Design and Test of a Prototype DART System

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Abstract

A 1.2-meter prototype Dual Anamorphic Reflector Telescope (DART) system has been built and tested. The key design feature of the telescope is a pair of membrane mirrors stretched to single curvature parabolic cylindrical sections. The parabolic figure of the mirrors is controlled by a pair of edge rails at two opposing ends of the membrane. The flexible edge rails are adjusted to parabolic to very high accuracy and can potentially be easily refigured on-orbit. The prototype telescope is lightweight and has demonstrated excellent optical performance for the farIR. The design is readily scalable to larger apertures and for operation at shorter wavelengths. Design and test results are discussed.

1. Introduction

The requirement for large aperture space imaging systems is driving the development of lightweight membrane reflector systems. Membrane systems have the potential to be ultra-lightweight, as well as advantageously scaling in size to very large apertures and deployments. The novel feature of the Dual Anamorphic Reflector Telescope (DART) system is that each membrane reflector is formed into a cylindrical parabola that has curvature in only one direction. These zero Gaussian curvature surfaces can be formed by shaping the boundary of the membrane surface without the need to apply any surface loading or strain gradients in the membrane centerline. These mirrors also have the potential to be deployed from flat sheets or potentially from rolls of flat material. The attribute of the mirror figure being determined from the boundary give the design an advantageous mass scaling to larger apertures. Areal density for the DART system is potentially two orders of magnitude lower than conventional optical systems.

2. Design

A 1.2m prototype DART system was designed and fabricated in order to demonstrate the DART concept. Design features of the system include the optical layout, a pair of single curvature cylindrical parabolic membrane reflectors, boundary shaping rails to control the surface figure of the membrane reflectors, tensioning devices to propagate the boundary figure interior to the reflector surface, a supporting truss structure to hold the mirrors and an alignment system behind one of the mirrors. The prototype DART system is shown in Figure 1.

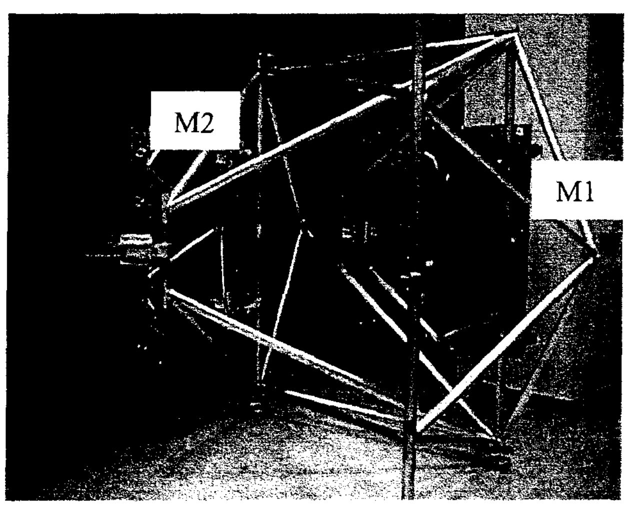

Figure 1. Prototype 1.2m DART system.

2.1 Optical Design

The optical layout is shown in Figure 2. The first mirror (M1) is an off-axis section of a cylindrical parabola. The second mirror (M2) is an on-axis section. Each mirror necessarily has different F/#s such that they converge the beam to the same focal point. The usable field of view (FOV) is approximately 1mrad without corrective optics. Figure 3 shows the predicted performance at a wavelength of 10um. Figure 4 shows the figure and alignment requirements on the mechanical implementation in order to maintain diffraction limited performance at 10um.

