The Portable 0.7-Meter CDK Alt-Az Telescope

Portable 0.7-Meter CDK Alt-Az Telescope

for
Research, Astrophotography, and Visual Observation

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Introduction

The 5-meter Hale telescope on Mt. Palomar, completed over a half century ago (1948), remains the largest equatorially-mounted telescope ever built. There are now some 18 larger telescopes ranging in aperture from the 6-meter Zelentchouk telescope on Mt. Pastukhov to the two 10-meter Keck telescopes on Mauna Kea. Every single one of these large mountaintop telescopes employs an altitude-azimuth (alt-az) mount for two fundamental reasons. First, alt-az mounts are very compact as compared with equatorial mounts. Second, unlike equatorial telescopes, the forks and azimuth structures of alt-az telescopes do not change their orientation with respect to local gravity, while their optical tube assemblies (OTAs) only change their orientation in one plane (altitude) instead of two (right ascension and declination). As a result, the cost of large alt-az telescopes and their enclosures is greatly reduced as compared to equivalent aperture equatorial telescopes.

We recognize that equatorial telescopes have certain advantages. Tracking only requires a constant-rate drive in one axis. An alt-azimuth telescope requires constantly changing drive rates in three axes: altitude, azimuth, and field orientation. However, since low cost, off the shelf microcomputer-based alt-az telescope control systems are now readily available, the question that interests us is whether or not the alt-azimuth revolution that began with large-aperture telescopes can now be extended to research-grade telescopes in the 0.5- to 1.0-meter aperture range?

Would such economical, modest aperture alt-az telescopes be scientifically useful if they could be developed? Large robotic survey telescopes are now uncovering thousands of interesting objects whose true nature can only be revealed through extensive follow-up observations. There simply is not enough large telescope time for such observations, so this task falls to modest aperture research telescopes. If the cost of such modest aperture telescopes could be significantly reduced, their numbers could increase, and the more extensive follow-up observations they could make would enhance our scientific understanding to the benefit of the astronomical community.

Of course, several thousand telescopes in the 0.5- to 1.0-meter class already exist; these are the classic Dobsonian design constructed by amateur astronomers. These telescopes have been optimized for visual observing and feature exceptionally low cost construction. Furthermore, hundreds of equatorially mounted 0.5- to 1.0-meter class telescopes in observatories around the world represent a proven design for research and imaging. We are tapping both of these knowledgeable, well established "telescope communities" for applicable ideas.

Our overall objective is to build a similar "community of knowledge" with respect to the development of low cost, modest aperture, research-grade alt-azimuth telescopes. As this open source knowledge base expands, it could spur both commercial production and individual construction of innovative, modest aperture, alt-az telescopes. Our objective is to encourage discussion and receive feedback from those interested in such designs, and to entice others to join in our development efforts or initiate their own.

In an earlier paper (Genet et al 2007) we suggested that "…the combination of low-cost alt-azimuth telescope control systems and affordable aerospace materials had reached a point where a revolutionary new class of lightweight, highly capable alt-azimuth telescopes is emerging." In this paper, we move beyond such generalities to a conceptual design for a 0.7-meter portable alt-azimuth telescope.

Our goals for this demonstration telescope include:

1.) Wide-field photo-visual optics for science, imaging, and visual observing.
2.) Ease of manufacture, implying that the telescope will be low in cost.
3.) Component cost budgeting that allocates money for performance.
4.) Go-to pointing with sufficient accuracy to satisfy research
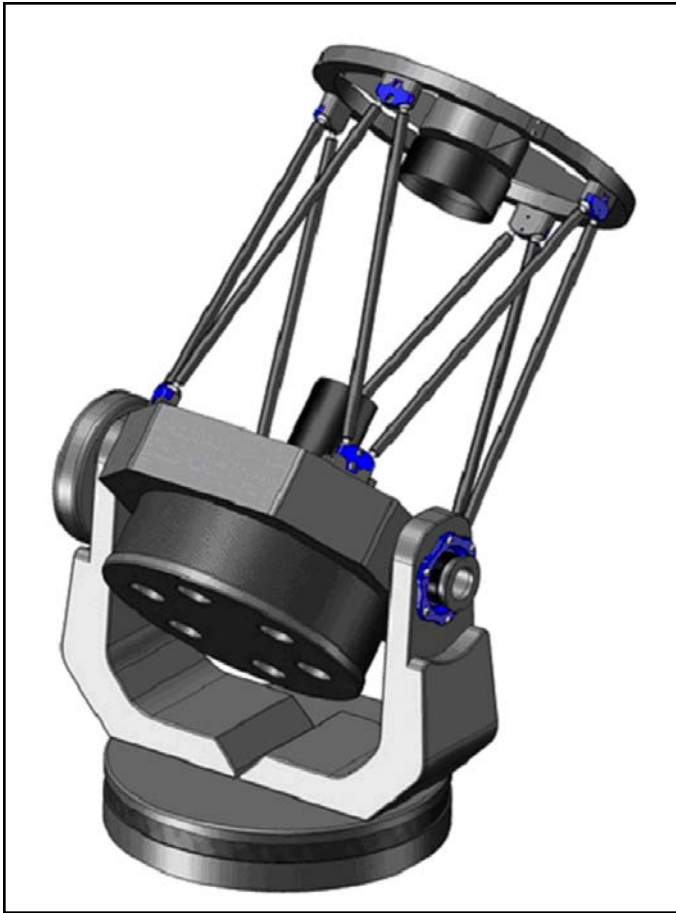
Renderings by Bob Peasely

Two views of our 0.7-meter alt-az conceptual design. The combination of an alt-az mount, lightweight structure, and dual Nasmyth foci could provide a compact, portable, low cost, easy to use, research-grade telescope.

requirements.

