A telescope made with cylinders

Constructing a 3 m sub-millimeterwave prototype

B. Ramesh[1], B. Gurumoorthy[3], S. Raghu Menon[3], N. Ramakrishna Reddy[2,3], P.G. Ananthasubramanian[1],
A. Ghosal[3], C.M. Ateequlla[1] & V. Dhamodaran[1]

***Abstract*— A novel four mirror optics suitable to constructing large telescopes at optical and submillimeter wavelengths has been proposed recently. To prove this concept, a 3 m prototype based on this optics is being constructed. Of the four mirrors in the proposed design, three are parabolic cylinders. We have explored and demonstrated an economical method of making parabolic cylindrical panels to an rms accuracy of 20 μm, sufficient to observe up to a frequency of 1000 – 1500 GHz. The tertiary and quaternary themselves will form a telescope of 0.6 m^2 area with a fan beam, allowing us to characterise this part of the optics. In this paper, we present the fabrication details of the second pair of mirrors and their physical measurements. The beam measurements await the completion of a radiometer which is under construction.**

***Index Terms*— Instrumentation: miscellaneous Submillimeter Telescope**

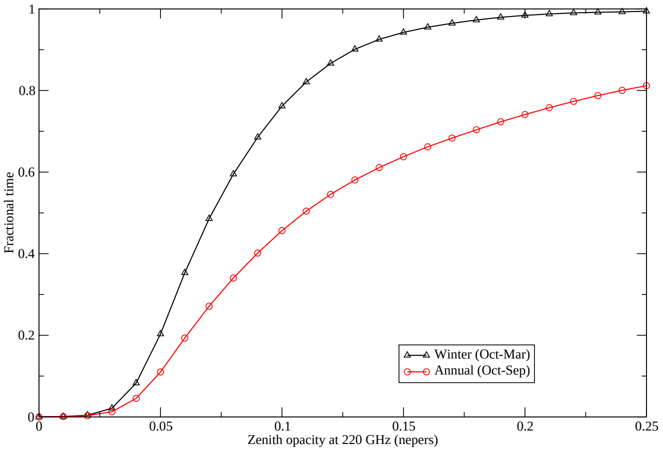

Fig. 1. The measured fractional time vs zenith 220 GHz opacity at Hanle averaged over 36 months.

I. Introduction

THE sub-millimeter waveband is important for photometric and spectroscopic studies of the high redshift Universe and of the deeply embedded star forming regions in our and nearby galaxies. The upcoming Atacama Large Millimeter-wave Array (ALMA) will have a large collecting area and high spatial resolution, but a small field of view. Its continuum bandwidth will be smaller compared to that of bolometers or photon-detectors. This creates both an opportunity and a need for an effective complement to ALMA: a large ($\gtrsim$ 30 m) single dish fitted with a modern photon-detector array can be faster than ALMA for continuum source detection. Besides being powerful in its own right, such an instrument can provide zero-spacing data for making more complete images with ALMA. It will also be a useful complement to the Giant Meterwave Radio Telescope.

Being naturally endowed with many high altitude desert sites in the Himalayas, India can be in the frontline in exploring this new frontier. A 220 GHz tipping radiometer has been monitoring the optical depth at Hanle (Latitude 32°46′46″ N; Longitude 78°57′51″ E; Altitude 4500 m, above MSL) for the last three years, almost uninterrupted [1]. Figure 1 shows the results. The fractional time for opacities less than 0.06 in the three winter periods mentioned are above 30% and the corresponding fractional time for opacities less than 0.1 are above 70%. The opacities show seasonal variations as normally expected and in general one month in summer (July or August) peaks in opacity values. Diurnal variations are not easily noticeable. These results indicate that Hanle is a promising site for sub-millimeterwaves and infrared astronomy during most of the year excluding the months of July–August. Figure 2 shows a picture of a site at a higher altitude of 5000 m.

