

# Shaping Of Parabolic Cylindrical Membrane Reflectors For The Dart Precision Test Bed

R. Morgan, Gregory S. Agnes\*, M. Dragovan, D. Barber,  
M. Marcin, C. White, J. Dooley  
*Jet Propulsion Laboratory*  
*California Institute of Technology*  
*Pasadena, CA*

A. Hatheway †  
*Alson E. Hatheway, Inc.*  
*Pasadena, CA*

The DART is a new telescope architecture consisting of a single aperture formed from two cylindrical parabolic reflectors. The system is ideally suited to using tensioned membranes for the reflective surfaces, owing to the zero Gaussian curvature of a cylindrical parabola. In this paper, we present experimental measurements for shaping the membranes by using curved boundary elements to achieve coarse shaping, and a pair of precision rails shaped by moments and forces at the ends, and lightly pushed into the surface, to provide fine shape control. An experimental testbed has been constructed to demonstrate the ideas using a 70cm by 80cm membrane reflector. A highly adjustable and precise membrane surface is achievable on the testbed through the use of precision mechanical design practices. Results from measuring the membranes using a scanning profilometer and from center of curvature testing are presented.

## Introduction

The Large Apertures (LA) Element of the Mission and Science Measurement Technology Program develops technology for lightweight optics, adaptive optical and RF systems for correcting wavefront errors, and concepts for deployment and assembly of large antenna and telescopes. These technologies will enable very large, ultra-lightweight apertures for bold new missions of discovery in the future roadmaps of the NASA science and human space flight enterprises, such as:

” Very large telescopes for imaging extra-solar planets, studying the formation of large-scale structure in the early universe, and continuously monitoring the Earth from distant vantage points. ” Large deployable and inflatable antennas for space-based radio astronomy, high-bandwidth communications from deep space, and Earth remote sensing with radar and radiometers.

The primary customers for the Large Apertures technology are the Astronomical Search for Origins (ASO) Structure and Evolution of the Universe (SEU) themes in Code S and the Earth Science Technology Office in Code Y. The overarching goal of the large aperture technology development is to provide in-

creased scientific return at lower cost and with shorter lead times.

The current generation of telescopes, both ground and space based, can trace their design and fabrication methods back to the telescopes of the 17th century. 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, 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 telescope be large, lowmass, and diffraction limited over a reasonable field of view. For applications in the infrared, the telescope needs to be cooled to cryogenic temperatures to reduce the thermal emission from the reflector surfaces.

The DART Dual Anamorphic Reflector Telescope is a system of two cylindrical-parabolic reflectors. One reflector produces a line focus; two reflectors, properly oriented, 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.

There are three key realizations that must be un-

\*Corresponding author. gregory.s.agnes@jpl.nasa.gov, AIAA Senior Member AIAA

†AIAA Senior Member

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derstood to recognize the potential of the DART architecture.

1. that the system of two cylindrical-parabolic reflectors not only will focus the incident light, but has a field-of-view similar to that of an off-axis parabolic reflector. The large focal surface allows for an array of detectors.
2. the cylindrical-parabolic reflectors can be implemented with tensioned membranes.
3. the aperture is completely unobstructed: Since there is no secondary mirror with its associated support structure to scatter and diffract light, the beam pattern of the DART system is clean. There is no reason why the wavefront error of the system should not be dominated by the small scale roughness of the individual membranes. For any scientific observations where the observations of low contrast sources (such as detecting a dim planet near a bright star) are necessary, the DART's unobstructed aperture enables the measurement to be made.

In support of the Large Aperture Element, the DART Task develops a telescope architecture suitable for large, ultra-lightweight space apertures to expand mission capabilities, and to enable new visions of the Earth and the Universe. Technology development of these ultra-lightweight optical systems includes mirror figure shaping, reflector surface modeling, single reflector and full telescope verification testbeds, 10m aperture configuration design, and aperture scale-up.

This paper describes the single reflector testbed, discusses the metrology systems, and presents initial results.

### On-Axis Testbed

A precision testbed was constructed for the purposes of exploring and quantifying the fundamental accuracy limits of the DART system. The goal is a terrestrial testbed capable of diffraction-limited imaging at mid-infrared wavelengths and to discover the fundamental difficulties to creating such a system.

The initial precision testbed examines a single membrane. The DART architecture is comprised of two cylindrical membranes, one of which is a segment of an off-axis parabola and the other of which is a shorter focal length and has the curvature profile of an on-axis membrane. Due to its axial symmetry, the on-axis membrane is more straight forward to implement and was chosen for the single reflector testbed. The emphasis of this effort is on precision - demonstrating, developing the necessary technology, understanding and technique to produce a surface accuracy of nearly 1  $\mu\text{m}$  over a 1 meter membrane. This will be a unique accomplishment, as other efforts have shown

a 40  $\mu\text{m}$  rms figure for a 1.2 m cylindrical membrane(LM), and 39  $\mu\text{m}$  rms for ROC = 3.04 m, dia = 33 cm (Dan Marker AFRL) and 100 nm rms ROC = 32 m, dia = 10 cm, Electrostatic Curvature, Simona Errico UofAz

The testbed researches fabrication, handling, assembly, shaping, control and characterization of cylindrical membrane reflectors. The testbed encompasses the design of the membrane tensioning and control hardware and the development of the metrology instruments. The membranes are 70 cm by 80 cm and made of copper foil, though other materials are readily substituted. The membrane figure goal is less than 2  $\mu\text{m}$  rms with a surface measurement accuracy of 0.15  $\mu\text{m}$  rms.

