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Advanced technology in the VATT

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ABSTRACT

The Vatican Advanced Technology Telescope (VATT) now being fabricated differs from traditional telescopes in many ways. The altitude over azimuth mount will be direct driven by large diameter motors. The cell for the f/1 borosilicate honeycomb primary mirror incorporates a thermal control system to stabilize the mirror temperature. The f/9 Gregorian secondary will be mounted on a six-axis stage and controlled to submicron resolution in order to maintain the strict collimation tolerances needed for the fast optical system. Though only 1.83 m in aperture, VATT incorporates many of the design features of larger projects in the 8 m class.

1. INTRODUCTION

The VATT is a cooperative effort between the University of Arizona and Vatican Observatory to build a high quality modern telescope, making use of a 1.83 m borosilicate honeycomb mirror which was cast at f/1 as a demonstration of the spin casting process developed at the University of Arizona.[1]

As of this writing many subassemblies and parts of the project are nearing completion at various facilities. The primary mirror is being polished at the University of Arizona Mirror Lab using a stressed lap (Martin *et al* in these proceedings). The highly aspheric secondary is being polished using conventional techniques by Space Optics Research Laboratories in Chelmsford, Massachusetts. The altitude over azimuth mount is being preassembled at L and F industries in Huntington Park, California. A temporary facility in Tucson holds the assembled dome and a temporary pier to support the mount during initial assembly, "shake down" and testing of the telescope and optics.

Excellent image quality is the crucial performance goal of the new generation of telescopes. The image quality of any telescope is a function of the quality and support of the optics, optical alignment both initially and continuously, mount tracking, and seeing both at the site and induced from the telescope, mirror, and facility. Every aspect of the facility and mount of VATT has been designed with the goal of realizing the potentially excellent seeing of the site atop Mt. Graham, Arizona. In this paper we describe some innovative features of VATT aimed at producing excellent images.

2. ALTITUDE OVER AZIMUTH MOUNT

One early point of debate amongst the design team was the choice of the mount—whether to build a traditional equatorial or to follow the more modern trend towards alt-azimuth. It is clear that larger telescopes in the 4-plus m class are more economically built with compact alt-azimuth mounts, but initial projections indicated the cost for either type mount would be the same for a 2 m class VATT.

In general the alt-azimuth mount is less massive but more complex, since both axes must track at continuously varying rates. They require modern computers and responsive servo systems to operate, trading silicon for steel. Instruments must be rotated on alt-azimuth telescope mounts to counter the field rotation, but since many instruments require rotation even when installed on equatorial telescopes, this was not a major determining factor.

An alt-azimuth mount was ultimately chosen for three reasons. First, its lower mass has less thermal inertia, so it can provide a cleaner thermal environment for the telescope optics. Second, its compact footprint can be contained in a smaller dome, not only lowering facility costs but also reducing the seeing associated with the volume and mass of the dome. Finally, gravitational flexures in an alt-azimuth mount are a function only of elevation angle rather than both right ascension and declination. Flexure mapping is thus easier and quicker in an alt-azimuth telescope. We anticipate using flexure mapping to hold focus and collimation in a manner similar to that used at the MMT.[2]