Building a large sub-millimeterwave telescope calls for unconventional approaches. The recently proposed novel four mirror optics (Fig.3; [2]; for an analysis, see [3]) may just allow this. We have undertaken to prove this concept by constructing a 3 m prototype telescope and measuring its performance. Of the four mirrors in the proposed design, three are parabolic cylinders. The fourth mirror is small and can be fabricated readily with a CNC machine. Therefore, as a first step, we undertook to evolve an easy, effective and economical way to make accurate parabolic cylindrical panels. In this paper, we present the fabrication and measurement details of a panel for the third mirror and the design of the fourth mirror.

In the next section we describe our first attempt to demonstrate that parabolic cylinders can be made inexpensively. In the third section we describe the way we have made a trial panel of the tertiary and present measurements showing that the panel is accurate to 20 μm rms. This has helped us to learn the issues involved in making a 1m x 0.2 m cylindrical panel to the accuracy of 20 μm. We hope to make the three tertiary panels and assemble them together achieving better than 15 μm rms overall. In the fourth section, we present the modified equation for the quaternary and the CAD file. This part is being

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[1] Raman Research Institute, Bangalore 560080
[2] ISTRAC, ISRO, Bangalore 560058
[3] Indian Institute of Science, Bangalore 560012

Fig. 2. A picture of Polakongka La, a possible higher altitude site.

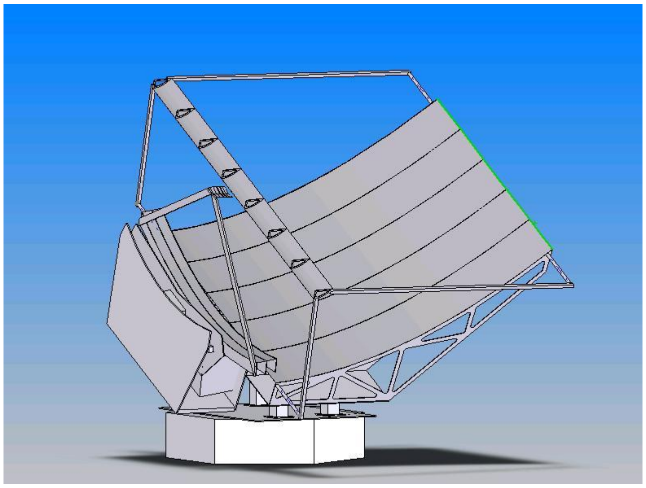

Fig. 3. Artist's view of the telescope

manufactured and will be soon available for testing. We hope to complete the assembly of tertiary and quaternary together by October, 2004. In the final section we summarise the results and present the roadmap.

II. Bending A Sheet To Precision

SMOOTH, flat sheets are commercially available. They can be readily used to make parabolic cylindrical panels with high surface accuracy at great economy provided one has an easy and effective way to bend them ensuring the desired figure. This seems readily possible according to a simple principle: for an ideal end-loaded beam, the height is a cubic function of its length [4]. For a cantilevered sheet of length L rigidly fixed at one end (x=0) and subjected to a uniformly distributed lateral pressure of intensity q (N/m^2), the deflection depends on the fourth power of x. The expression for the lateral deflection w(x) in such a situation is given by,

$$w(x) = \frac{L^4}{(D\pi^4)} \Sigma \frac{q}{m^2} sin(\frac{m\pi x}{L}) \quad \text{where,} \quad D = \frac{Yh^3}{12(1-\mu^2)} \qquad (1)$$

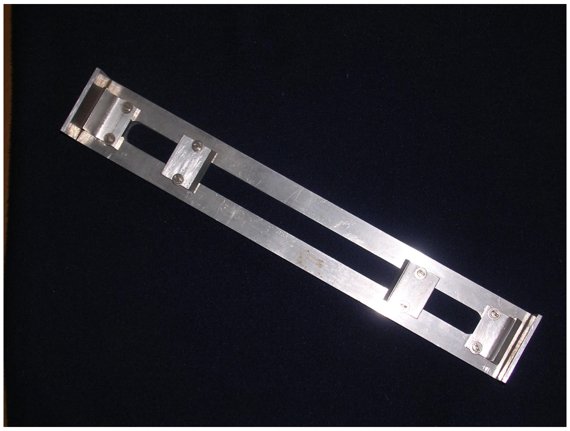

Fig. 4. A photo of the jig of wedges used.