5.) Open-loop tracking to satisfy research and imaging requirements.

6.) Field de-rotation with sufficient accuracy to allow wide-field imaging.

7.) Structural stiffness to resist wind pressure and gravitational loading.

8.) A high precision, wide bandwidth control system to counter wind pressure.

9.) Flexible, maintainable computer-standards-compliant control software.

10.) Portability.

Why We Chose a 0.7-m Nasmyth CDK

The optical tube assembly (OTA) of the telescope is one of the principal drivers for the telescope design. The OTA's width, length, and moment of inertia determine many of the mechanical properties of the mount. The width is determined by the aperture of the telescope, but the length and moment of inertia are determined by the optical design.

Our first major decision, therefore, was to pick an aperture and optical design. Because we were interested in telescopes in the 0.5- to 1.0-meter range, we selected an aperture at the geometric middle of that range: i.e., 0.70 meters.

At first, we considered a Newtonian parabolic configuration with a Wynne corrector. This combination has worked well for many telescopes. Low cost parabolic correctors are available from TeleVue, Baader, and Lumicon, and larger diameter Wynne correctors are available from Keller. This tried-and-true approach has much to commend it, and it is entirely appropriate for smaller apertures and lightweight instruments such as CCD cameras. However, most of these correctors have limited backfocus distance, which may preclude the use of both an off-axis guider and deviator plate or other backfocus-hungry instrumental combinations, although a Keller corrector with a longer backfocus distance is available from DreamScopes.

We then considered a Newtonian configuration with a hyperbolic primary mirror and a two-element corrector. Unlike the Wynne design, correctors for hyperbolic mirrors are specific to the focal length of the primary. Nonetheless, the corrected hyperbolic system can simultaneously provide generous backfocus and large, well corrected flat fields. In addition, the corrector lenses for these systems can be manufactured in large diameters at reasonable cost. Their generous backfocus facilitates the incorporation of a deviator plate, off-axis guider, filters, and other instrumentation as needed. The large field of view allows, simultaneously, both large format cameras and access to a wide selection of guide stars, necessary if one desires a bright guide star for high frequency deviator plate corrections. We highly recommended this configuration for 0.5 meter class telescopes.

As the aperture increases, access to a Newtonian focus via increasingly tall ladders becomes unattractive even for most

experienced visual observers, not to mention educators with young students. Furthermore, placing large scientific instruments at the Newtonian focus increases the moment of inertia of the OTA and lowers its natural resonant frequency. Such instrument placement also adds to the wind cross-section at its most leveraged point.

For these reasons, we chose for our 0.7-meter telescope's basic optical configuration a Nasmyth focus with a tertiary mirror. eyepiece and instruments are at the pivot point of the altitude axis, so even with large changes in instrument loads, no counterweights are required and the instrument's moment of inertia is minimized. A tertiary mirror, admittedly a significant complication, is required because a compact, portable alt-az configuration is not well suited for access at the Cassegrain focus.

A Nasmyth focus is inappropriate for a small aperture telescope because the native focal plane will be located too close to the ground for convenient use. However, as the aperture is increased, a comfortable sitting height is eventually reached. This minimum natural height is achieved at approximately 0.7 meters of aperture, although smaller telescopes could use piers or other methods to raise the height of the focal plane. At larger apertures, such as 1.0 meters, there are comfortable standing-height eyepiece positions.

Three optical systems meet the criteria for our Nasmyth-focus telescope: the classical Cassegrain, Ritchey Chrétien, and corrected Dall Kirkham Cassegrain. We chose the corrected Dall Kirkham (CDK) for its wide, well corrected flat field, generous backfocus, and its relative insensitivity to secondary mirror lateral misalignment (the secondary mirror is spherical). PlaneWave Instruments manufactures an OTA with CDK optics designed by one of the authors (Rowe); this design has proven to work well for demanding, wide field astrophotography.

