THE DART SYSTEM FOR FAR-IR/SUBMILLIMETER SPACE MISSIONS

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1. Introduction. The current generation of telescopes, both ground and space based, can trace their design and fabrication methods back to the original telescopes of the 17th century[1]. There is no *a priori* reason that a space telescope should look anything like a ground based one. In the space environment the mechanical elements of the telescope are in free fall and hence do not feel the effects of gravity (other than tidal forces, which are too small to have any effect), so constraints imposed by gravity are nonexistent. Nor is there any reason that the traditional methods of fabrication, essentially the rubbing of two pieces of glass together with some abrasive grit in between, should be used to figure the optical surfaces used in a telescope. The overriding consideration is that the space telescope be large, lowmass, and diffraction limited over a reasonable field of view.

The DART[2] is a system of two cylindrical-parabolic reflectors. One reflector will produce a line focus; two reflectors, properly oriented, will produce a point focus. This system is ideally suited to using tensioned membranes for the reflective elements, and hence a lowmass telescope system. For FarIR/submillimeter missions the DART presents a compelling new telescope architecture that is scalable to large apertures, and with its large membrane area is well suited to passive cooling. Two other white papers are referencing the DART system as a possible telescope to enable each mission concept.

2. DART Optical Layout and Analysis. An intrinsic property of any surface is its Gaussian curvature. A surface with zero Gaussian curvature is either flat or has the shape of a trough, so that one of the principal curvatures is always zero. Such a surface can be formed by tensioning along only one axis. If the shape of the surface in the curved direction is a parabola, then a line focus results for an incident plane wave. To produce a point focus, a system of two trough-shaped reflectors properly oriented with respect to each other must be used. A perspective view of such a system is presented in figure 1.

In order for this system to focus and have a completely unobstructed aperture the focal lengths of the two individual reflectors must be unequal. The aberrations of the system are identical to those of an off-axis paraboloid with focal length f_1 in the direction which the first reflector focuses, and f_2 in the orthogonal direction, with the subscripts referring to the first or second reflector. For the specific system displayed in figure 1, the extent of the focal surface is ± 25 resolution elements[3] fully sampling the

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[*] JPL: E.Cohen, J.Dooley, A.Chmielewski; Lockheed-Martin: J. Tolomeo, G. Cross, D. Tenerelli, P. Forney

[1] e.g. Gregory(1663), Newton(1668), and Cassegrain(1672)

[2] Dual (or Dragovan) Anamorphic Reflector Telescope; Astro-ph/0001241

[3] A resolution element is the *radius* of the Airy disk.

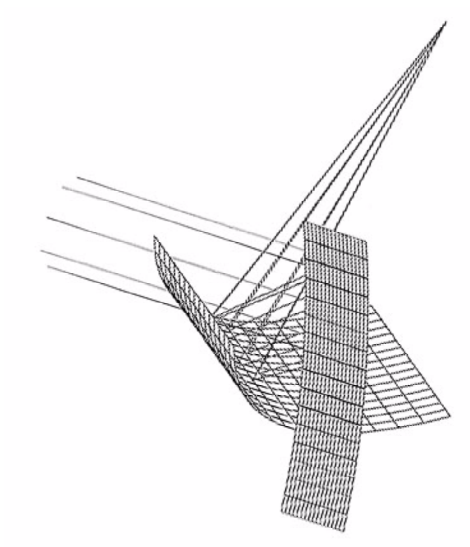

FIG. 1. The layout of a two mirror reflector system where the individual reflectors are parabolic cylinders. The orientation and curvatures of the individual reflectors are chosen so that a point focus results for an incident plane wave. The reflectors as illustrated are greatly oversized to emphasize the curvatures of each reflective element. It is clear by inspection that the system is completely unobstructed. What is less obvious is that the system has a reasonable field of view, as illustrated in figure 2.