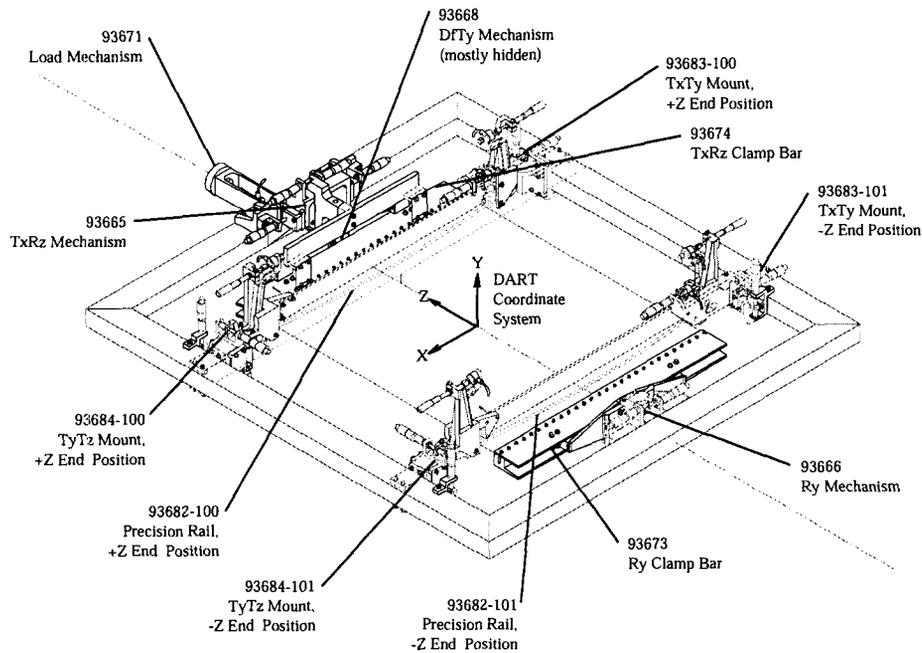
### Design

In the single reflector testbed design, the reflector is formed by stretching a membrane in one direction to provide stiffness and enforcing the curvature in the perpendicular direction through a combination of shaped edge clamps and precisely-shaped rails which lightly push into the stretched membrane. Clamping bars along two opposing edges hold the membrane in tension while the other two edges are free. The tension forces are reacted through the edge clamp bars into a preload frame. The preload frame also serves as a mounting fixture for the precision shaping rails and as an interface to the mirror support and alignment systems. A diagram of the current design is shown in Figure 1. Note the alignment mechanisms at each clamp bar that adjust the membrane preload and boundary displacements. The alignment and shaping adjustability is a key feature of this testbed design. The baseline membrane is 50 micron metal foil and measures 80cm by 70cm rectangular, but other membranes can be substituted readily. The modularity of the design is purposeful; it is expected that the membrane shaping hardware will be modified and improved before the full telescope testbed is constructed.

### Membrane Installation

Membrane installation involves preparing and installing a membrane into the tensioning frame. Membranes wrinkle easily when handled, so a handling procedure was developed. Once in the frame, the membrane is not directly handled. The frame is handled as an assembly and placed in front of the metrology instruments. Next the clamp bars are aligned. Then the precision rails are mounted on the frame and aligned.

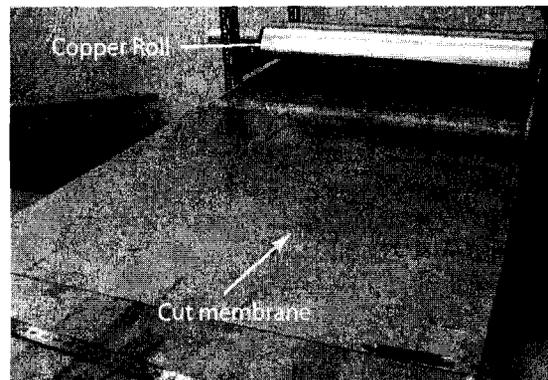
For membrane installation, we developed an installation jig. The jig supports the membrane in a curvature matching the clamp bars and holds the clamp bars in alignment while the membrane is secured. The jig provides repeatability for the placement of the clamp bars with respect to the tensioning frame.



**Fig. 1 Mechanical layout of a single reflector mounting frame, showing the parabolic clamping bars, the alignment mechanisms and the precision shaping rails.**

#### *Installation Procedure*

1. Prepare the membrane (Figure 2). The membrane is cut and slid onto a thin sheet of aluminum and set aside.
2. Move the DART test bed from the optical bench. Remove the micrometer from the back of the lower clamp assembly, and transport the DART test bed from the optical bench to a table where it is laid down on blocks. Reduce the tension on the membrane. The old membrane is removed and the clamps are taken off the test bed. Check condition of installation jig (Figure 3).
3. Prepare for installation. The back halves of the clamps are attached to the installation jig and checked for alignment (Figure 4).
4. Installation of the membrane. The membrane and the aluminum sheet that support it are placed in the jig. The membrane is aligned to the clamps and the support sheet is slid out of the jig. The front halves of the clamps are placed and bolted onto the back halves one at a time. 6-32 bolts that provide the clamping force are tightened from the center out. Torque = 20 inch/ounce (Figure 5)
5. Reassembly of DART test bed. The tensioning frame is carried to the installation jig, aligned to the clamps, and the clamps are attached to the frame. (Figure 6)
6. Removing test bed from jig. Electronics are connected to the load cell that measures the tension



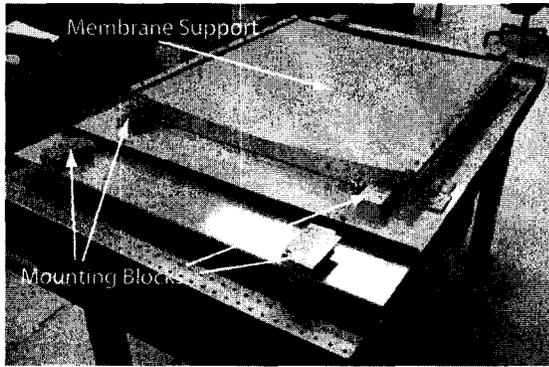
**Fig. 2 A single membrane cut from the roll, ready for installation.**

on the membrane. The back clamps are disconnected from the jig. The reflector frame is raised 1/8" off of the jig with shims and the tension on the membrane set at 20 pounds. The electronics are disconnected from the load cell. The reflector assembly is lifted off the jig and set upright on the lab floor. (Figure 7)

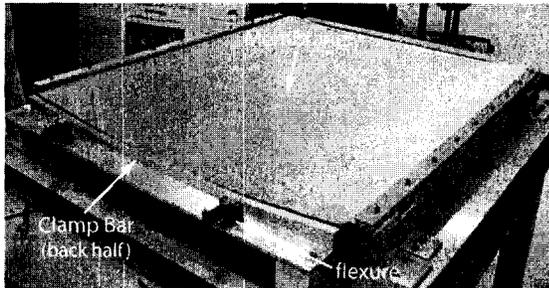
7. Final assembly steps. Two flexures that stabilize the upper clamp jaw during the lift off of the jig are removed. A micrometer on the back of the lower clamp jaw is installed. The reflector assembly is lifted on to the optical bench. (Figure 8)

#### **Initial Adjustment**

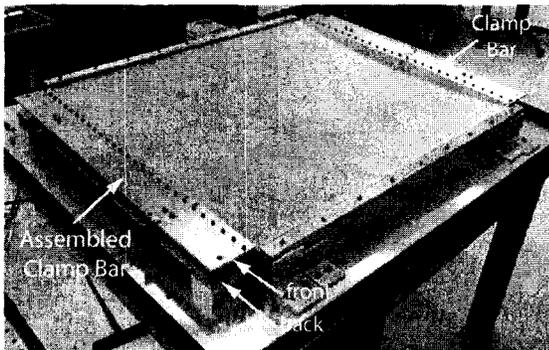
The initial adjustment of the membrane is accomplished using templates, plastic shims and visual observation. The initial adjustment is normally performed



**Fig. 3** The installation jig just before placement of the clamp bars. The jig supports the membrane during installation.