Fig. 5. A photo of the test piece produced using the fixture, reflecting tree-tops outside the window. A reflecting film has been stuck to help visual assessment of the quality of the surface.

Here, D is the flexural rigidity of the plate, Y its Young's modulus, h its thickness and μ its Poisson's ratio [5].

Therefore, if the bending is arrested at many points in-between, one could use such 'cubic or quartic splines' to piece-wise approximate a parabola (or other similar curves). Figure 4 shows a jig where we have attempted to use this principle for accurate bending. It has been made in the following way: four aluminium wedges, two each of 7 mm and 25 mm height, were made and fixed at predefined positions, symmetrically about the midpoint on an 8 mm thick aluminium flat. The machining and positioning accuracies of the wedges were only about 100 μm. A transparency sheet was first laid on a surface plate. A glasswool mat was then spread on and glued to it using a commercial glue. Again another transparency sheet was glued over it. This sandwich under semi-cured condition was draped onto the jig of wedges and allowed to cure in-situ. Once cured, the stiff *cylindrical* skin was covered on all sides making a *vessel* in which the resin solution was poured to make a poly-urethene foam (PUF) back-up. After curing, the open side of the PUF was sliced into a plane and a 1 mm thick aluminium sheet was bonded. The curvature along the length was measured by mounting the surface on a lathe-bed and using an LVDT dial guage mounted on the tool post. The

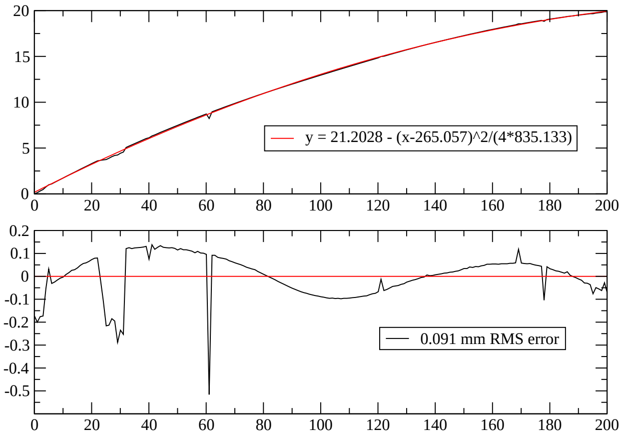

Fig. 6. Measurements showing 90 μm *rms* error. Profile measured on the surface before sticking the reflecting film.

lathe had a linear motion accurate to better than 10 μm and a digital read out to easily monitor the independent co-ordinate along the length of the profile. The output of the scan therefore was a series of (x,y) values that could be then processed to compare with the nominal geometry. Figure 5 shows the photo of the piece made. The top panel of Fig. 6 shows the raw data and a quadratic fit to it. Residuals after removing the fit from the measured profile is shown in the bottom panel. The *rms* error is about 90 μm with large contributions coming from the waviness. This, we suspect to be due to the sag between contact points. Nonetheless, this experiment demonstrated that fine tuning of such a method can indeed lead us to accurate cylinders to about 20 μm *rms*. We note that sufficiently stiff panels as light as 6 kg m^{-2} can be made in this manner.

III. Constructing the tertiary panels

THE above method of making a cylindrical panel, while satisfactory, brings up some practical issues. Especially, such a manufacturing method needs to be characterised for its long term and weather dependent effects. This we plan to do. Meanwhile, we modified the method to use more traditional materials and manufacturing processes. Firstly, we decided to use aluminium sheets rather than transparency sheets (which eventually we meant to vacuum-coat with aluminium thin film). This straightaway increases stiffness although contributes to weight as well. Secondly, we decided to use profiled laminates, cut using CNC machines, along the curved direction instead of the wedges along the cylinder's axial direction. Thus, one such a laminate is kept at every 150 mm along the cylinder's axis to support the cladding. A natural benefit is that the stiffness of the sheets along the cylindrical direction automatically increase owing to the bending in the orthogonal direction.