The Nasmyth optical configuration provides a convenient, fixed height eyepiece for visual observations, as well as an instrument location at the altitude axis that does not require rebalancing even with instruments of widely differing weights.
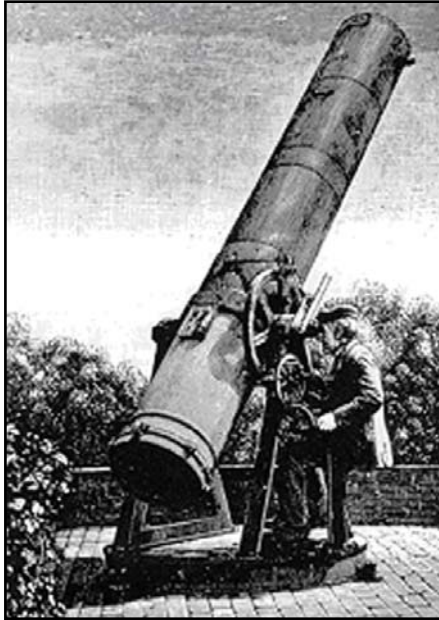
Optical Design

The optical layout of the 0.7-meter CDK is shown in Diagram 1. The tertiary mirror can rotate 180 degrees making both Nasmyth focus locations available.
We selected this optical configuration for the following reasons:
1.) It has a wide, flat, well-corrected field over a very broad wavelength region.
2.) The spherical secondary has no optical center, making the telescope easier to collimate than other Cassegrains. In addition, a sphere is easier and much less expensive to figure than the convex hyperboloid needed in other Cassegrain designs.
3.) The under-corrected primary is easier and less expensive to figure than its counterparts.
4.) The CDK can be designed with long back focus distance between the corrector and the focal plane, making it ideal for a

Nasmyth configuration where the light must pass through the altitude bearings and field de-rotator.

Two very common Schott glasses, BK7 and SK11, are used in the two-element corrector. The prolate ellipsoidal primary mirror is 64% corrected from a sphere to a paraboloid. At f/6.45, the telescope is quite fast for a Cassegrain configuration, providing the user with excellent etendue (the product of the collecting area and field solid angle) when a large imaging sensor is used. This well corrected field supports the largest commercially available CCD sensors available today, and should continue to do so well into the future. The large, flat field is very useful for a variety of off-axis guider (OAG) configurations.

Optical Manufacturing

We considered several approaches to manufacturing the 0.7-meter, f/3.0 primary mirror blank. Traditional slumped or flat "full thickness" (55-mm) Pyrex has worked well for mirrors of this size when supported by 18- or 27-point whiffletrees and would be a good choice. However, faster initial thermal cooling and better temperature tracking can be achieved with mirrors with lower mass and greater air contact area. Examples include cast open-back mirrors, fused cellular mirrors such as those made by Hextec and Wangness, and fused sandwich mirrors such as those made by Hubble Optics.

For our 0.7-meter prototype telescope, we chose to utilize a two plate Hubble Optics fused sandwich mirror with one intermediate layer of circular spacers (patents pending in both China and the United States). Each plate and the spacer layer is 19 mm thick, for an overall thickness of 57 mm (2 ¼ inches). There are 372 spacers, each 16 mm in diameter, distributed in 9 rings. The mirror will weigh about 70 lbs., which is less than an equivalent solid 0.7-meter 55-mm thick Pyrex mirror. With correct air flow, this blank will equilibrate much faster than a solid equivalent. In addition, we expect it to have less self-weight deformation.

## Microcomputer Controlled Telescopes, the Historical Perspective

Several of us have been involved, over the years, in the development of microcomputer controlled telescopes. Genet's 1982 Real Time Control with the TRS-80 was, perhaps, the first book on real time control with microcomputers. In 1983, Louis Boyd and Genet achieved totally automatic operation with a telescope that continued in use for 25 years. Microcomputer Control of Telescopes by Mark Trueblood and Genet was published in 1985. It featured amateur built systems along with analyses, circuitry, software, and formulae. An updated version of Trueblood and Genet's book, Telescope Control, is still available.

