Both on and off axis correctors assume incoming rays originate from an ideal spherical surface. However, even with the proper choice of materials and careful manufacture, microgravity, differential pressure, on station attitude adjustments, and other forces may lead to non- spherical distortions. Our analyses suggest that distortions will occur over large physical and temporal scales (>1 meter and minutes to hours) with peak amplitudes of between ~1 and 5 mm. The shape of the TST spherical reflector will be measured in situ at optical wavelengths using established deflectometry techniques [7]. An adaptive mirror located at the conjugate plane of the spherical primary will be used to compensate for non-spherical distortions. Under NIAC our team built a working breadboard of a figure control system using deformable mirror material attached to small actuators. This will be further investigated during the TST mission concept study to determine the optimum approach, expected performance, and development pathway leading to an integrated system suitable for TST.

VI. Conclusion

Space-based inflatable spherical reflectors are a game-changing technology that has the potential of making the dream of space-based 10+ meter telescopes a reality. Looking outward, such telescopes would provide an unprecedented view of the distant universe, as well as detailed studies of young planetary systems and solar system objects. Looking downward, such telescopes will similarly provide an unparalleled view of the Earth for remote sensing activities. The key TST technologies are well understood, having been investigated and prototyped during our NIAC study and other related work. The concept is scalable from microwave to terahertz frequencies.

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