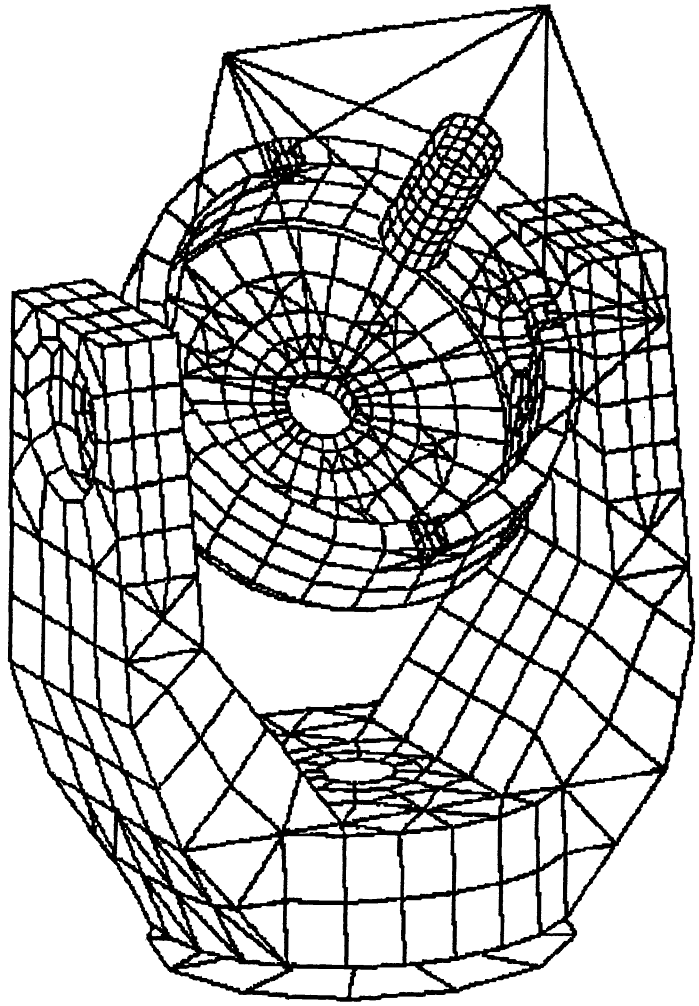

Figure 1: View of the finite elements model.

As in the design of the MMT, a high structural resonant frequency has been a goal in this project. A stiff structure has minimum gravitational and wind deflections and is more likely to exhibit repeatable flexural behavior.[3] The structural design which emerged was largely the work of a design team formed by engineers at L and F Industries and Paragon Engineering.

The 26,000 lbs. moving mass is supported on a 12 pad hydrostatic bearing. Other bearing combinations were examined, but the hydrostat provided highest axial stiffness together with lowest friction. A ball bearing pintle defines the vertical axis. The axis of the 9,200 lbs. altitude structure is defined and supported by two duplexed pairs of angular contact ball bearings.

A view of a finite elements model of the structure is shown in Figure 1. Massless elements were incorporated in the model to represent the axes of the primary and secondary mirrors. This allows prediction of miscollimation associated with wind and gravitational flexure. A very respectable 19 Hz lowest resonant frequency (neglecting the pier) is predicted from the model. Adding the 30 foot tall pier naturally introduces lower frequencies, but since they are not in the control loop, they do not directly affect the control bandwidth. The pier's mass also makes exciting these frequencies unlikely.

Large diameter motors (about 40 inch), available from Sierracin Magnedyne, were selected to drive the azimuth and elevation axes. Directly coupling these motors to the driven axes eliminates many problems which affect gear or friction driven telescopes. In particular, direct drives avoid the cogging inherent in gears and the random errors due to slip in friction driven systems. Direct drives also eliminate the windup of the gear boxes or friction wheel transmissions. The locked rotor resonant frequency for a direct drive system approaches the lowest structural resonant frequency, and the control bandwidth about half this. For VATT we expect a control bandwidth near 10 Hz.

The motors are considerably oversized; they are designed to produce up to 1000 ft.-lbs. of torque. Tracking the VATT will normally require 15 ft.-lbs. and occasionally up to 400 ft.-lbs. of torque depending on wind conditions. This corresponds to a power dissipation of only 0.5 Watts idle and up to 200 Watts peak. The heat from the motors, hydrostats, and other sources on the telescope is removed from the optical path by an exhaust fan at the base of the pier, the warm air being exhausted on the prevailing downwind side of the site.

3. MIRROR CELL

Several axial support patterns for the 1.83 m primary were studied using finite elements analysis. This study was carried out as part of the Columbus project by the Italian firm BCV and resulted in a pattern of 36 supports acting at two force magnitudes. With an aspect ratio of six, this mirror is very stiff, so no attempt will be made to correct the primary figure by controlling the discrete support points. This allows a relatively simple pneumatic support system of the bellofram type described by Mannery *et al*[3] to be used. Two sizes of bellofram cylinders are used to generate the two required forces with a single supplied pressure. Grouped into three sectors, the cylinders will be supplied with air pressure regulated by load cells built into the axial defining points.

