Appendix C. The DART System

Background
In Section VI, we briefly reviewed the Dual Anamorphic Reflector Telescope (DART) concept as being a possible architecture for a single-aperture large far infrared and submillimeter telescope. While we believe that the technology for DART is not yet well developed enough to support such a near-term implementation of SAFIR, our team believes that such a concept has a large potential for a following generation of telescope with a much larger focal plane aperture, and technology investment in it therefore offers important long-range science potential. In this spirit, we include in our report the following more detailed description of DART.

DART (Astro-ph/0001241) 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.

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.

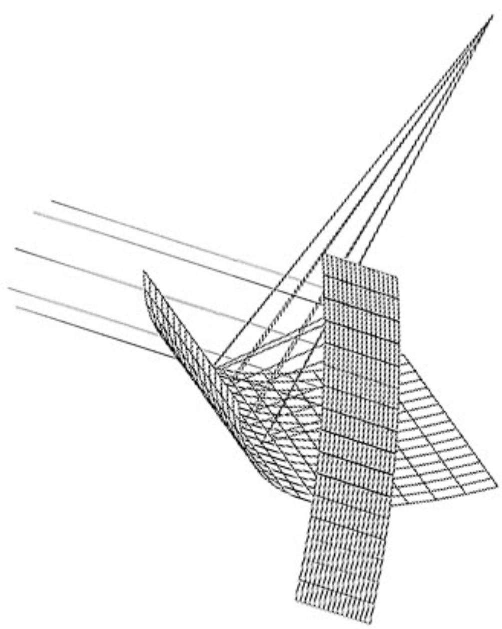

Figure 1: The layout of a two mirror reflector system where the individual reflectors are parabolic cylinders. The orientation and curvatures of the individual reflectors are chosen so that a point focus results for an incident plane wave. The reflectors as illustrated are greatly oversized to emphasize the curvatures of each reflective element. It is clear by inspection that the system is completely unobstructed.

The aberrations of the system are identical to those of an off-axis paraboloid with focal length f_l 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 100x100 resolution elements fully sampling the focal surface. The Airy disk is not circular, but has eccentricity $e=sqrt(1-(f_l/f_2)^{-2})$ and for the system shown in Figure 1, $f_l/f_2=5/3$ or e=0.8.

In Figure 2 is displayed a geometrical ray trace of the 5/3 layout. The aberrations scale with the product of the individual focal lengths $f_l \bullet f_2$ since the dominant aberration is coma, similar to a traditional optical system where the comatic aberration scales as f^2.

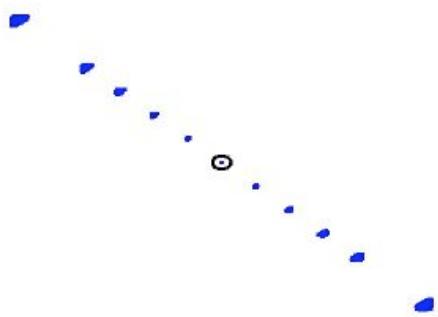

Figure 2: The parabolic-cylindrical surfaces are formed by tensioning a reflective foil over a frame which has a parabolic contour along one axis and is rigid enough to support the tensioning. The alignment of the two reflectors is critical to the performance of the system. An arrangement of six adjustable rigid struts connecting the two reflectors completely constrains all degrees of freedom while allowing the adjustment of the relative orientation of the two reflectors (Stewart, D. 1965 Proc. Instn. Mech. Engrs.180, 371.).

Physical Implementation of the DART System

A 1.2 m DART prototype/testbed was developed under the NASA New Millennium Space Technology 6 study phase program. Lockheed partnered with JPL for the initial work on the first DART telescope, with funding provided by the New Millennium ST-6 experiment. The result was a success, with a functional prototype produced in four months. With further work after the project ended, the Lockheed group produced an image of a hot target through the complete optical system. The interest has continued with a deployment concept that can enable the launch of a 10 m class DART system. The working system (located at Lockheed-Martin in Sunnyvale, CA) is diffraction limited at 40 µm, and has a mass density of 7 kg/m^2 for each individual reflector. The following figures illustrate the system, and demonstrate the imaging capability at 10 µm.

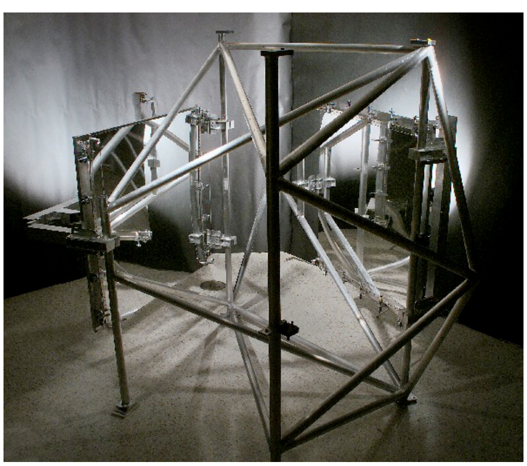

Figure 3: The two reflectors are mounted on a rigid truss structure. The reflector at left has a 6-degree of freedom mount to allow for precision alignment. A collimated beam enters from the left, hits the righthand mirror, continues on to the left most mirror, and exits the system on the right.