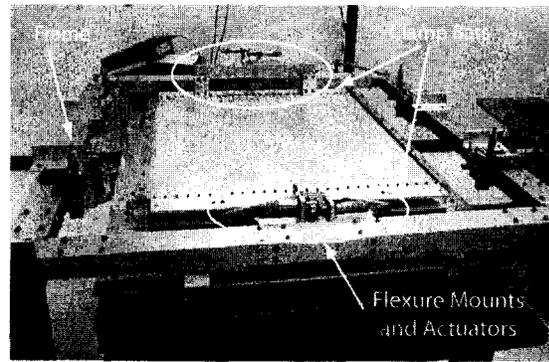


**Fig. 4** The back halves of the clamps are attached to the installation jig and checked for alignment. The membrane is transferred to the jig.

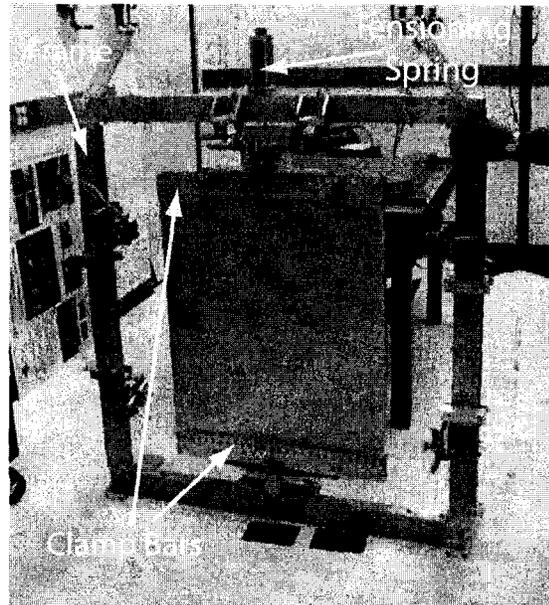


**Fig. 5** The front halves of the clamps are placed and bolted onto the back halves.

with 20 lb. of force on the upper clamp. The upper clamp assembly weighs about 10 pounds, so the tension on the membrane is approximately 10 pounds. When the test bed is picked up off of the installation jig the micrometers that position the clamp jaws are snubbed. This stabilizes the membrane while it is being transferred to the optical table and sets the starting point for the adjustments. Aluminum templates machined to the same curve as the clamp jaws are used to check the curve of the membrane. The templates are set on blocks near the mounting location for the precision rails. Plastic shim stock is used to measure the irregularities in the membrane shape.



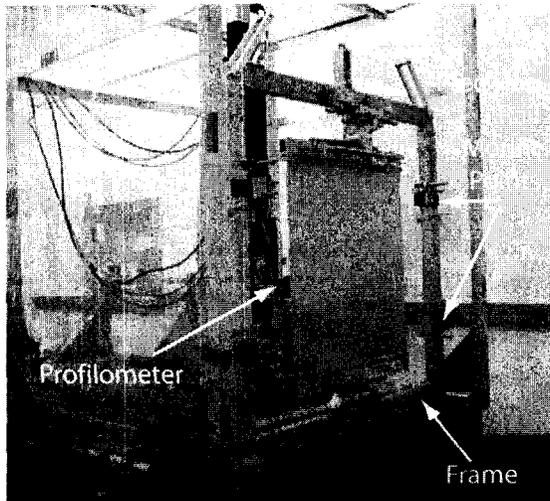
**Fig. 6** The tensioning frame is carried to the installation jig, aligned to the frame, and the clamps are attached to the frame.



**Fig. 7** The reflector frame is raised 1/8" off of the jig with shims and the tension on the membrane set at 20 pounds. The reflector assembly is lifted off the jig and set upright on the lab floor.

The critical adjustments are the rotation of the lower clamp about Y and the rotation of the upper and lower clamps about X. The correct rotation of the lower clamp about Y is accomplished by backing off the micrometers that restrain its location and allowing the tension in the membrane to pull the clamp into position. The micrometers are then snubbed; minor adjustment may still be required to optimize this rotation.

Rotation of the lower clamp about X is accomplished by driving forward micrometer #7 behind the clamp. This rotates the upper edge of the clamp forward. Visual observation and the templates are used to determine the correct adjustment. Rotation of the upper clamp about X is accomplished by changing the point where the force is applied to the clamp. A threaded drive above and near the center of the upper clamp



**Fig. 8** The reflector assembly is lifted on to the optical bench in front of the profilometer.

moves this point in Y. Visual observation and the templates are used to determine the correct adjustment. There is some interaction between the adjustment (rotation about X) of the upper and lower clamps. Several iterations of these adjustments may be required in order to create the best shape in the membrane. There are micrometers that can adjust the translation of the upper clamp in X. This adjustment is not usually required. The initial condition created by the installation jig is adequate in most cases.

When the membrane shape is acceptable it is scanned. After the initial scan the force on the upper clamp is increased to 30 pounds and the membrane is scanned again. Then the force is increased to 40 pounds, our final tension and the membrane is scanned again. The micrometers that control the rotation of the lower clamp about Y should not be snubbed while the tension is being increased. Locking down these micrometers while increasing the force will cause unwanted rotation about X. Next the rotation of the upper clamp about Z is adjusted using information acquired from the scan of the membrane. The membrane is then rescanned.

The precision rails are installed now. The precision rails are mounted on the frame, but not in contact with the membrane. The precision rails are driven forward using four micrometers (10,11,12,13) until there is contact at the outside edges of the membrane. The four micrometers are then driven forward equally in small steps until the precision rails are in contact across the full width of the membrane. The contact is checked with a .0005 thick plastic shim. When contact across the membrane is accomplished the membrane is scanned. Further adjustment of these four micrometers may be required in order to achieve the best RMS for the membrane. Each adjustment is followed by a scan until it is determined that the best shape has been

achieved.