Diagram 1
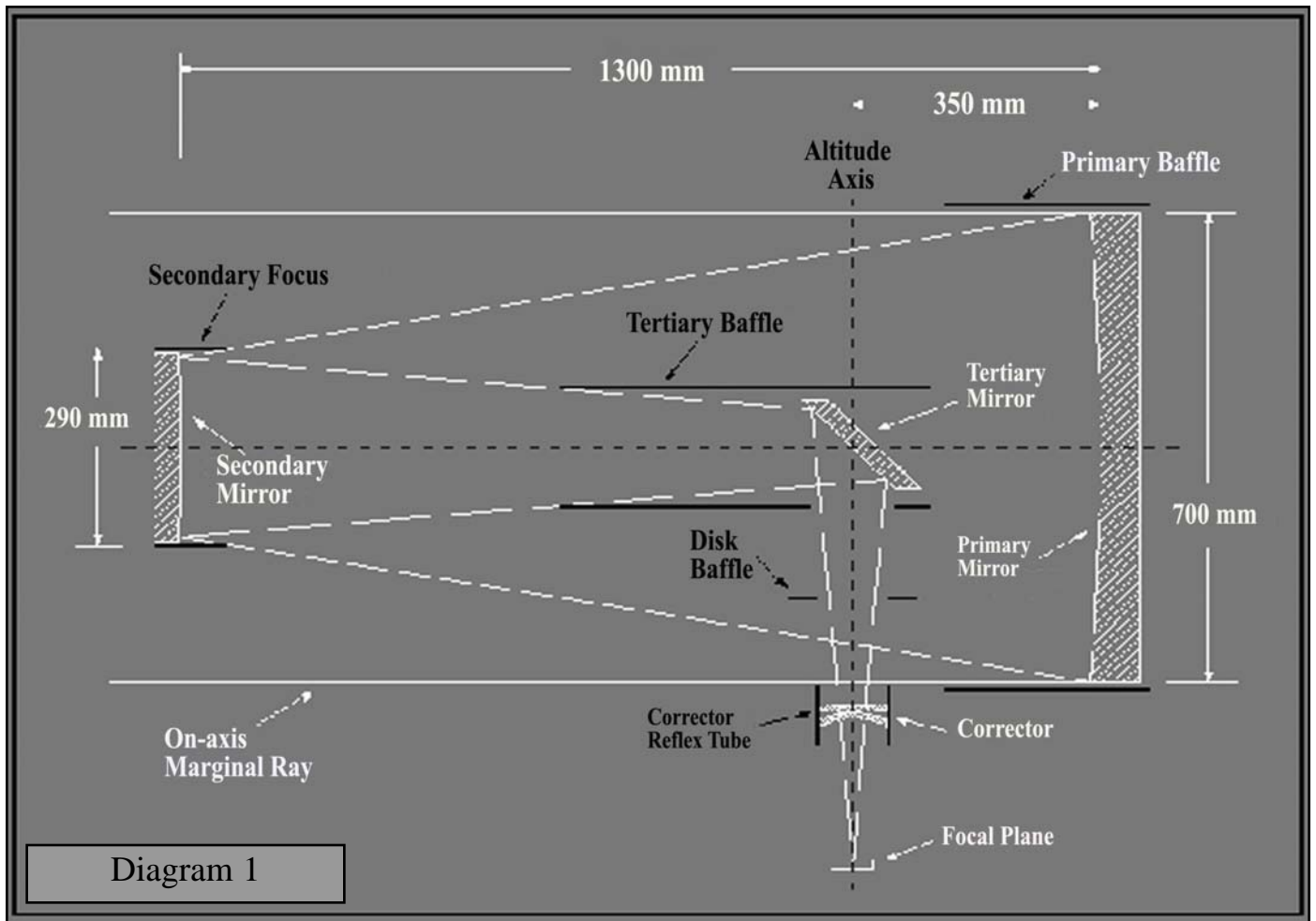
The optical layout of the 0.7-meter CDK telescope. The optical axis and altitude axis are coincident-often called the Nasmyth-focus configuration. The telescope is fully baffled over a 60-mm diameter image circle. The linear central obstruction is 41% (17% in area) and the effective focal ratio is f/6.45. The auxiliary disk baffle prevents undesired illumination of the focal plane from the opposite side of the telescope.

|	Radius 1	Thickness	Radius 2	Aperture Diameter	Spacing
Primary	-4200 mmSC=-0.64			700 mm	1250 mm
Secondary Baffle				284 mm	50 mm
Secondary Mirror	-3000 mm SC=0			270 mm	550 mm
Tertiary Baffle				188 mm	500 mm
Tertiary Mirror	Flat			135 mm Minor axis	372 mm
Lens 1 - BK 7	-1203 mm	12 mm	-356 mm	100 mm	1 mm
Lens 2 - SK 11	143.3 mm	7 mm	-109.3 mm	100 mm	274.3 mm
Focal Surface	Flat				

The optical prescription of the 0.7-meter CDK telescope. SC is the conic deformation constant. The primary is a prolate ellipsoid that is 64% corrected from a sphere to a paraboloid. The secondary mirror and all four lens surfaces are spherical. The secondary and tertiary baffle dimensions and locations are provided.
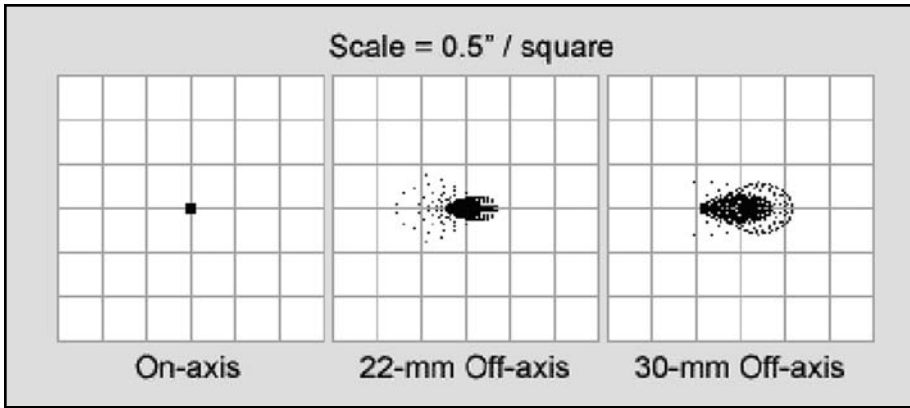
The polychromatic geometrical ray trace of the 0.7-meter CDK at three off-axis distances and three different wave lengths. Each small grid square is one-half arc second. The wavelengths used in the ray trace were 400 nm, 550 nm, and 800 nm. The telescope is very well corrected over a broad band, and will be seeing limited under almost all situations.