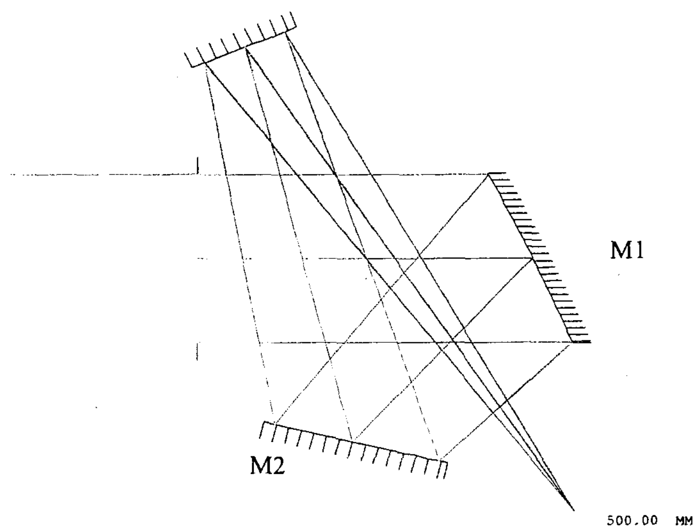

Figure 2. Optical Layout. The flat mirror was removed in the prototype.

WAVELENGTHS 10000.0 nanometers

	FIELD FRACT	DEG	BEST COMPOSITE FOCUS RMS (WAVES)	STREHL
	X 0.00	0.00	0.0000	1.000
	X 0.50	0.012	0.0072	0.998
Vertical Field	X 1.00	0.023	0.0138	0.992
	X -0.50	0.012	0.0072	0.998
	X -1.00	0.023	0.0137	0.993
Horizontal Field	X 0.00	0.00	0.0000	1.000
	X 0.50	0.016	0.1013	0.667
	X 1.00	0.032	0.2027	0.200

THE COMPOSITE RMS IS 0.08048 WAVES

Figure 3. Ideal optical performance

2.2 Mechanical Design

The optical design was implemented mechanically by constructing two single curvature cylindrical parabolic membrane mirrors. Each mirror consists of a membrane reflector stretched between two parabolic end rails as shown in Figure 4. Various membrane materials and thickness were used as the reflector membrane. To date, materials with thickness of approximately 0.002 inch have given best performance.

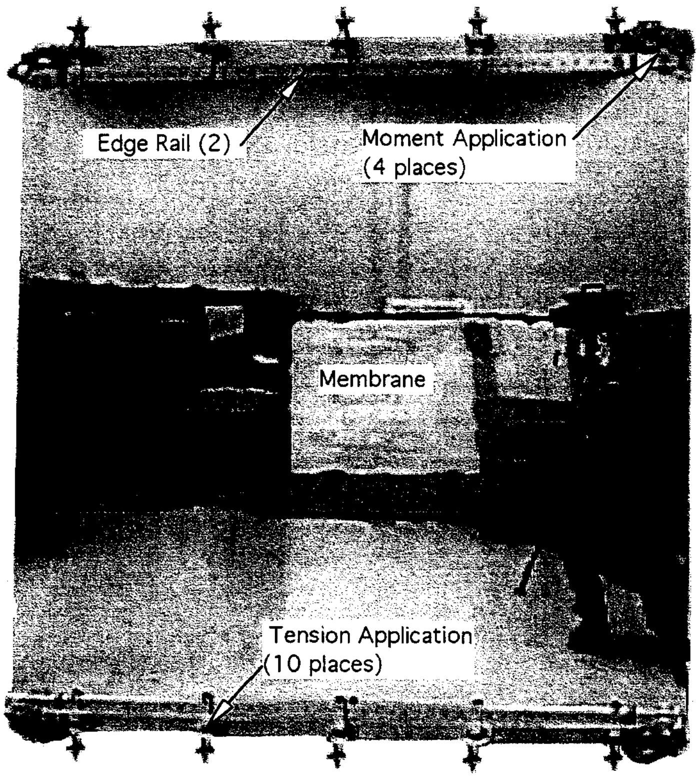

Figure 4. Mirror assembly.