## Metrology

Measuring the surface of a one-meter cylindrical membrane presents a particular challenge. The metrology must be noncontacting, produce minimal vibration, and service a large aperture of cylindrical shape. Additionally, the metrology tools are needed to measure the membrane as it undergoes the shaping and adjustment process. This places a requirement of a very high dynamic range and ease of alignment on the system.

The optical metrology systems encompass a suite of tools with a tiered approach. The metrology tools are an interactive component of membrane shaping and are also used for precision characterization of the final shape. Qualitative techniques assist with coarse shaping. Quantitative instruments inform finer shaping.

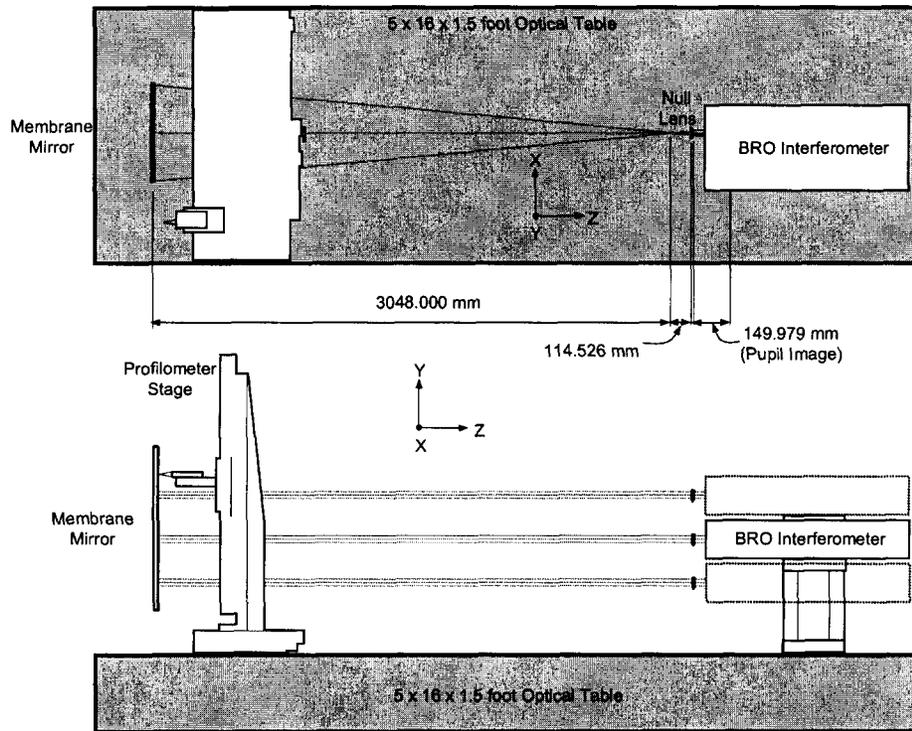
The coarsest shaping is performed by mechanical templates as part of the initial adjustment described in the previous section. At this stage, the membrane is examined optically with center of curvature imaging. This shows the entire membrane and is especially useful for showing wrinkles and other large scale features. It is only qualitative. Next we use the profilometer to refine the membrane shape. The highest precision measurements are provided by the interferometer.

We have implemented two quantitative metrology instruments: a non-contacting, scanning profilometer and an infrared interferometer. The profilometer is a laser confocal displacement measuring unit on an XYZ scanning stage. The noise is under  $2 \mu\text{m}$  rms with repeatability limited to 10 microns. The performance of the profilometer has been characterized in the environment, on a calibration flat, and on a 1 meter cylindrical membrane. The infrared interferometer uses a cylindrical null lens that allows a subaperture of the membrane to be viewed. It has a dynamic range of  $320 \mu\text{m}$  and acquires data quickly, freezing environmental effects.

### Center of Curvature Imaging

Center of Curvature imaging reveals the entire membrane. The images show qualitative and dramatic results of overall membrane smoothness and large scale ripples. It is a verification of the coarse shape. It is useful for diagnosing repeated features in the copper material and systematic errors created by the tensioning frame.

Center of Curvature imaging is traditionally used on rotationally symmetric optics with a knife edge (Foucault test) or a grating (Ronchi test). For a source placed at the center of curvature of a sphere, all light rays return on themselves. To an observer also at center of curvature, the point source will appear as uniform illumination across the surface of a perfectly spherical mirror. For a perfectly spherical cylinder,



**Fig. 9** The reflector, profilometer and interferometer sit on the same optical table. During interferometric measurements, the profilometer stage is moved to the edge of its range, leaving the membrane unobstructed.

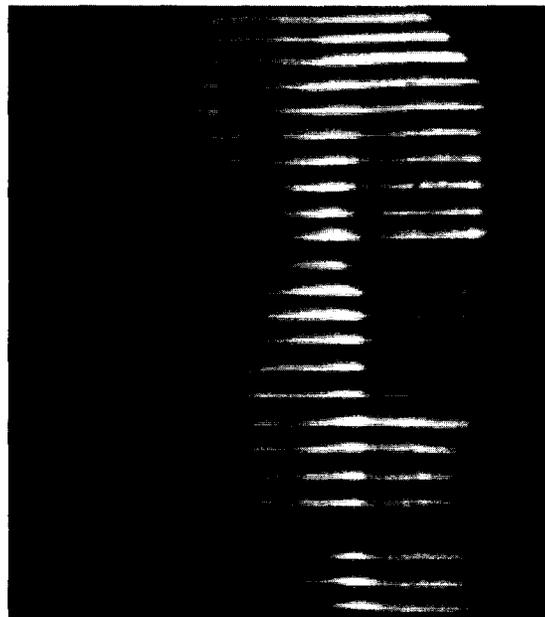
a point source appears as a uniform line. A string of sources (parallel to the cylindrical axis) produces a ladder of lines, as illustrated in Figure 10. Gaps or breaks in the line indicate a different radius of curvature or a different local slope.

Figures 11 and 12 are images of the cylindrical membrane taken at center of curvature. The sources are lightbulbs 1 inch size mounted on a 5 foot long pole. The image is taken with an infrared camera, a microbolometer array identical to the camera in the interferometer. Both membranes are seen to be very smooth over a large central area. Outside the useable aperture at the left and right edges, the membrane curves up. The images show smoothness for a good alignment of the clamp bars. When the precision rails are added, the ripples in the membrane migrate to the zone between the rails and the clamp bars, leaving the central aperture smooth.