A. Material

Material used for the reflecting surface of a telescope should have the following properties - high specific strength to weight ratio, stiffness, good impact strength, electromagnetically reflecting, good conductor of heat and electricity, high resistance to corrosion, low coefficient of thermal expansion and high dimensional stability. In addition to these, the material must also be available in the form of thin sheets/sections and must be easy to machine and fabricate.

The materials used traditionally are mild steel, brass, stainless steel, aluminium alloys and composites/FRP. Steel is not considered because of considerations of weight. Composites/FRP is not chosen because errors during manufacturing (of the order of 100 μm) will not allow meeting the requirement that the *rms* of the reflecting surface be within 10 μm to the nominal shape. The dimensional integrity of composites/FRP over time is poor due to warpage caused by temperature variations and differential thermal expansion between coating and the substrate. Moreover the costs of fabrication are high when the number of components to be made is small.

In contrast aluminium is a good candidate for the reflecting surface as it meets all the requirements listed above. Sheets of various gauges and specifications are readily available. Aluminium sheets also possess easy formability.

This allows the fabrication of the tertiary mirror in a simple and economical method while allowing for scaleability with respect to the size of the mirror. The mirror is made by cladding a thin sheet of Aluminium over a set of laminates that capture the parabolic profile of the tertiary mirror. Analysis of such a structure when subject to wind loads expected at the final site (the telescope is expected to be operational at wind speeds of 30 kmph) using a commercial Finite Element Analysis tool (ANSYS) indicates that a sheet of 1 mm thickness is adequate to meet the accuracy required of the reflecting surface. The span between the laminates was set to be 200 mm in the analysis.

B. Method of Manufacture

The fabrication of the tertiary mirror involved three main steps. First the laminates were made by CNC machining. The laminates were then assembled at a spacing of 150 mm to form the substrate for cladding. A 1 mm thick sheet was then clad over this to form the mirror.

CAD model of a laminate with the parabolic profile along with the locator holes (for spacing the laminates before cladding) was generated in SolidWorks. A rendering of the CAD model of the laminate is shown in Fig.7. While it is quite feasible to obtain the laminate for the entire span of 3 m in a single setting on some CNC machines, it was decided to make the laminates in 3 parts (each 1 m in span). This was done for two reasons. As the telescope to be deployed will have a span of 30 m that can only be made in parts and assembled. It was therefore decided to make the scaled prototype also in the same way so that the processes once validated can be repeated to get the additional pieces required for the larger mirrors. The span of 1 m also provides greater options in terms of the machining vendors resulting in a more economical process.

Slots (see Fig.7) were positioned in each of the three parts of the laminate to enable correct assembly after machining.

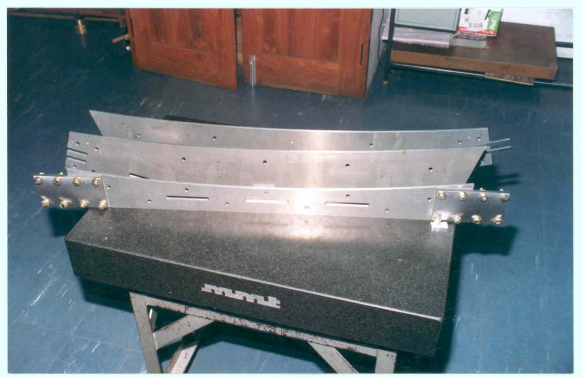

Fig. 7. A photo showing the profile segments, ground keys, slots and side-plates to ensure alignment.