The end rails are formed with a combination of end moments and forces to produce a highly accurate parabolic shape. Corrections to the rail shape are made with a simple set of adjustments to the applied moment and end forces. The advantage to this design is that the rail can be stowed as straight beams and then deployed to a proper curvature. Elastic properties of the beam rail provide smooth parabolic shape with the advantage they do not require shape forming actuation sited along the curvature length other than the requirement for tension mechanism to stretch the membrane. This provides a weight savings as well as offers the opportunity for various mirror deployment schemes.

An optical support structure behind each membrane is required to react the membrane tension. The primary design criteria of the optical support structure is to resist buckling failure. The support structure was used as a platform to mount the perimeter figure and tension adjustment mechanisms as well as a means for mounting the entire mirror assembly to the surrounding telescope truss structure.

An alignment mechanism for the mirrors is located behind mirror M2. It has manual micrometer adjustment for each of six degree of freedoms with a total travel of approx. 2mm in each direction and micron resolution. Rough adjustment of both mirrors M1 and M2 is achieved using shims and slotted hole attachments. Fine adjustment of M2 relative to M1 is accomplished with this mirror alignment mechanism.

The prototype supporting truss structure is made of 2" aluminum tube 1/8" thick as shown in Figure 3.9.1.2. The tubes are welded together to form a lightweight support structure for the mirrors. The placement of the tubes is such that the mirrors are unobstructed. The size of the truss fits within a 2.3m cube envelope. The truss is intended to facilitate lab usage and alignment of the mirrors.

The entire telescope size as shown in Figure 1 is approximately enveloped by a 2.3-m cube. Two mirror assemblies are mounted to the truss designated M1 and M2. Each mirror is made from a thin, membrane of aluminized material. Two membrane mirrors can be seen in Figure 1 on the right center (M1), and left center (M2) of the picture. The optical path is from the left side of the Figure 1 to M1 to M2 and to a detector on the far right. In figure 1, M2 is seen with the reflected image from M1.

3. Mechanical Analysis

Finite Element analysis was used to establish the mechanical design concept performance of the mirror surface. The important parameters to be studied were the attachment boundary condition at the shaped edge rail, the amount and location of tension application on the membrane, and the effect of gravity on the system. The membrane tension serves to stiffen the membrane as well as propagate the edge shape from the parabolic end rails. The analysis was to show whether the predicted figure of a membrane formed to parabolic cylindrical shape and pre-tensioned could meet the mechanical figure requirements for a 10um wavelength diffraction limited system.

The initial design of the mirrors incorporated a 0.012inch thick aluminum membrane while a latter design used 0.002inch . Depending on the boundary constraint conditions and membrane tension, the resulting deformation pattern of the membrane met or exceeded the mechanical figure requirements. In the case of circumferentially free parabolic edges, very little out of plane deformation is observed. In the more realistic case of circumferentially fixed boundary, the out of plane displacement was large near the boundary with a plateau in the central region. One way to eliminate this out of plane displacement was to pretension the membrane prior to attaching and trimming to the parabolic edge rails. This method was therefore adopted in the assembly process. A second result of the analysis was that approximately five or greater tension application sites were required per side in order to achieve sufficiently uniform stress in the membrane to avoid excessive out of plane deformation. This analysis also was used to size the boundary shaping rails so that they were significantly stiffer than the membrane material. Finally, the supporting structure and membrane were analyzed for 1g effects. The mirrors were oriented vertically in order to minimize gravity effects. With these design and assembly details set, the design was ready to be fabricated and tested.

One of the advantages of the membrane optic concept is very small areal densities can be achieved for the mirror assembly. The mass of the mirror is dominated by the figure mechanism at the perimeter and the need for some structure behind the membrane to react the tension. The figure mechanism mass at the perimeter of the aperture increases proportionally more slowly than the aperture area of the mirror resulting in areal densities that actually decrease with aperture size. This trend is true until buckling requirements of the reaction structure become critical and begins to drive the mass of the system. At very large apertures the mass of the reaction structure, which grows in proportion slightly faster than the reflector aperture area, begins to dominate the total mass. For the simple calculations shown in Figure 5 this is estimated to occur somewhere around 25m aperture. However, the areal mass density is still quite small even for apertures greater than 25meters.