To complete the support study we asked BCV to model several lateral support schemes including a sling, a mercury bag, and a push-pull counterweight system. The latter was found to be the most effective. The chosen design calls for 16 lateral actuators acting through whiffle trees to apply forces at the perimeter of the mirror's top and back plates. Bellofram actuators act through simple levers to supply the required support forces. Here again, load cells are used to regulate the air pressure supplied to the bellofram.

The predicted surface deformation assuming a perfect figure in the absence of gravity is 5.4 nm RMS (22.9 nm p-p) while zenith pointing, and 5.8 nm RMS (36.4 nm p-p) at horizon pointing. This more than meets the allowed error budget.

The use of a discrete point support pattern leaves the back of the mirror open for forced air ventilation of the individual honeycomb cells. Air is circulated by 8 on-board fans through liquid-to-air heat exchangers to control the air temperature. Waste heat—most of which is generated by the fans themselves—is removed via a liquid loop to the base of the pier where a refrigeration unit controls the liquid temperature to drive the mirror to ambient air temperature. The waste heat from the mirror, cell, and circulating fans is ultimately dumped to the ambient on the prevailing downwind side of the facility.

One early point of concern with this design was the effect of fan vibration introduced so close to the primary. To test for any ill effect, several fans were clamped to the cell of one of the MMT's six 1.83 m diameter mirrors. A laser interferometer with a limiting resolution of about 100 nm amplitude was unable to detect any fan vibration.

4. GREGORIAN SECONDARY AND COLLIMATION MOUNT

The secondary focal ratio for any two mirror telescope is set by the primary focal ratio and the magnification of the system, M. Roughly, the secondary focal ratio is $(1 +/- 1/M^2)$ times the primary focal ratio, with the plus sign used for Cassegrain systems and the minus sign for Gregorian.[5] For VATT the primary was cast at f/1; for the desired f/9 system focal ratio a Cassegrain secondary has to have a focal ratio about f/1.1. The secondary must be aspheric by about 600 waves. Standard techniques for testing Cassegrain secondaries, such as the Hindle sphere, become unwieldy at such fast focal ratios.[6] Refractive tests are expensive and at such a high asphericity have a residual wavefront error which makes testing unreliable at about the $^1/_4$ wave level.

Cost and reliability of test results led us to a Gregorian optical system (Figure 2). Though the secondary is faster (focal ratio f/0.9), its elliptical cross section allows a definitive test between the two foci of the ellipse with only one reflective spherical test optic (Figure 2a). The aplanatic Gregorian system is comparable to the Ritchey-Chrétien and in most respects is slightly superior.[7] An historical objection to the Gregorian has been its tube length. While a slow Gregorian is certainly longer than a slow Cassegrain, in fast systems the Gregorian can be made even shorter than the Cassegrain by using the light baffle as the secondary mounting tube.

The very fast optical system and the goal of producing excellent images leads to extremely tight collimation and focus error budgets, a very challenging aspect of the structural and systems design. The allowable defocus, which scales as the square of the primary focal ratio, is the most stringent at only 13 μ focus motion per arcsecond RMS image enlargement.

Coma limits the allowable secondary decenter. However, a decenter can be compensated by a tilt provided the combination is equivalent to rotating the secondary about prime focus. Tilt-decenter compensation is limited by astigmatism which is greatest at the edge of the field. For VATT the 0.3 arcsecond image goal allows for no more than 0.1 arcsecond RMS image enlargement anywhere over the 15 arcminute field due to miscollimation and misfocus. This results in allowable miscollimations of 1.3 μ defocus, 8.64 μ decenter, and up to 136 μ decenter compensated by 372 microradians of tilt. The predicted gravity flexure is about 30 μ so it is clear that active collimation is essential. We are encouraged by the MMT experience where flexure mapping is used to coalign 6 telescopes to typically $^1/_{30}$ of the uncorrected alignment.