Fig. 8. A photo showing profile being measured across a joint on the assembled laminate.

The three pieces forming the laminate were machined in a vertical CNC machine. The data on the parabolic contour was generated from the CAD model with a step size chosen to maintain the interpolation error over the step to be within 3 μm. Each piece was machined in a single set-up but with some modifications in clamping during the machining process. All the locator holes and the slots were machined with respect to the same reference frame in the single set-up.

Highly precise and ground keys were then used to assemble the three pieces to form a single laminate (see photo in Fig. 8). The profile obtained was then measured using an LVDT dial guage (range 20 mm, least count 0.001 mm).

Two laminates were then assembled to form the substrate for cladding. A total of ten spacers were used to locate the two laminates with respect to each other and bolted in place. The assembled substrate was again scanned to validate the parabolic profile defined by the two laminates in the assembled position. A 1 mm thick Aluminium sheet (local waviness less than 10 μm) was then cladded over the assembled substrate. A quick setting glue was applied over the laminate surface. The 1 mm thick sheet was then placed over followed by a 3 mm thick rubber sheet. A roller was then used to roll over along the length of the laminates to enure that contact between the sheet and the laminate was uniform along the length. The rubber sheet was removed after the glue set and the mirror was taken for measurement.

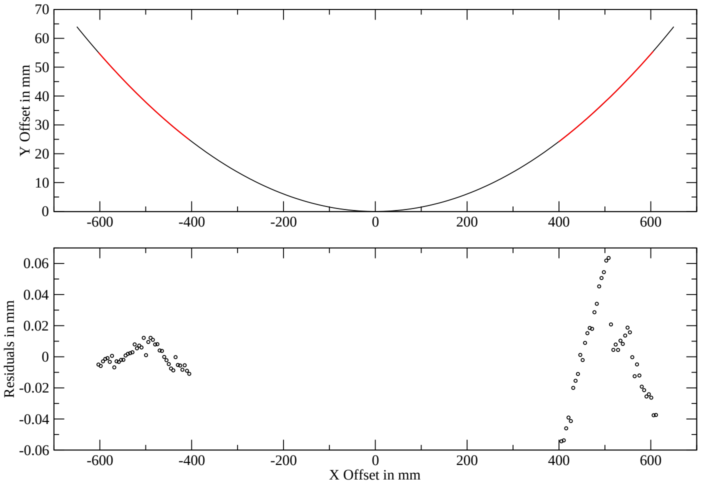

Fig. 9. Top panel shows the measurements (red) laid over nominal profile (black). The bottom panel shows the residuals across the joints. Some adjustments seem necessary.

Fig. 10. A photo showing mirror, formed by cladding a 1 mm thick sheet over the substrate made by assembling the two end laminates in parallel and aligned using ten spacers, on the test bed.

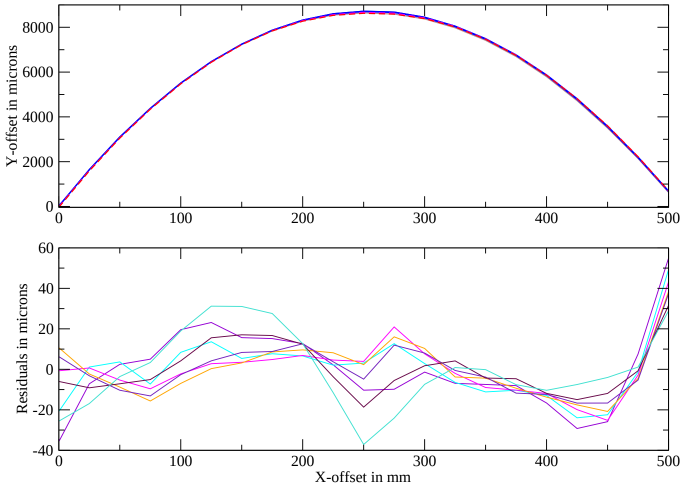

Fig. 11. Top panel shows raw data and quadratic fits to them along seven profiles, separated by 25 mm. Bottom panel shows the residuals after the fits. The rms is within 20 μm.