### Profilometer

The profilometer measures the surface height of the membrane as it situated vertically on the optical table, as shown in Figure 14. The profilometer is capable of scanning one square meter of area with a surface height range of 5 cm. It is composed of a laser head mounted on a fine resolution z-translation stage mounted on a large, 1-meter of travel XY stage.

The Laser head measures surface height by the active confocal principle. It is made by Keyence, model



**Fig. 11** An infrared image of a vertical series of point sources positioned at the center of curvature of a cylindrical membrane made of 5 mil thick Kapton. This image shows good alignment of the clamp bars.

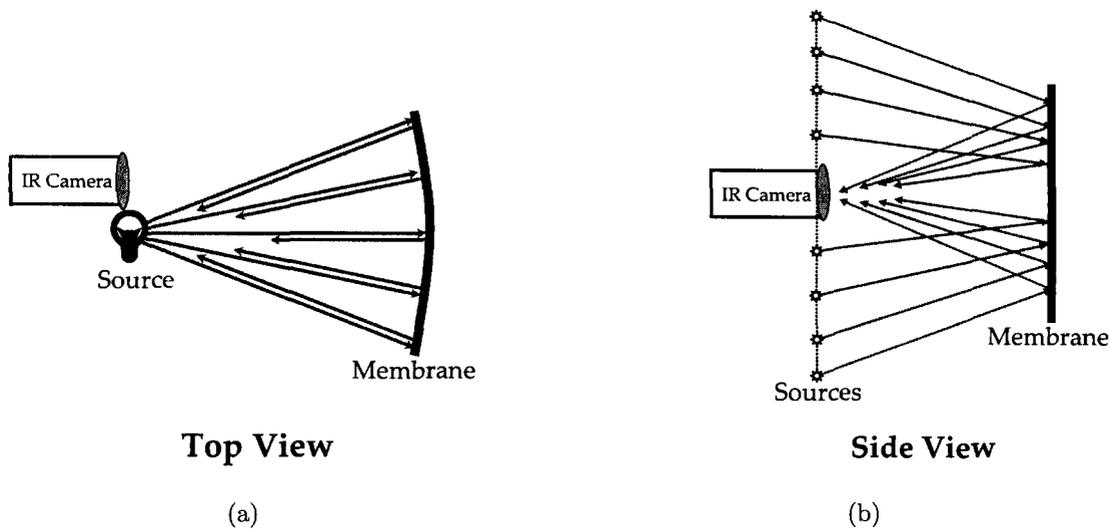


Fig. 10 In the Top View (a) of cylindrical membrane under center of curvature test, all rays from a point source return to the source. In the Side View (b), the membrane acts as a flat mirror.

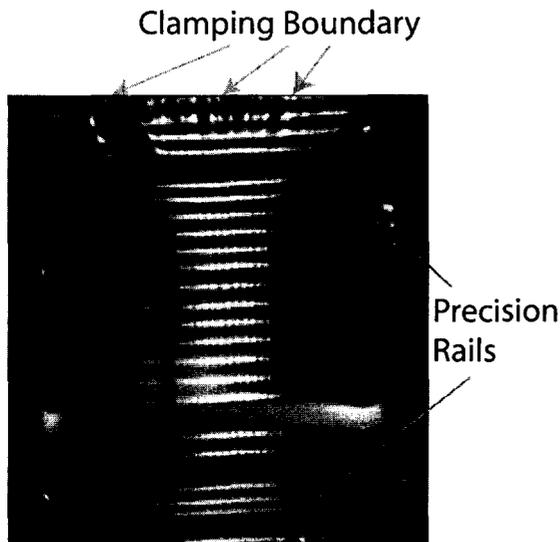


Fig. 12 This infrared image shows a vertical series of point sources positioned at the center of curvature of a copper membrane. The precision rails smooth the membrane and push ripples to the outer edge.

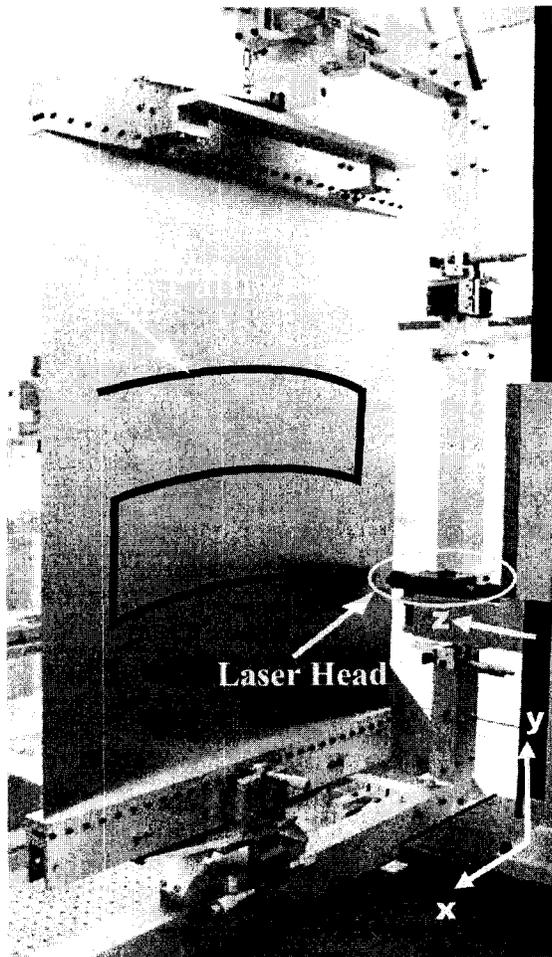
LT-8110 and has a  $0.2 \mu\text{m}$  precision with a 2 mm range. To increase the range, the laser head is mounted on an Aerotech, computer controlled Z translation stage with 5 cm range. The z-stage and the laser head are operated in a closed loop mode in order to follow the shape of the surface under measurement. The z-stage is moved until the laser head reads zero surface height. This allows for arbitrary shapes to be measured and does not require *a priori* knowledge of the surface pro-

file. This is particularly important for shaping the precision rails and for characterizing the clamp bar shapes.

The Aerotech system is coupled to a PCI format, Unidex 500 series motion controller card. Data from the Keyence displacement meter is read using an Agilent 1433B 8-channel, 196kSa/s Digitizer. LabVIEW for Windows 2000 was the chosen acquisition and control development platform since it provided the greatest compatibility with all components. The DART Profilometer data acquisition system has been designed to control all these elements within an integrated interface as well as provide access to the Matlab analysis package for data reduction and display.