Clear Aperture	700 mm
Effective Focal Length	4516 mm
Effective Focal Ratio	f/6.45
Back Focus	274 mm
Central Obstruction	41%
Fully Baffled Field Diameter	60 mm
Polychromatic RMS Spot	8 microns
Diameter at Field Edge from	0.36 arcseconds
Ray Trace (400mm - 800mm)	
Vignetting at Field edge	7.5%

The main performance characteristics of the 0.7-meter CDK telescope.
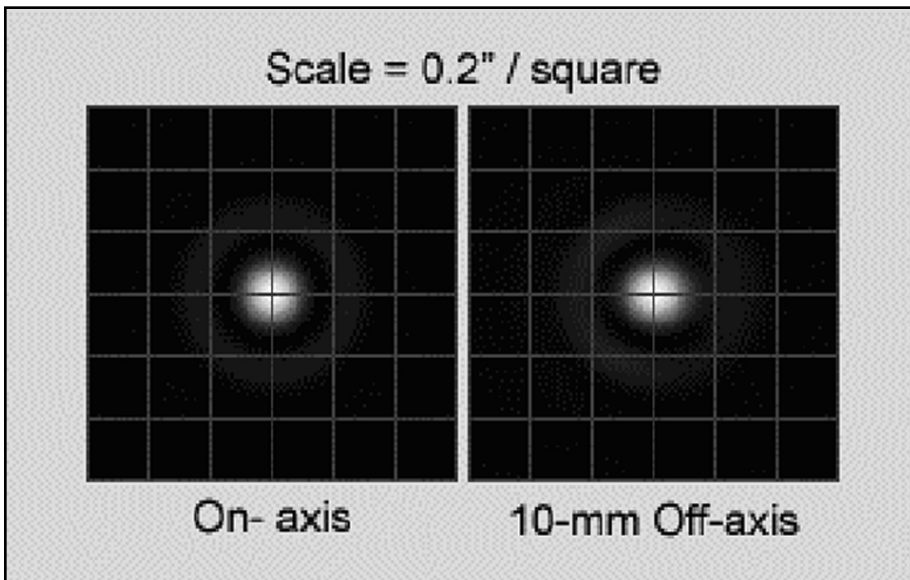
The diffraction performance of the 0.7-meter CDK at 550 nm. Each small grid square is 0.2 arc seconds. The 41% central obstruction has been included in the simulation. The on-axis Strehl ratio is greater than 0.97. In other words, there is less than 3% degradation in the peak intensity of the full diffraction image versus the theoretical value. The Strehl ratio remains greater than 0.8 over a 20 mm field diameter.

Bartels began developing his computer controlled telescope in 1988. The system incorporated two innovations. First, he altered the chipset of x86 computers for real-time control in order to micro-step two stepper motors by generating eight concurrent pulse width modulation (PWM) signals in software. The digital PWM information was outputted via the parallel port to a simple and inexpensive current switching circuit. Second, the stepper motor control was tied to a precision coordinate translation engine with error correction for alt-az mounts running on a 286 or 386 personal computer. Currently, we estimate that over 1,000 telescopes worldwide are running versions of this system.

Servos have gained in popularity with the introduction of Gary Myers' ServoCAT and Gray's Sidereal Technology controller in the past several years. These systems feature small box microprocessors capable of interfacing with PC and Mac software based on the ASCOM initiative. ASCOM offers a set of interface standards and instrument drivers, encouraging open source sharing that allows astronomical software applications to control a variety of motors, encoders, mounts, focusers and cameras.

Telescope Motion and Control

For small to intermediate telescopes operating within a dome or outside under mild conditions, simple open-loop stepper control systems-or their servo equivalent with low resolution encoders on the back of gearhead servomotors-are often adequate when used to drive telescopes through worm gears, belts, or friction drives. In these cases, pure telescope mass and the stiffness provided by the gearing can help resist the occasional wind gust. Even then, backlash and gear train compliance can easily ruin an imaging session under moderate wind conditions. It doesn't take much wind disturbance to cause significant trailing during an exposure.