C. Measurements

To maintain the desired final accuracy of 10 μm *rms* on the mirror surface, the profile as defined by the laminate and the substrate and the final mirror were scanned using two different systems. One was by mounting the profile to be scanned on a lathe bed and a LVDT dial gauge on the tool post as described earlier. The profile was sampled with a step size of 10 mm.

The second technique made use of a touch probe analog scanner from Renishaw. The profile to be scanned was placed on the bed of the scanner and aligned so that one of the scan axis was along the length of the profile (x-axis). As the output from the scanner is an analog signal that is then sampled by the control software and a dense set of points on the surface is obtained for fitting and comparison.

Top panel of the Fig. 9 shows the nominal and measured profile (in the vicinity of the junctions between the pieces forming the laminate). A span of 100 mm on either side of the two junctions was measured. The residual (difference between the nominal and measured) is shown in the bottom panel.

Figure 10 shows the measurement set up on the precision lathe bed. Top panel of Fig. 11 shows seven sets of measurements along the parabolic profile of the mirror, taken every 25 mm apart. The stepping in the orthogonal direction was also 25 mm. The residuals (difference between the fits and the measurements) are shown in the bottom panel. Figure 12 shows the surface plot of the measured data and the nominal surface. The scan was along the parabolic profile and the stepping in the orthogonal direction was ~ 10 mm.

As can be seen that by using readily available machining facilities and nominal locating devices it is possible to achieve a surface to within 20 μm *rms*.

IV. QUATERNARY

THE analysis of the new optics [3] provides the shape equation for the quaternary. However, for practical reasons the third mirror has been lifted by 300 mm and tilted by an angle, $\alpha = 6^\circ$ about a line parallel to Y axis and passing through the point (0,0,300). The final focus (x_0,0,z_0) has been shifted to (−344.944,0,0) i.e. $x_0 = -344.944$ and z_0=0. These changes modify the quaternary equations as given below. The third mirror focal length $f_3 = 1650\ mm$. Let O be the final focus. Let Q' with coordinates (x_1,0,z_1) be the left most point on the *imaginary* focal line of the tertiary. The chief ray reflecting off the tertiary at (0,0,300) will reach this point in the abscence of the quaternary. The values of x_1 and z_1 are given by,

$$x_1 = \frac{-f_3 \sin 2\alpha}{\cos \alpha} = -2\ f_3 \sin \alpha \quad (2)$$

$$z_1 = 300 + \frac{f_3 \cos 2\alpha}{\cos \alpha} \quad (3)$$

Then, a general ray passing through the point P (x,y,z) on the quaternary will converge (in the abscence of the quaternary) onto a point Q (xx,0,zz) on the tertiary focal line. The values of xx and zz and the distance, d, between these points, P and Q, are given by,

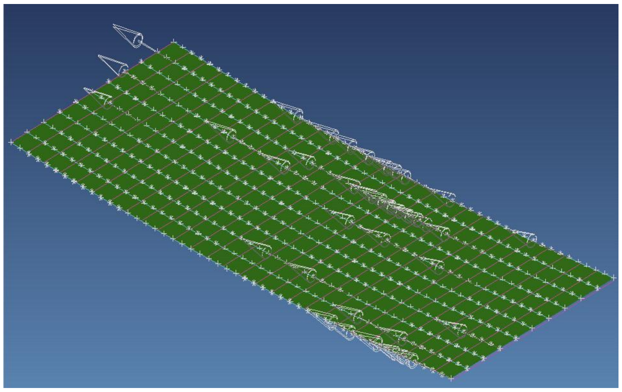

Fig. 12. Figure shows the errors displayed as a surface. The cones indicate large deviations. The surface fitting yields an *rms* error of ~30 μm.