The X translation stage is an Aerotech linear motor with 1 meter of range. The Y stage is an Aerotech vertical linear ball screw motor with 1 meter of range that rides on top of the X stage. The XY stage has a resolution of 100 nm and maximum slew rate of 1 meter per minute. Due to vibrations caused by the stage, measurements cannot be made while the stage is scanning. The stage must stop and settle for at least 0.1 second before taking a surface height measurement. This causes the membrane scans to be time consuming. A high resolution scan with measurements on a 5 mm grid requires 6 hours. We typically use a faster three line scan with 1 cm samples in the x direction and 18 cm separation in the y direction of the lines. This scan takes 15 minutes and is used for refining the membrane shape. The majority of the results presented use this scan.

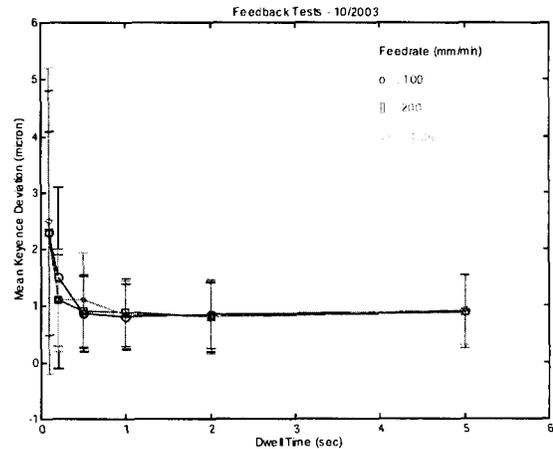
The triple-line scan data is fit to a parabolic cylindrical surface. The radius of curvature and the rms



**Fig. 13** The profilometer laser head is mounted on an XYZ translation stage. The stage allows for full scanning coverage of the membrane.

error from the fit is reported. The main figure of merit on membrane quality is the rms error from the best fit cylinder. Several other features are used for diagnostic analysis of the membrane. The triple-line scan data is broken into individual lines and fit to individual parabolas. The skew of the top to the bottom are compared to show any misalignment of the top and bottom clamp bars and/or precision rails. The fit error on the top/bottom sections are compared to the center section to determine propagation of tension across the membrane. The copper material repeatedly exhibited poorer figure in the middle line scan while the Kapton exhibited poorer performance on the outer edges.

A series of standard triple scan runs were taken to tune two operating parameters: the feed rate and the dwell time. The mean displacement measurement was of course zero since the feedback was in operation. The



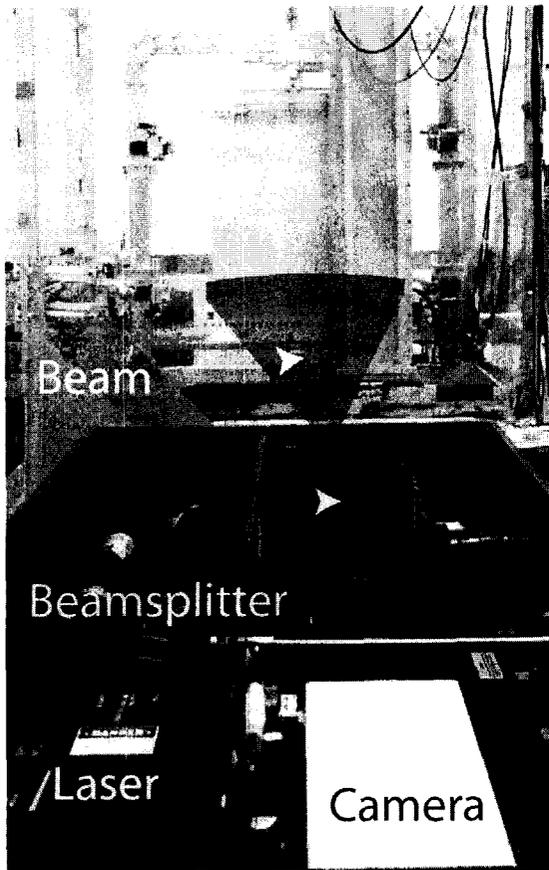
**Fig. 14** The mean deviation of the displacement measurement determines how well the system performs. There were 363 points in each data sample. They show that the resolution of the displacement measurement is at the 1 micron level provided you have a dwell time greater than or equal to 0.5 second and a feedrate of 200 mm/minute or slower.

mean deviation of the displacement measurement determines how well the system performs. There were 363 points in each data sample. Plotted in Figure ?? are the results of this study. They show that the resolution of the displacement measurement is at the 1 micron level provided you have a dwell time greater than or equal to 0.5 second and a feedrate of 200 mm/minute or slower. Sources of noise (mechanical, electronic) in the current system prevent doing any better.

### Interferometer

While the profilometer is capable of scanning the entire membrane surface within the precision rails, such a scan is slow and has a repeatability uncertainty of  $10 \mu\text{m}$ . Interferometry provides a faster, near instantaneous measurement and a higher precision. The data acquisition is performed in 0.25 seconds, (longer for averaged measurements), so most of the environmental vibration effects on the membrane are frozen. The vibrations not frozen can be averaged out over repeated measurements. These fast measurement facilitate in the repeated measurements required for model validation and influence function characterization. The copper material used in the membrane is diffuse at visible wavelengths but smooth in the infrared. Consequently, the interferometer must use an infrared laser and detector.

In the interferometry setup, the single reflector is tested at center of curvature. A small ZnSe null lens produces a cylindrical reference beam that matches the ideal parabolic cylindrical surface. The reference beam measures a subaperture of the cylindrical membrane that is 80 cm wide by 30 mm high. The spatial sampling is 4 mm wide by  $120 \mu\text{m}$  high.



**Fig. 15** Photograph of infrared interferometer placed at center of curvature of the membrane. A small null lens produces a testbeam that is 30 mm tall and 80 cm wide.

The infrared interferometer is a heritage instrument manufactured in 1985 by BRO. It is a phase shifting, infrared interferometer with a 30 mm diameter collimated output. It uses a 1.5 W CO<sub>2</sub> laser at 10.6  $\mu\text{m}$  wavelength. The detector is a 320x240 microbolometer array with standard video output. The phase shifting is performed by a computer controlled PZT on the internal reference mirror. The BRO interferometer has a measured precision of 0.13  $\mu\text{m}$  and dynamic range of 340 mm.