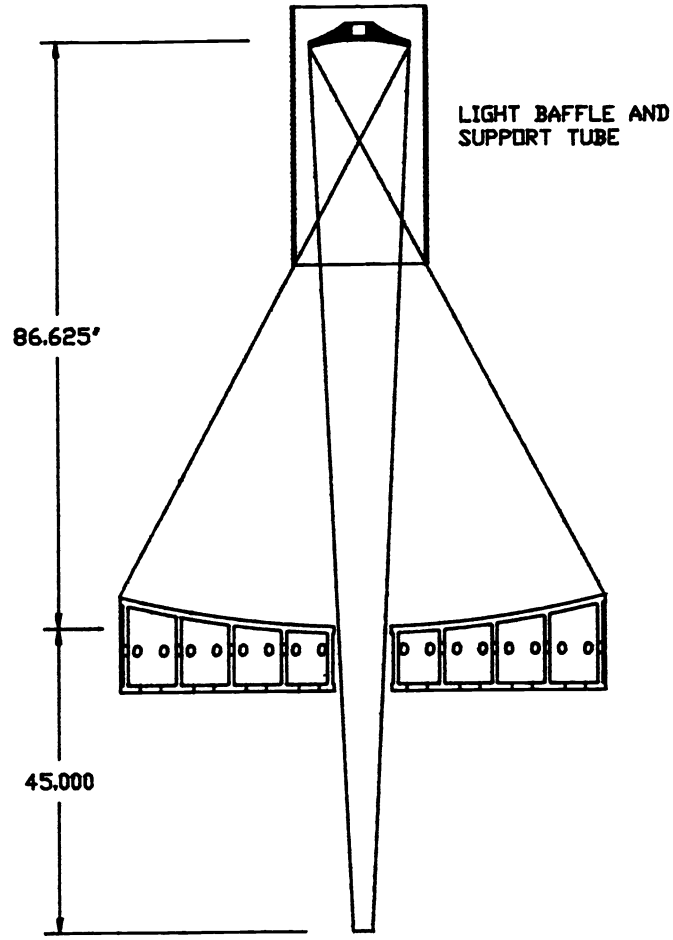

Figure 2: Layout of the f/1 to f/9 aplanatic Gregorian optics.

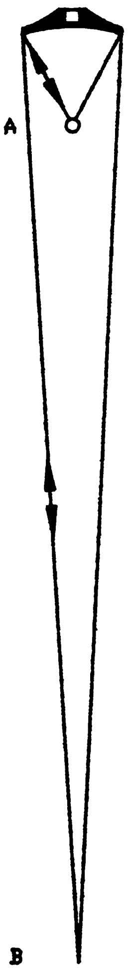

Figure 2a: Double pass test for the ellipsoid secondary.

The 15 inch diameter Zerodur secondary is lightweighted using an arched back, center mounted design. At 28 lbs. it is about $^1/_3$ the weight of a solid disc. It will be mounted on a flexural stage adjustable in focus, tilt, translation, and a limited rotation about the optical axis. The mount design has been adapted from a mount for a 5 inch diameter tip-tilt mirror, developed by David Shemwell of Spectra Technology, which was successfully operated at over 300 Hz bandwidth. This mount features very high resonant frequency, ease of construction and low cost.

The design (shown in Figure 3) consists of three flexure bars which hold the center hub of the mirror with respect to an outer hub which is rigidly attached to the secondary spider. The flexure bars define two lateral translations and rotation about the optical axis. Differential expansion between the inner and outer hubs results in a slight rotation about the optical axis—an elegant form of thermal compensation. The remaining degrees of freedom are defined by three axial hardpoints. Each hardpoint is actuated by means of a stepper motor, a 60:1 single stage "harmonic drive" gear reducer, and a micrometer to give $^1/_{10}$ μ per step resolution with about one step hysteresis and no loss of position on power-down.