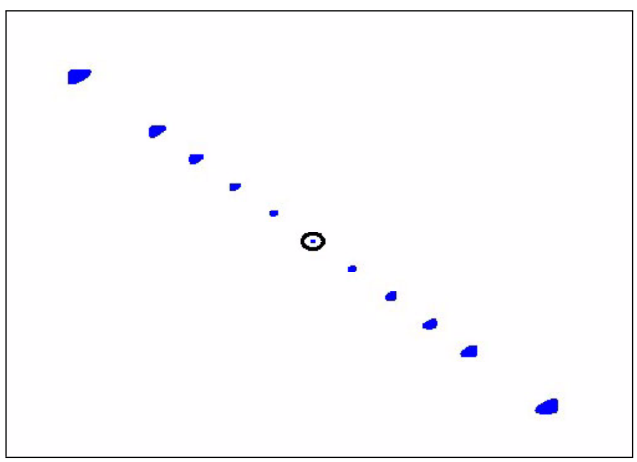

FIG. 2. *A geometrical optics ray tracing spot diagram for the DART system of figure 1. The Airy disk is illustrated by the ellipse at the center. The Strehl ratio is greater than 0.75 over the* ± 25 *resolution element field illustrated; thus most of the field is diffraction limited. The field of view scales as* $f_1 \cdot f_2$.

focal surface. The Airy disk is not circular, but has eccentricity

$$e = (1 - (f_1/f_2)^{-2})^{1/2}.$$

For the system shown in figure 1, $f_1/f_2 = 4/3$ or $e = 0.66$.

In figure 2 is displayed a geometrical ray trace of the $f4/3$ layout. The aberrations scale with the product of the individual focal lengths $f_1 \cdot f_2$ since the dominant aberration

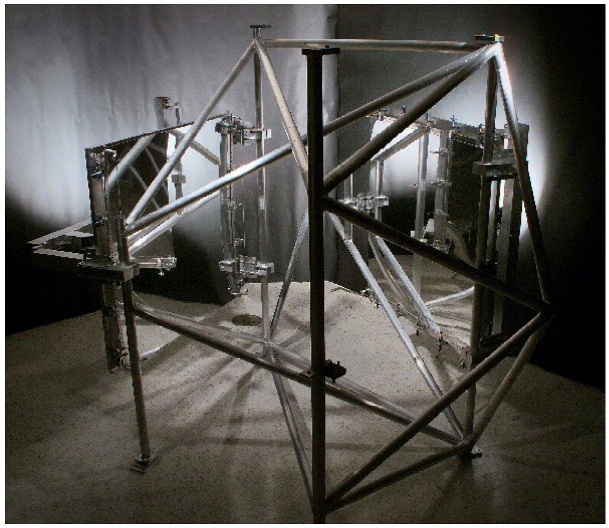

Fig. 3. *The two reflectors are mounted on a rigid truss structure. The reflector on the left has a six degree of freedom mount to allow for precision alignment of the system. A collimated beam enters from the left, hits the righthand mirror, continues on to the left most mirror, and exits the system on the right.*

is coma, similar to a traditional optical system where the comatic aberration scales as f^2.

The parabolic-cylindrical surfaces are formed by tensioning a reflective foil over a frame which has a parabolic contour along one axis and is rigid enough to support the tensioning. The alignment of the two reflectors is critical to the performance of the system. An arrangement of sixadjustable rigid struts connecting the two reflectors completely constrains all degrees of freedom while allowing the adjustment of the relative orientation of the two reflectors[4].

3. Physical Implementation of the DART System. A 1.2 m DART prototype/testbed was developed under the New Millennium Space Technology 6 study phase program. The working system (located at Lockheed-Martin in Sunnyvale, CA) is diffraction limited at 40 μm, and has a mass density of 7kg/m^2 for each individual reflector. Figures 3 and 4 illustrate the system, and demonstrate the imaging capability at 10μm. The constructed system was designed, built and tested in less than 8 months.

4. Discussion.

4.1. Shape Control. The shape of the reflective surface is determined by the tensioning of a membrane over a stiff boundary. The shape of the boundary is determined by the bending of a beam. By choosing the correct application of forces and moments at the edge of the beam a parabolic shape is obtained[5].

The membrane surface will have predominantly a cylindrical shape with a slight negative curvature due to the Poisson effect (the fact that a material shrinks a small

[4] Stewart, D. 1965 *Proc. Instn. Mech. Engrs.* **180**, 371.
[5] J. Tolomeo, ST6 Final Report, Aug. 2001.