A portable telescope, almost by definition, cannot fight external disturbances by being massive. It can, however, fight wind gusts by utilizing "electronic stiffness" provided by a fast servo control loop. Such lightweight telescopes, if they have stiff structures and low

0.7-meter CDK Performance
400 nm - 800 nm
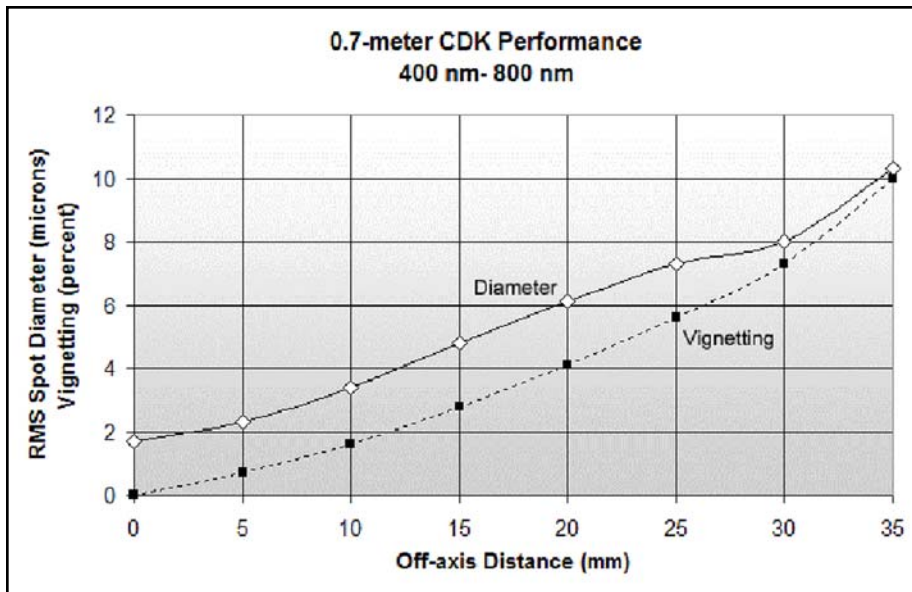
The overall performance of the telescope as a function of off-axis distance. Vignetting is in percent and the polychromatic geometric RMS image diameter is in microns. The performance of the telescope is excellent over a 70-mm circle, and remains usable over an 80-mm diameter. This graph details the geometric polychromatic RMS spot size and vignetting of the fully baffled telescope. The simulated wavelength range is 400 to 800 nm. It should be noted that one arcsecond is 20 microns at the image plane for this telescope.
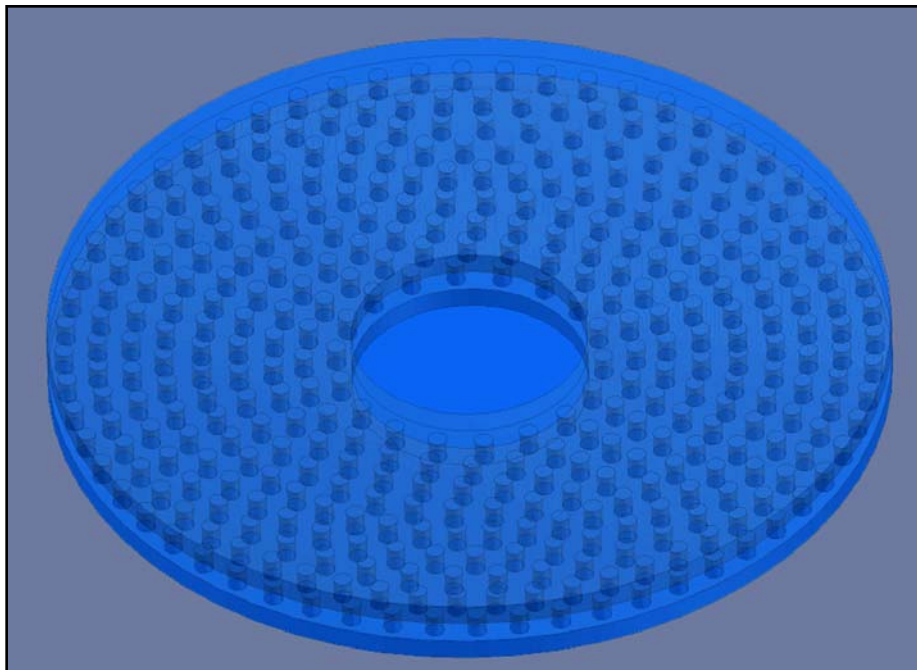
The primary mirror blank will be a fused sandwich structure consisting of three layers. The internal spacer layer is composed of circular glass disks fused to the inner and outer glass plates.

moments of inertia, allow wind gusts to be countered-one gust at a time-on millisecond time scales by the servos. This requires very stiff and low inertia OTAs and mounts, ultra-high resolution encoders on both telescope axes, and responsive, stiff drives free of backlash and compliance.