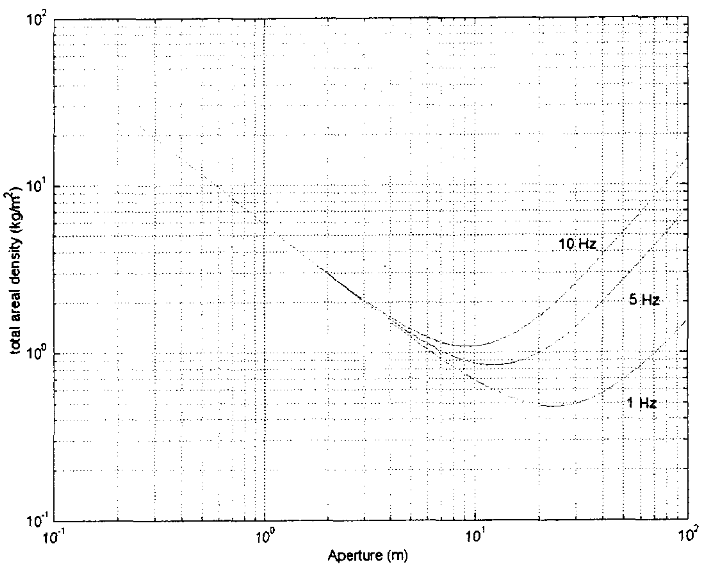

Figure 5. Areal density predictions for each DART membrane mirror assembly.

4. Test

4.1 Materials

Membrane material selection is a critical feature of the system. A series of materials have been tested and more materials will continue to be tested as they are identified. To date, 0.002" (50um) thick aluminized Mylar has provided best results. Preventing damage during handling of the membrane material was found to be difficult. In the case of aluminum, plastic buckling and initial deformation were found to be detrimental to the optical performance. For thin film membranes, wrinkling and tearing has presented similar handling difficulties. Due to the size of the commercially available aluminized membrane material, joining and seaming may be required for reflectors greater than 2meters. If necessary, the joints could be masked to prevent scatter.

4.2 Alignment

Rough figure of the membrane mirrors was achieved using a Leica LTD 500 laser tracker and a tooling ball reflector in contact with the membrane surface near the edge rails. The telescope is oriented in the lab so that the beam path is horizontal and therefore gravity effects on the mirrors are minimized. Adjustments with the Mirror Figure Adjustment Mechanism were made to bring the mirror into agreement with nominal calculations for the optical design. Rough alignment was achieved by sliding and shimming the mirror assembly on the mirror mounts. Fine alignment adjustment of the mirrors was achieved by moving mirror M2 relative to M1 in six-dof using the alignment mechanism behind M2. Subsequent refinement and testing of the telescope optical system consisted of a series of qualitative visual inspections, knife-edge, and Ronchi testing of the mirror at focus.

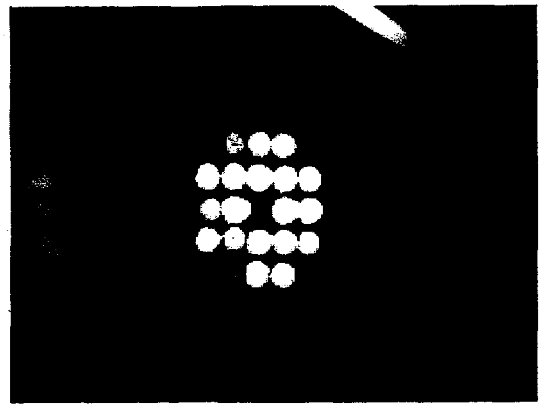

Figure 6. Testing with Hartmann mask

4.3 Figure

Laser tracker profilometer measurements at the mirror edge rails provided a good estimate of the curvature at the edge of the membrane. Measurements were made prior to and after installation on the telescope Truss Structure. For the preliminary testing to date, parabolic shape was achieved with deviation from parabolic of less than 0.001" RMS for the best mirror at an appropriate curvature at vertex. This is also roughly the expected resolution capability of the laser tracker system. The corresponding surface deviation is roughly 25μm RMS. Assuming similar results for both mirrors gives an expected combination surface figure error of approximately 35μm RMS. It is expected that surface error is less than this, but this is an upper bound that could be detected with our laser tracker system.