To provide lateral actuation the three flexure bars were modified with an additional ring-shaped flexure at the mid-point of each bar. This acts on the principle of a ring strain gauge in reverse. A step-motor and gear reducer assembly similar to the axial actuators moves a micrometer mounted inside the ring. The micrometer distorts the ring into an ellipse pulling the two ends of the flexure bar together translating the mirror. The arrangement provides 0.5 mm of lateral travel with very low hysteresis.

The three axial hardpoints which control tip-tilt are also fitted with piezo electric stacks capable of introducing up to 10 arcseconds of image motion with very fine resolution and fast response. Given the lightweight, stiff mechanical design we expect to be able to tip the secondary at rates up to about 30 Hz for rapid guiding. VATT is thus designed with some simple adaptive optics capabilities for development in the future as the project matures.

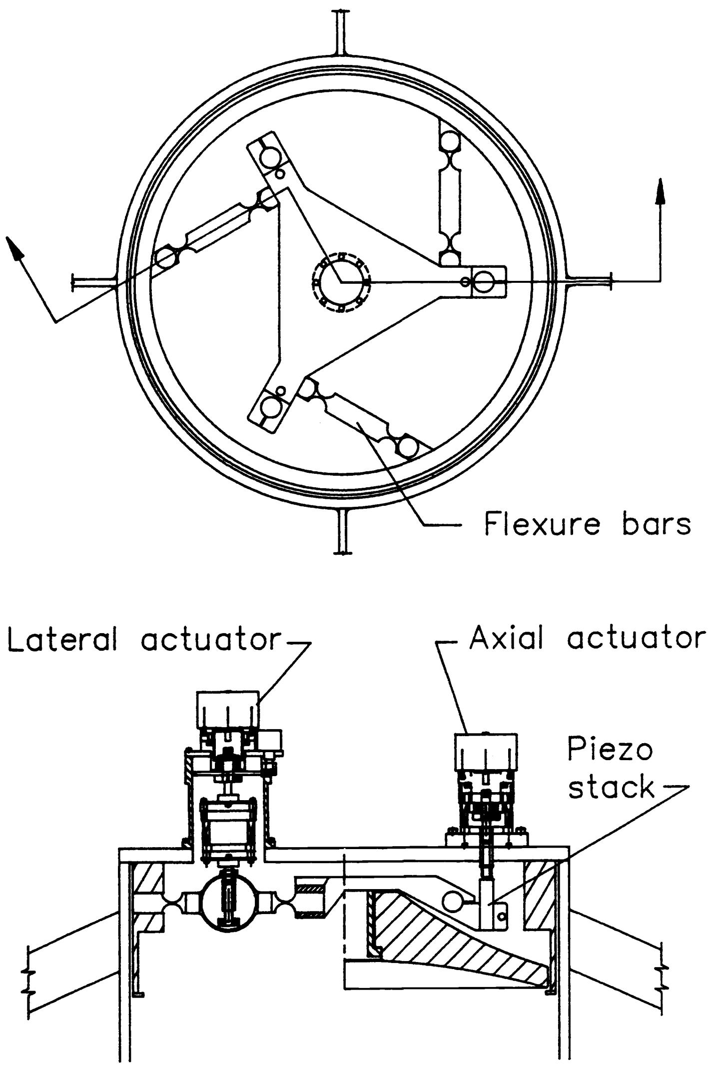

Figure 3: Six axis collimation stage.

5. SUMMARY

We have described several novel features of VATT. Though in the 2 m class, VATT is a new generation telescope and addresses many of the same issues now facing larger telescope projects.

We would like to express our thanks to all who have contributed to this project. Especially we thank David Chivens and Terry King of L and F Industries, Steve Gunnels of Paragon Engineering, John Ray of Steward Observatory, and Roland Shack of the Optical Sciences Center. We also thank Fred A. and Alice Lennon, and Thomas J. Bannan for their generous financial support.

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