Since gear backlash is effectively impossible to counter in a high bandwidth servo loop, one is left with two options: (1) one or two stages of friction reduction driven by a moderate-torque motor, or (2) a direct drive system where a high torque motor is mounted on each axis itself. It should be noted that

both of these approaches have been used to good effect on large alt-az telescopes, and both should work well on smaller systems. It is, however, worth quoting Pierre Bely from his classic The Design and Construction of Large Optical Telescopes:
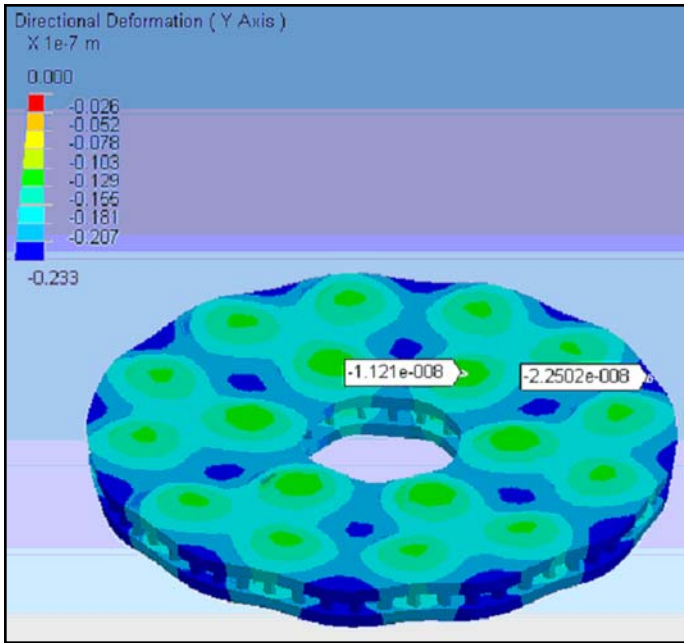
In contrast to all other drive mechanisms, in which the force is concentrated on a pinion or wheel, direct drives distribute the thrust along the structure, thus minimizing localized deformation and maximizing the structural stiffness. This results in the highest drive stiffness possible. ... Another key advantage of direct drives is their insensitivity to mechanical misalignment, dramatically reducing telescope installation time.

While challenging, we elected to use direct drive motors and ultra-high resolution encoders directly coupled to the axis and controlled by fast (wide bandwidth) servo electronics. We feel that the reduction in mechanical complexity, alignment, and maintenance afforded by direct drive may be worth the cost of the large diameter motors.

Since our telescope will use tightly coupled motors and encoders, the servo software becomes the heart of the telescope's motion control. As our point of departure, we have chosen the current version of Sidereal Technology's control system. The existing software is ASCOM compliant, so it works well with high-level "planetarium" software such as Maxim DL and TheSky. We are adding hardware and software to support the operation of the ultra-high resolution encoders and AC synchronous brushless motors.

Direct Drive Motors

Large diameter, frameless, direct drive motors are available off the shelf. They are, however, somewhat expensive, typically costing several thousand dollars per motor. They are designed to handle large loads at high RPM with excellent efficiency. For those who wish to construct telescopes on a limited budget, these off-the-shelf motors may be overkill for our very low speed, modest torque requirements. We are fortunate, however, that the permanent magnets and coils required to construct a simple, axial flux direct drive motor are quite inexpensive-less than $300 for a motor that is adequate for the 0.7-meter telescope.

Directional Deformation (Y Axis)
X 1e-7 m

0.000

-0.026
-0.052
-0.078
-0.103
-0.129
-0.155
-0.181
-0.207

-0.233

-1.121e-008   -2.2502e-008

The fused-sandwich mirror FEA results. In this model the mirror is being supported by an 18-point whiffle-tree. The peak-to-peak deformation of the mirror's surface is approximately 11 nm, i.e. about 1/50 of a wavelength, well within the desired tolerance.

The motors must supply sufficient torque at reasonable current to overcome wind gusts and static imbalance while accelerating the telescope axis at the highest desired slew rate. The Nasmyth-focus configuration completely eliminates altitude axis imbalance associated with instruments and eyepiece, easing the direct drive torque requirement for this telescope.

Torque Requirements for the 0.7-meter telescope

Motor drive electronics are inexpensive for peak currents up to 5 amps, and portable telescope control systems can be powered by two 12-volt batteries in series, so we designed our direct drive motor for 5-amps per phase at 24 volts. Under normal usage conditions of light wind, sidereal tracking, and good balance, the torque needed will be quite low. Thus the DC current draw will also be low, eliminating the need for expensive, high-efficiency motors.

Although radial-flux motors have the highest efficiency and motor constants, they also require stamped and laminated cores and machined rotors and stators. An alternative, lower cost (but lower efficiency) approach is to employ an axial-flux configuration with a large diameter rotor and stator. The large diameter is needed to supply the requisite torque. The 0.7-meter telescope has ample room, so no penalty is incurred for a large-diameter motor. To simplify the motor and its assembly, steel is used only under the magnets; the stator has no magnetic core material.

AC Synchronous Motor Driver

Most modern direct drive motors are three phase brushless, with current supplied to the phases via solid state linear amplifiers or pulse width modulated (PWM) switches. Motor

position Hall-effect sensors often supply the position information needed by the controller to correctly phase these switches. Washing machines, air conditioning compressors, and many other machines now use brushless DC motors. However, this simple motor control scheme is not adequate for our situation.