The Hartmann Mask proved a valuable tool in providing the rough figure of the membrane (Figure 6). Surface figure was achieved on each mirror in a sequence. M1 was first figured to the proper radius while M2 was held to be nearly flat. Once a sharp vertical line was achieved at the focal plane with M1, M2 was subsequently adjusted. As the curvature of M2 was increased, the line focus could be observed to converge towards a point focus. By visually inspecting the focusing beam substantially in front of the focal plane, the pattern of the Hartmann mask could be observed to be converging. Differentials in the converging rectangular pattern were indicators of necessary figure adjustments to the corresponding region of the M2 surface. Figure adjustment was accomplished using both the curvature mechanism on the parabolic rail as well as adjusting the tension field on the membrane.

Fine surface figure will be achieved using the Hartmann mask analysis technique and quantitative Hartmann analysis software. Spatial mapping of surface deviation and transformation to Zernike fits are possible. Because of the input range capabilities of available software, the technique requires that the surface deviation be limited a few wavelengths. To date, this analysis has not been performed. Results presented in the next section were obtained from qualitative visual inspection of the beam pattern

5. Results

5.1 Areal Density

The mass of a full mirror including membrane, tension mechanisms, figure mechanisms, and reaction structure behind the membrane was about 25lbs, or 11kg. Using the full aperture of each square mirror this gives an areal density of less than 10kg/m^2 per mirror. This is slightly higher then the prediction of Figure 7 but that is partially due to the fact that this prototype was not designed to optimize weight, but rather to function robustly in a lab environment. The mass can be significantly reduced, particularly in the reaction structure. This areal density represents a significant achievement in membrane reflectors and is much better than the expected development time that is often mentioned in reports on Gossamer technology. To date we have not quantified the figure over the entire mirror aperture and are currently in the process of accomplishing this.

5.2 Encircled Energy

Encircled energy measurement of the focus was the most effective diagnostic tool for determining optical quality. For the initial configuration using 0.012inch thick aluminum sheets approximately 400um diffraction limited performance was achieved based on a focused spot size of 8mm FWHM. For the initial testing a 0.4m diameter collimator was used that limited the test aperture of the system. The encircled energy values reported were obtained using a silicon detector and optical power meter, which can measure down to nanoWatts. The apparatus consisted of a Newport Corporation Model 818-SL detector, a Model 883-SL Attenuator (not used for "at focus" measures), Model 835 Optical Power Meter.

Subsequent refinement of the figure mechanism produced encircled energy measurements indicating diffraction-limited performance of approximately 160um. The collimator was moved to two completely different input positions to the prototype entrance aperture, and each position produced identical encircled energy values at focus, giving reasonable confidence that the prototype has substantially uniform optical quality over a significant region of its entire aperture.

Several membrane material refinements were subsequently made over the subsequent few months. To date best results have been achieved with a 0.002 double-sided aluminized Mylar. This material comes in maximum 24" (0.6m) strips, so the largest aperture tested to date is 24" x 24" (0.6m x 0.6m). Using a 16" (0.4m) collimator, a encircled energy spot of approximately 2mm FWHM at 0.63um wavelength was obtained corresponding to a diffraction limited performance of approximately 45um. Subsequent testing with a larger collimator on 0.6m x 0.6m area of the aperture have produced similar results.

Hartmann analysis was expected to be the easiest to implement test of optical quality. In practice, this was not the case. At the current state of optical surface quality, the large variation in Hartmann aperture intensities, resulting from mirror surface slope errors and scattered light, is more than the Hartmann Mask Analysis Software Version-1.0, by Santa Barbara Instrument Group, can handle. An example of a Hartmann test setup is in Figure 8. In the future, it is expected improved software and mirror figure will result in the Hartmann test being as, or more, useful than the encircled energy test.