Data acquisition is facilitated by Intellwave software on a dedicated PC. Intellwave allows for calibration of the PZT, controls the phase shifting and synchronizes it the incoming video signal. It reduces the images of phase shifted fringes to generate a surface map.

## Results

We have performed over twenty membrane installations and adjustments. We have developed procedures for installation and adjustment that optimize the membrane figure. The best membrane figures are listed in Table 1. This table represents membranes made of electroformed Copper 70  $\mu\text{m}$  thick, 35  $\mu\text{m}$

thick, and 5 mil thick, aluminized Kapton. The best figure was achieved with Kapton, 35  $\mu\text{m}$  rms. An exemplary data plot from a profilometer measurement of the Kapton membrane is shown in Figure 16. Plots of the surface error of the membranes listed in Table 1 can be found in Appendix ??

Notes on each membrane:

The 70 micron/62.5 cm wide membrane was the last 70 micron copper membrane installed. The RMS for a 50 cm scan is similar with or with out the precision rails.

The 35 micron/62.5 cm wide membrane was the last of three installed this year. This membrane had a large area that was better than the RMS number suggests.

The 70 micron/70 cm wide membrane was the last the three membranes we installed to show repeatability in the installation process (see section .

The 5 mil. Kapton membrane is under 25 lbs. of tension, the copper membranes are all at forty pounds. The current results suggest that the precision can improve the radius of curvature but do not improve RMS.

## Clamp Bar Characterization

The clamp bars are machined with a spherical profile. The target profile for the membrane is parabolic, however the difference between a parabola and a sphere with 120 inch radius of curvature is 2.5 mils P-V, which is about the standard machine precision available. The true parabolic shape will be produced by the precision rails.

The clamp bars were scanned using the profilometer to characterize the accuracy of the curves and to determine any deformation present when the two halves are clamped together. The curved surface of the clamp bars was measured with the profilometer. Each curve was fit in least-squares fashion to a sphere. The best fit radii were found to be within 0.8% of the target. The deviations from a sphere were also small, being near 16  $\mu\text{m}$ , which is close to the repeatability limit of the profilometer. Near the clamp bar, the membrane follows the shape of the clamp. The radius of curvature is between the radii measured for the front and back clamps.

The distortion due to clamping the front and back bars together was determined by measuring the flat, outsides of the bars. The flat sides of the upper and lower front and back halves were measured separately. Then the front and back halves were clamped together at the normal 20 pounds of torque, with a narrow strip of membrane to act as a spacer. After clamping, the flat sides were remeasured. A small amount of distortion was present when the two halves are clamped together - 0.1 mm of curvature. The effect of the distortion on the curved surface was calculated. The distortion measured on the flat side was subtracted from the inner curve for each of the 4 clamp halves.

**Table 1 Surface error of membranes made of 70  $\mu\text{m}$  thick copper, 35  $\mu\text{m}$  thick copper, and 5 mil thick Kapton. The listed figure of merit is the rms deviation from a best fit parabolic cylindrical surface.**

Scan Width	No Precision-Rail		Precision-Rail	
	50 cm	60 cm	50 cm	60 cm
Membrane				
70 micron copper 62.5 cm wide November 2003	.0679 mm	.1632 mm	.0604 mm	.1261 mm
35 micron copper 62.5 cm wide February 2004	.1230 mm		.0700 mm	
70 micron copper 70 cm wide September 2003		.205 mm		.103 mm .0902 mm
5 mil. Kapton 70 cm wide March 2004	.0389 mm .0441 mm .0502 mm	.0503 mm	.0513 mm .0437 mm .0351 mm	.0631 mm .0514 mm

The distortion is the same direction and magnitude for the top and the bottom. Consequently, the global error contributed to the membrane is low order, only a change in the radius of curvature, not the surface regularity.

The clamp bars after inspection are considered to be within specifications and not a source of error for the membrane figure. The alignment of the clamp bars and the tension points on the clamp bars are still under investigation.

**Precision Rail Characterization and Effect**

The precision rails were shaped while measuring them with the profilometer. The ideal shape was a parabola with Radius of Curvature of 3.048 m. The lower rail deviated by 24  $\mu\text{m}$  rms and the upper rail deviated by 36  $\mu\text{m}$  rms as shown in Figure 20.

Once the rails are mounted, the true shape of the membrane is determined by the depth to which the rails is pushed into the membrane. The membrane shape was determined by measuring the membrane on the side opposite of the precision rails. The membrane follows the shape of the rails rather well, except for expected deviations near the outer edges, as seen in Figure 21.

**Alignment and Repeatability Testing**

To determine the repeatability of the membrane installation and alignment procedure, three membranes were installed with the identical process. The membranes were made of 70  $\mu\text{m}$  thick copper, 70 cm wide. The membranes were cut from the roll of copper with the same orientation to the curvature. The membranes were scanned over a 60 cm wide aperture with the profilometer. The measured surfaces were fit to a parabolic cylindrical surface with a Radius of Curvature of 3.04 m. The errors from the ideal parabolic

**Table 3 To determine the repeatability of the membrane installation and alignment procedure, three membranes were installed with the identical process. The membranes were scanned with the profilometer over a 60 cm aperture and the surface fitted to a parabolic cylinder with Radius of Curvature of 3.04 m. Listed in the table is the error from the fit for each membrane with and without precision rails.**

membrane	rms fit error ( $\mu\text{m}$ )	
	No Precision-Rail	Precision-Rail
first	158.0	100.0
second	208.0	118.8
third	157.4	107.6

cylinder were 100, 119, and 108  $\mu\text{m}$  rms with precision rails. These results show that surface figure is repeatable to under 9%.

**Summary**

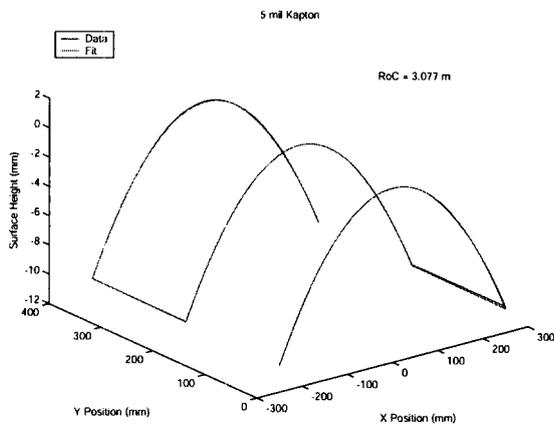
An on-axis testbed has been created for the DART architecture. Using a combination of Center-of-Curvature, Profilometer and Interferometer metrology, measurements have been made of several copper and kapton membranes. Currently, the team is determining what membrane and support characteristics lead to the most accurate membranes. An effort to validate nonlinear finite element models is underway.