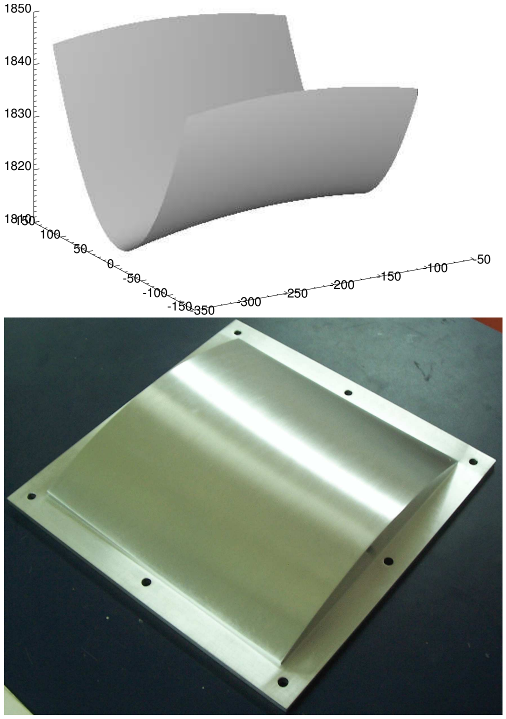

Fig. 13. The fourth mirror seen in projection and it being made on the CNC.

$$xx = x \cos 2\alpha + (z - z1 + x1 \tan \alpha) \sin 2\alpha \quad (4)$$

$$zz = z_1 + (xx - x_1) \tan \alpha \quad (5)$$

$$d = \sqrt{(x - xx)^2 + y^2 + (z - zz)^2} \quad (6)$$

In this case, the shape equation becomes,

$$K = \sqrt{(x - x_0)^2 + y^2 + (z - z_0)^2} + \frac{f_3}{\cos \alpha} - d \quad (7)$$

$$= \sqrt{(110 \tan 2\alpha)^2 + z^2} + \frac{f3}{\cos \alpha} - \frac{110}{\cos 2\alpha} \quad (8)$$

where the constant K is found using the chief ray. The rest of the shape is defined accordingly.

The top panel of Fig. 13 shows the surface plot of the quaternary. Its CAD model was generated with the software

SolidWorks. As can be seen, the shape is like that of a saddle. An aluminium alloy block has been machined to this shape on a CNC machine as the bottom panel of Fig. 13 shows. Measurements are being made to ensure that the shape is as desired and an *rms* of $\lesssim$ 10 μm is achieved.

V. Discussion

FROM the data presented so far, it is clear that we have been able to make a 0.2 m x 1 m trial parabolic cylindrical panel using available material and manufacturing processes meeting the specification to an *rms* accuracy of $\sim$ 30 μm. The tertiary has been fabricated with commercially available aluminium sheets using readily available CNC machining facilities. The envelope of the machine required has been restricted to 1 m specifically to exploit the competitive scenario prevailing in this class of CNC machines.

As the measurement show, it is possible to achieve a 10 μm *rms* accuracy over a span of 3 m by machining and fabricating the profiles of 1 m span, and assembling them carefully. This fabrication exercise has been useful in identifying the issues regarding the nature and type of locating devices to be used to ensure accurate assembly in order to produce panels to an *rms* accuracy of $\sim$ 10 μm. We are confident of achieving this and completing the three panels of the tertiary and the fourth mirror soon. Given the details of this fabrication process, it seems scaleable to fabricate both the primary mirror (3 m x 3 m) and the larger 30 m telescope.

VI. Summary and Scope

USING common CNC machines and manufacturing processes a 0.2 m x 1 m parabolic cylindrical panel with a surface smoothness of 30 μm *rms* has been made. Improving it to $\sim$ 10 μm *rms* seems readily possible. We hope to complete the tertiary, the quaternary and their assembly by October 2004. Thereafter, the tertiary movement mechanism will be fabricated allowing elevation tracking. This mirror pair itself forms a 0.6 m^2 telescope with a fan beam. Once the radiometer is completed, this beam will be measured. Since all the other mirrors are also cylinders, the same procedure used for making the tertiary panels will be used to make the primary and secondary mirrors. We hope to complete the construction of 3 m the prototype telescope by October 2005.