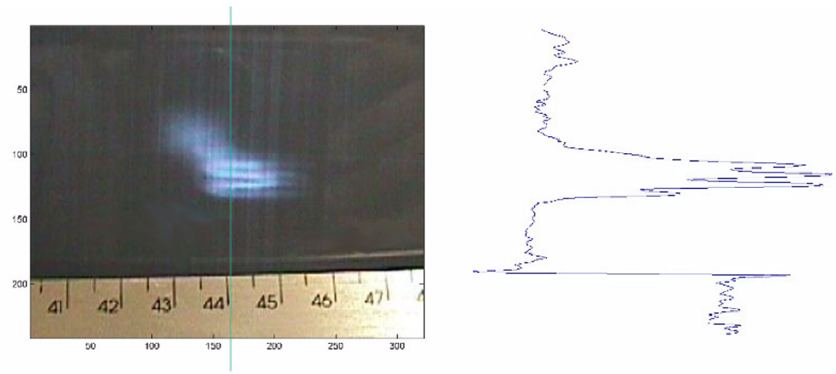

FIG. 4. *The image of a hot coil of wire as imaged through the DART system at 10μm. The intensity profile is displayed to the right of the image. The peaks are clearly evident. The ghost to the upper left is residual scattering from a slight misalignment of the collimator. The image is not sharp because the telescope is diffraction limited at 40μm.*

amount in the direction perpendicular to the applied force). Several methods are being investigated to minimize this effect; for the FarIR the magnitude of the effect is less than $\lambda/10$.

4.2. Scaling relations. Current technology millimetric telescopes have densities of order 10kg/m^2, a factor of $\sim 10^3$ between the mass of the reflecting layer and that of the support structure. For optical telescopes the situation is much worse where the current state-of-the art has density of order 150kg/m^2; the supporting substrate a factor of $\sim 10^6$ more massive than the reflecting layer.

The areal density of the reflecting layer is given by $\sigma_r = \rho_r t$ with t the thickness of the reflecting layer, and ρ_r the density. The thickness of the reflecting layer of a high electrical conductivity metallic film can be determined, to good approximation for a specific reflecting material, by considering the skin depth

$$\delta = 1/\sqrt{\pi c \mu \sigma_e / \lambda},$$

where σ_e is the conductivity of the reflecting surface, λ is the wavelength, and $\mu = 400\pi\text{nH/m}$. With a thickness of $t = 5\delta$, the surface is opaque and the wave is reflected with low loss[6]. For a very good conductor such as copper $\sigma_e = 5.7 \times 10^7 (\Omega\text{m})^{-1}$. In the case of optical light ($\lambda = 0.5\mu\text{m}$) the film only has to be $\sim 50\text{nm}$ thick to reflect the incident light; for millimeterwaves ($\lambda = 1000\mu\text{m}$) a $\sim 1\mu\text{m}$ thickness is required. This gives an areal density $\sigma_r \sim 8 \times 10^{-3}\text{kg/m}^2$ in distinct contrast to the areal density of the substrate material, which can be many orders of magnitude greater.

By examining existing telescopes one finds that the areal mass density of the supporting substrate (generally some form of glass) is $\sigma \propto d^\beta$, where d is the aperture diameter and $\beta \sim 0.5$. This is independent of the technology used, or the epoch when

[6] Goldsmith, P. *Quasioptical Systems*, IEEE Press, 1998.; Bock et al. *Applied Optics* **34**, 4812-16 (1995).