**Acknowledgements**

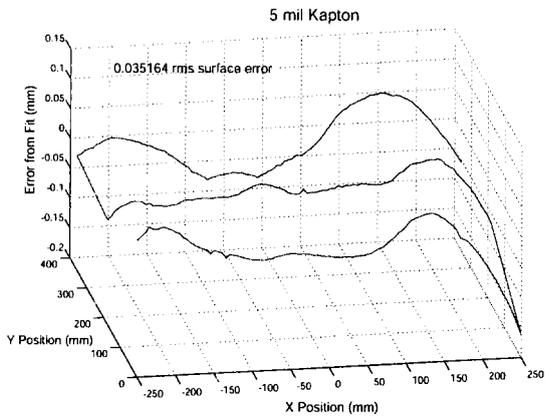
The work described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. This work was funded within the Large Apertures (LA) Element of

**Table 2** The curved surface of the clamp bars was measured with the profilometer. Each curve was fit in least-squares fashion to a sphere. The measured radius of curvature and rms deviation from a best sphere is listed. The radii of curvature match to within 0.8%. The surface error is close to the repeatability limit of the profilometer.

measurement	best fit sphere $R_C$ (mm)	rms fit error ( $\mu\text{m}$ )
lower front	3053	16
lower back	3037	14
upper front	3044	13
upper back	3025	10
upper membrane	3037	10

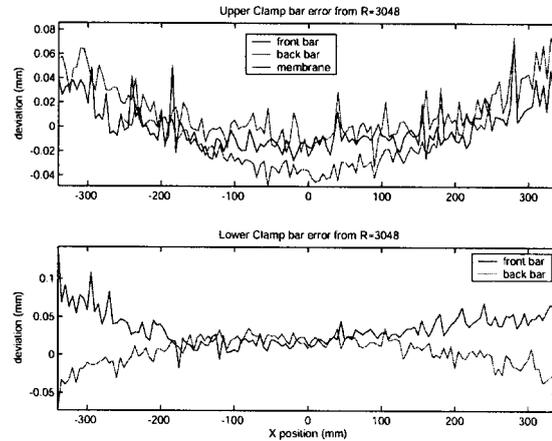


a) fig1label

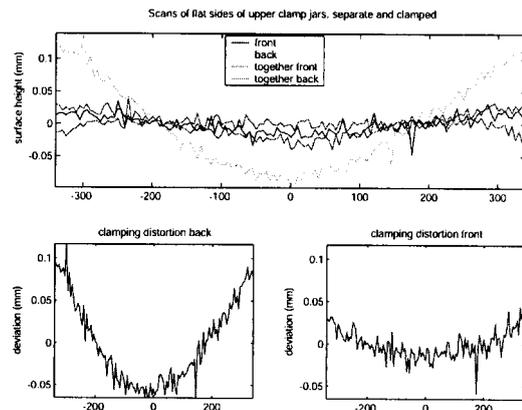


b) fig2label

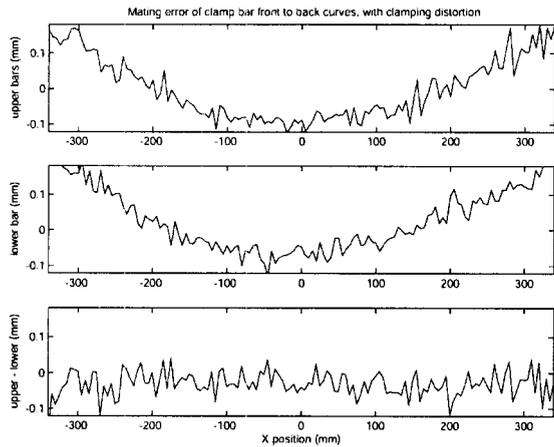
**Fig. 16** Profilometer scan of the membrane surface height fitted to a parabolic cylinder. The best fit radius of curvature is 3.077 m. The error from the best fit parabolic cylinder is 35  $\mu\text{m}$  rms.



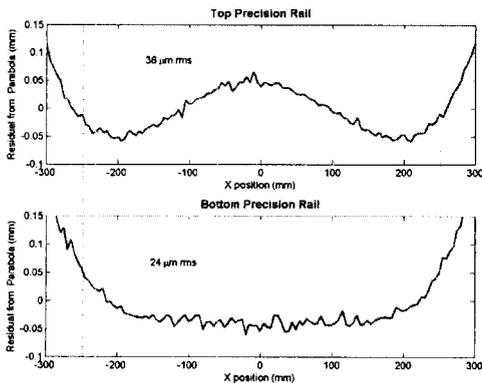
**Fig. 17** The inner, curved surface of the clamp bars was measured with the profilometer. The deviation from the ideal sphere of Radius of Curvature 3048 mm is plotted.



**Fig. 18** The outside, flat surface of the clamp bars was measured using the profilometer. The flat surface is distorted by 0.1 mm P-V by clamping the bars together.

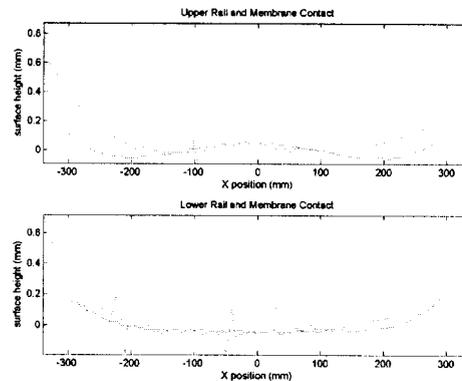


**Fig. 19** The distortion on the bar due to clamping was added to the measured curved surface. Plotted is the difference between the front and back curved surface of the clamp bars, both the upper and lower pairs. The membrane is assumed to have this shape near the clamp boundary. Any difference between the upper and lower membrane boundary should appear as global surface error. The difference between the boundaries is uniformly random and  $50 \mu\text{m}$  P-V. This error is within the additive measurement noise.



**Fig. 20** The precision rails was measured with the profilometer. The deviation from the ideal parabola of Radius of Curvature 3048 mm is plotted.

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**Fig. 21** The precision rails contact the front surface of the membrane. At the contact height, the back surface of the membrane was measured by the profilometer. The deviation from the ideal parabola of Radius of Curvature 3048 mm is plotted. Expected roll off at the edges is seen.