5.3 Imaging

Once a small spot (FWHM <2) at the focal plane was attained, imaging of an extended target through the DART telescope was subsequently achieved. Our detector was a 10um wavelength camera (Infrared Components Corp) a few feet behind focus. The camera was used to re-image the focal plane and capture data to computer. The image source was a heated wire located at the focal plane of the collimator telescope. The test setup is shown in Figure 10.

Initial tests with the 0.012inch thick material did not achieve sufficient figure to get meaningful images. The first successful image was made using a 24" wide strip of double aluminized 0.002inch thick. A 16" collimator provided the source beam effectively testing a 16" aperture on the DART mirror. The image of the four-line grating produced from a soldering gun heated wire is shown in Figure 11. The spacing on the grating is approximately 0.15 inch (3.8mm) center-to-center of source lines at 10um wavelength. Considering the 6000mm focal length of the collimator, this corresponds to an angular resolution of approximately 3mrad. This is consistent with the 45um diffraction limited number calculated from the encircled energy measurement at 0.63um.

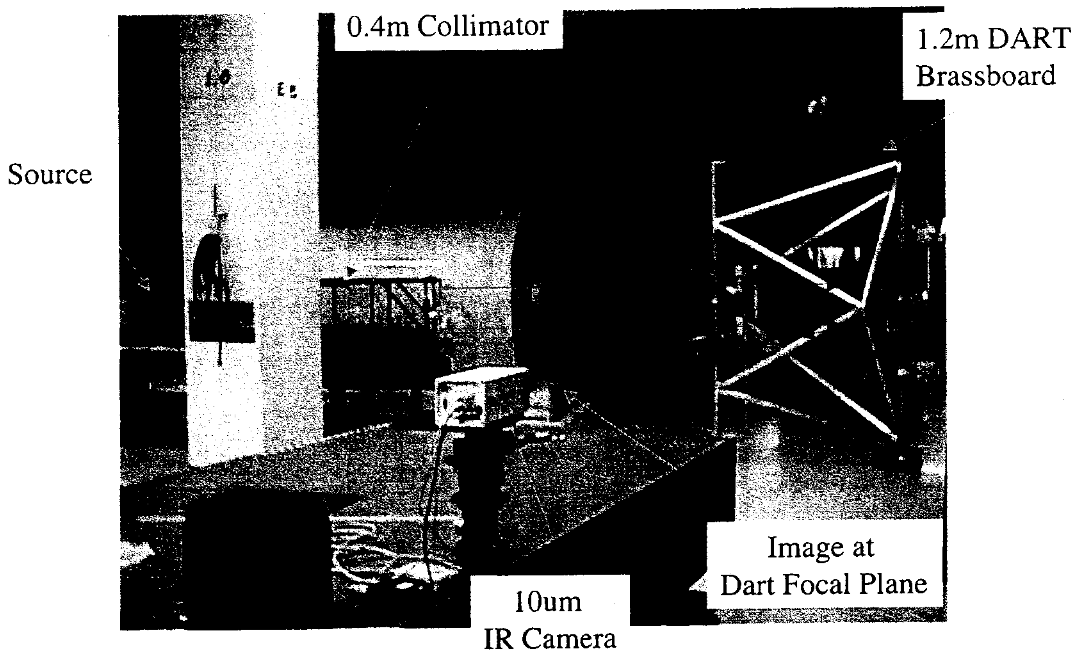

Figure 7. Test Configuration for Imaging.