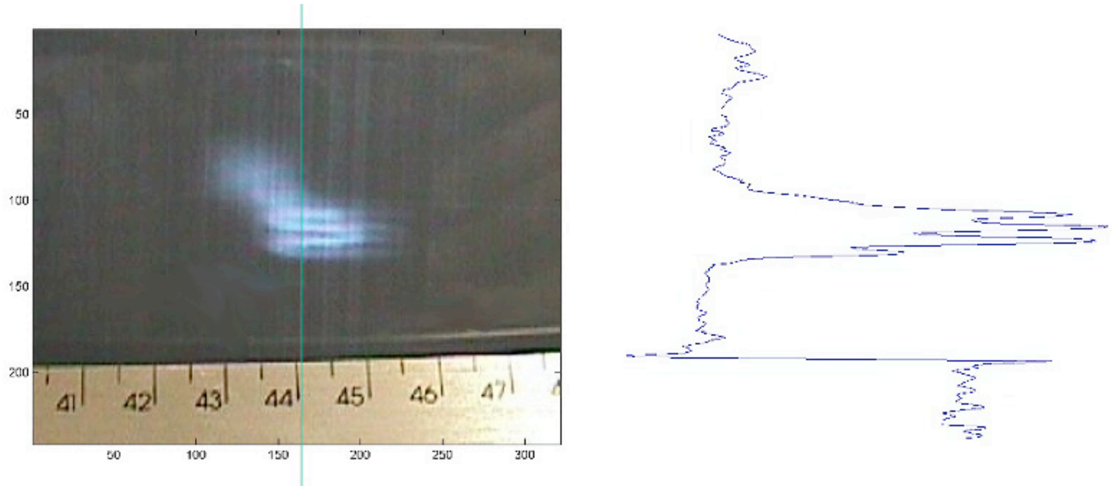

Figure 4: The image of a hot coil of wire as imaged through the DART system at 10μm. The intensity profile is displayed to the right of the image. The peaks are clearly evident. The ghost to the upper left is residual scattering from a slight misalignment of the collimator. The image is not sharp because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

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 (J. Tolomeo, ST6 Final Report, Aug. 2001).

The membrane surface will have predominantly a cylindrical shape with a slight negative curvature due to the Poisson effect (the effect that a material shrinks a small amount in the direction perpendicular to the applied force). Several methods are being investigated to minimize this effect; for the far-IR the magnitude of the effect is less than $\lambda/10$.

Scaling relations

Current technology millimetric telescopes have densities of order 10 kg/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 150 kg/m^2; the supporting substrate a factor of $\sim 10^6$ more massive than the reflecting layer.

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 the telescope was constructed. In comparison, the areal density of a membrane reflector system scales differently, and is straightforward to calculate. The results are presented in Figure 5 below. The results have the same characteristic shape: that a membrane telescope has a mass density that decreases with increasing aperture size.

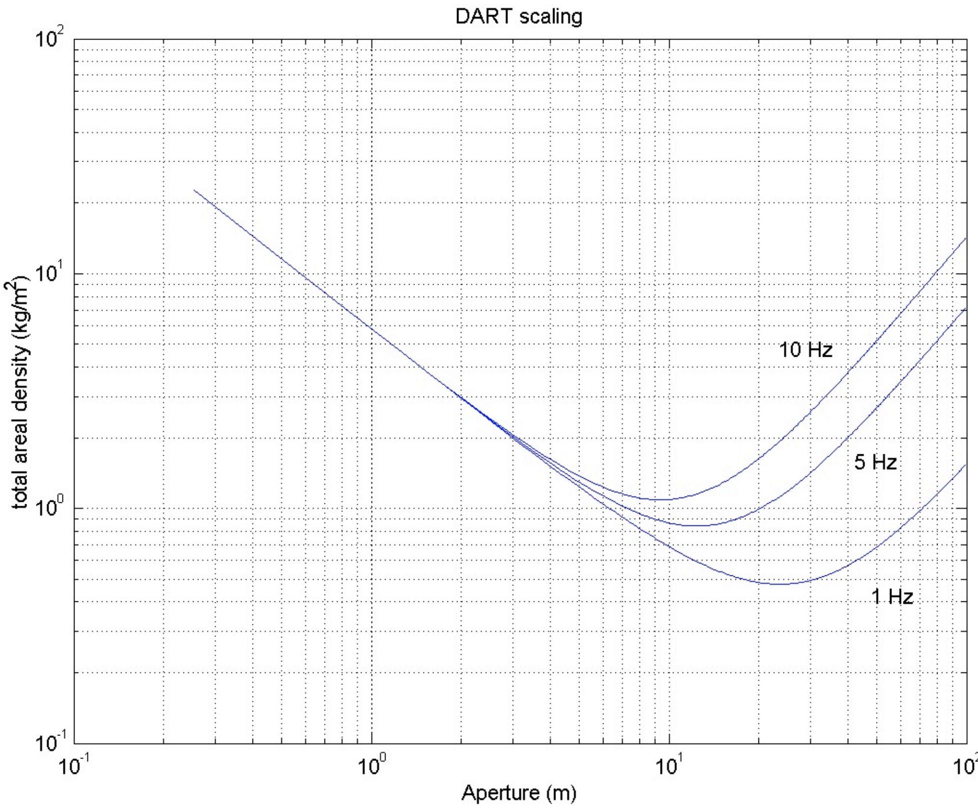

Figure 5: The scaling law for a DART membrane telescope shows the economies in areal density that the design offers for large sizes.

This is in distinct contrast to the scaling relationship for existing telescopes where $\sigma \propto d^{0.5}$. 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 membrane telescope system can be reduced by orders of magnitude if the relatively massive supporting substrate can be minimized while maintaining the desired reflective surface.

Summary

There are three key elements to the DART system:

1) An arrangement of cylindrical-parabolic reflectors can be made that will focus light from a distant source to a point, without any obstruction to the incident beam.

2) 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 far-IR array. By adding a tertiary reflector the field of view can be increased, much like the standard RC design of many current telescopes.

3) 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 1 kg/m^2.

Future development of the DART system must include:

- Investigating auxiliary optics that will widen the field of view.
- Developing technology to produce large high quality reflective membranes.
- Demonstrate a cooled DART system in a space environment using a low cost, near term mission.