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Ramesh Balasubramanyam is currently working as a scientist at the Raman Research Institute. He studied B.E in Electronics and Communication at the Regional Engineering College, Trichirapalli, Tamilnadu, India and obtained his B.E. degree from Madras University, Tamilnadu, India in 1985. In 1993, he obtained his Ph.D. in Physics from the Physics department of the Indian Institute of Science, Bangalore. His areas of interest include radio astronomy and instrumentation for astronomy.

B. Gurumoorthy is currently a Professor in the Centre for Product Design and Manufacturing and the Department of Mechanical Engineering at the Indian Institute of Science in Bangalore, India. He received his B. Tech in Mechanical Engineering from Indian Institute of Technology, Madras in 1982. He received his M. E. and Ph. D. in Mechanical Engineering from Carnegie Mellon University, Pittsburgh, U. S. A. in 1984 and 1987 respectively. His current research interests are in the areas of geometric modelling, features technology, reverse engineering and rapid prototyping.

S. Raghu Menon is an M.Des student at the Centre for Product Design and Manufacturing, Indian Institute of Science, Bangalore, India. He received his B.E. in Mechanical Engineering form M.S. Ramaiah Institute of Technology, Visveswaraiah Technological University, India in 2003. His research interests are in the areas of product design, mechatronics, system design, machine tools & automation.

N. Ramakrishna Reddy is currently a Scientist/Engineer 'SE', in ISTRAC, ISRO, Bangalore, India and is studying ME (ISRO-Sponsered) in the Department of Mechanical Engineering at the Indian Institute of Science, Bangalore. He received his Diploma in Mechanical Engineering from Board of Technical education Tamilnadu in 1982 and his B.E in Mechanical Engineering from Bangalore University in 1996. During 1982-1984, he gained tool room experience in the area of inspection and quality control of inspection guages, jigs, fixtures, moulds and press-tools. He has 20 years experience in the design, manufacturing, realization, installation, commisioning and establishing ground stations with large antenna systems for ISRO's satellite/launch vehicle - TTC network all over the globe. His research interests are in the mechanical design and analysis of antenna structures and drive system design for large antennas.

P.G. Ananthasubramanian is currently working at the Raman Research Institute. He received his B.Sc in Physics from Madras University in 1981, Bachelor of Engineering degree in Electronics & Communication from Institution of Engineers (India) in 1989 and and M.Tech in Electronics design and Technology from Indian Institute of Science, Bangalore, in 1994. He has contributed to the development of millimeter & submillimeter-wave radio astronomy receivers at RRI and other places. During a 2 year stay at Cavendish Lab., Cambridge as a Research Associate, he was involved in the development of 350 GHz array receiver for JCMT, Hawaii and a prototype 183 GHz water vapour radiometer for ALMA, Chile. His current insterests include high altitude site characterisation and observational astronomy.

A. Ghosal is currently a Professor in the Department of Mechanical Engineering and in the Centre for Product Design and Manufacturing at the Indian Institute of Science in Bangalore, India. He received his B. Tech in Mechanical Engineering from Indian Institute of Technology, Kanpur in 1980. He received his M. S. and Ph. D. in Mechanical Engineering from University of Florida and Stanford University in 1982 and 1986 respectively. His current research interests are in the areas of kinematics, dynamics and control of robots and multi-body systems and design of mechanical systems.

C.M. Ateequlla has been working at the Raman Research Institute since 1980. He obtained his B.E. degree in Mechanical Engineering from the University of Mysore in 1972. He worked at National Aeronautical Lab., Bangalore and Bharat Earth Movers Ltd., Bangalore for brief periods before joining RRI. He has worked in fabrication and commissioning aspects of various projects at RRI.

V. Dhamodaran is currently working at the Raman Research Institute.