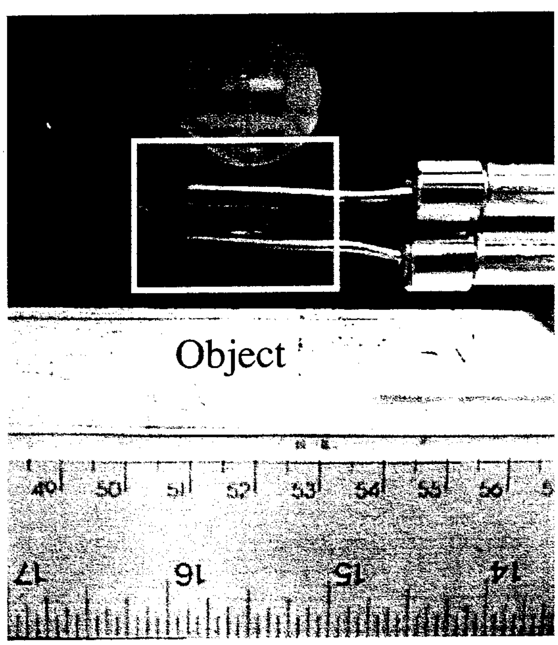

Figure 8. IR source at collimator focal plane.

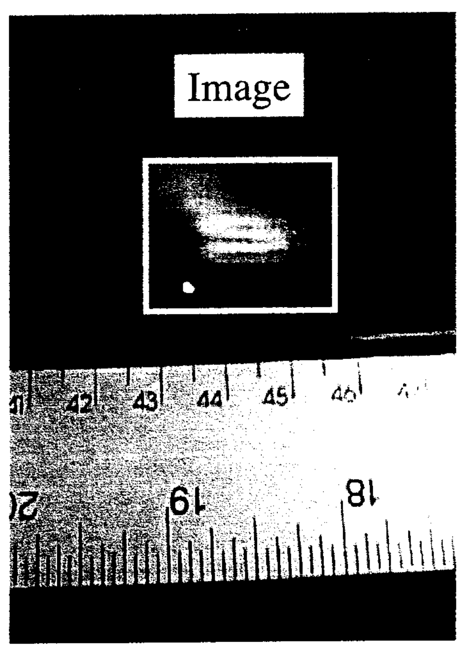

Figure 9. 10um Image at DART focal plane

6. Discussion

The significant feature of the DART system is the application to very lightweight large apertures. Conceptually the reflector could be deployed from a roll of material which makes packaging during launch compact. Deployment could potentially be in one direction only in a flat sheet and then curvature imposed from the edge rails. The areal density of 25m class apertures is estimated to be two orders of magnitude smaller than conventional space optical systems.

The successful performance result of the analysis and testing is the image of the heated coil in figure 11. The image is slightly blurry since the wavelength of the detector is 10um and it is expected that there is some zonal error remaining in the mirror figure. To date results have been limited to the center 0.5m of the aperture based on test equipment and membrane material availability. The 10kg/m^2 areal density number is calculated over the entire aperture. The critical attribute of the candidate membrane materials is whether they are flat in the unstressed condition. Generally, small spatial scale surface roughness was not a problem at the farIR wavelengths of interest. However, the larger scale imperfections and creases were found to be extremely detrimental and are believed to be residual stresses and deformations resulting from the manufacturing process of these membranes. Generally these could not be pulled out with the membrane tension.

Experience on the prototype gives confidence that significant improvement of figure can be achieved as more materials are investigated. The critical feature of the candidate material is flatness in the stress-free condition. Other considerations are a acoustic and ground vibration isolation as well as gravity effects and tension versus thickness sizing for a given aperture size.

7. Summary

The DART system consists of a pair of single curvature parabolic cylindrical membrane mirrors oriented relative to each other to give an un-obscured off axis field of view. The mirrors are currently imaging over a 0.6m square aperture with diffraction limited performance at approximately 45um. Continued testing and figure adjustment is expected to bring the entire clear aperture to similar diffraction limited performance. The areal density of each mirror in the lab is less than 10kg/m^2 and this value is felt to be a very conservative estimate of future developments. The DART system represents a significant technical and schedule advance for the development of large, ultra-lightweight membrane reflector systems.

Acknowledgements

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