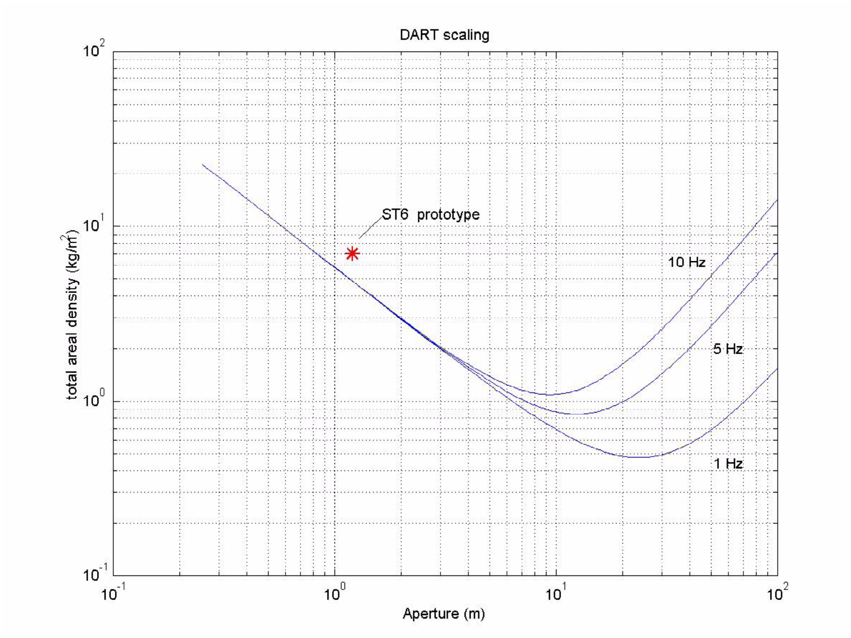

Fig. 5. *A scaling relationship for DART telescopes. The existing prototype has an areal mass density of 7kg/m^2, falling just above the theoretical line.*

the telescope was constructed. In comparison, the areal density of a membrane reflector system scales differently, and is straightforward to calculate. For the reflective membrane

$$\sigma_r(d) = \rho_r t_r(d).$$

For the supporting boundary

$$\sigma_b(d) = 4\rho_b h(d)\Delta d/d$$

where $h(d)$ is the functional dependence of the boundary thickness with diameter, and Δd is the width of the boundary. The total density is simply the sum

$$\sigma(d) = \sigma_r(d) + \sigma_b(d) = \rho_r t_r(d) + 4\rho_b h(d)\Delta d/d.$$

The areal density decreases with greater aperture; only if the ring has $h(d) = h_o(d/d_o)^\alpha$ with $\alpha > 1$ does σ grow with d,

$$\sigma(d) = \rho_r t_r(d) + 4\rho_b\left(h_o/d_o\right)\left(d/d_o\right)^{\alpha-1}\Delta d.$$

A more detailed numerical analysis can be performed, with the results presented in figure 5. The results have the same characteristic shape: that a membrane telescope has a mass density that decreases with increasing aperture size.

This is in distinct contrast to the scaling relationship for existing telescopes, $\sigma \propto d^{0.5}$. Thus, not only is a membrane reflector less massive to begin with, but the areal density can actually *decrease* with larger apertures if the ring and membrane are appropriately chosen. Clearly, the areal density of a telescope system can be reduced by orders of magnitude if the relatively massive supporting substrate can be minimized while maintaining the desired reflective surface.

5. Summary.

5.1. Key elements of the DART system:.

- An arrangement of clyndrical-parabolic reflectors can be made that will focus light from a distant source to a point, without any obstruction to the incident beam.
- The aberrations of such a system are dominated by coma and are similar to those found at the prime focus of a standard parabolic reflector. The diffraction limited field of view of such a system is large enough to accommodate a large format FarIR array.
- The individual reflecting surfaces can be constructed using low areal mass density membranes, with the consequence that the mass density of a complete telescope can approach 1kg/m^2.
- Low cost for large apertures.
- Well suited for passive cooling.

5.2. Recommendations for future development of the DART system:. The remarkable simplicity of the DART design enables the rapid fabrication of a low cost, high quality telescope. A number of subsystems are in the initial stages of study and need to be aggressively pursued:

- Investigating auxiliary optics that will widen the field of view. An initial design has increased the field of view by a factor of 10.
- Identify and develop technology to produce large high quality reflective membranes. The DART prototype used commercially available metal and polymeric membranes. Scalable solutions for high quality membranes at least 10 meters wide are being investigated.
- A 5m DART could be built within one year, with sufficient funding. This would demonstrate scalability from our current prototype to a size useful for a science mission.
- Demonstrate a cooled DART system in a space environment using a low cost, near term science and technology mission.