For telescopes, the motors must be operated in an AC synchronous, servo-control mode. The position of the telescope is sensed with ultra-high precision encoders on the two telescope axes, the position error is calculated, and the torque feedback is computed. The three phases of the motor are then energized

| Maximum Rotational Inertia	16 kg-m^2
Maximum Desired Acceleration	0.25 radians / sec^2
Torque Needed for Acceleration	4 N-m
Approx Torque to overcome Wind Gusts	8 N-m
Torque Due top Imbalance	2 N-m
Peak Torque Needed from Motor incl margin	20 N-m

based on this feedback torque.   One of us (Gray) has modified his Sidereal Technology control system to drive brushless AC synchronous motors.

We have chosen to use 10-bit PWM current switches over linear amplifiers for reasons of cost, simplicity and power efficiency. Although PWM drives can cause undesirable jitter at the telescope's axes if their resolution is too low, initial analyses showed that a 10-bit PWM has sufficient resolution for servo bandwidths of 10 Hz or greater.

The other difficulty with high current switching is the noise conducted on signal, power, and ground lines, and also the

The plan view of the motor. The poles of the magnets alternate between North and South. The coils are connected in series in three phases, where the phases are given by the numbers. The outside diameter of the coil support is 20 inches (0.5 meters). The magnets are 0.5" X 1.0" X 2.0".

Steel Annulus (Rotor)

Coil Support (Stator)

Coil (24 total)

Magnet (32 total)
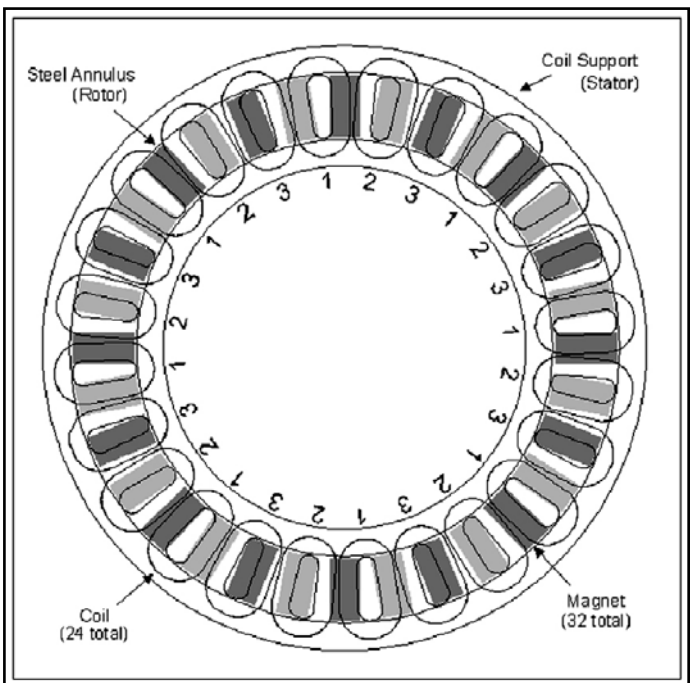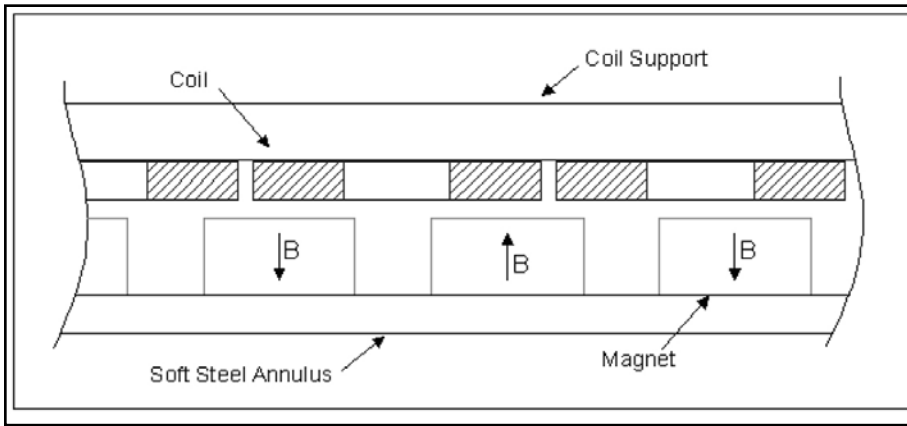
A portion of the cross section of the axial-flux motor. The coils are 0.25" thick and the gap is 0.12". For the highest flux through the coils, the gap should be kept as small as possible. The soft steel annulus provides a return path for the magnetic flux. In this version of the motor, the coil support is non-magnetic. Higher flux can be achieved if the coil support is also soft steel, but this makes the motor harder to assemble and disassemble, and increases the thrust load on the bearings.

Magnets	(32) Type N42 NdFeB, 0.5" X 1.0" X 2.0"
Coils	(24) 20 AWG 100-turn, L=10 cm / turn
Average Magnetic Field in Coil	0.29 Tesla
Force Constant (per phase)	23 N/amp per phase
Average Radius	0.23 meters
Torque Constant	5 N-m/amp per phase
Winding Resistance	5 ohms per phase

Direct drive motor performance parameters.

electromagnetic interference introduced into nearby, sensitive components, such as encoder read heads or CCD cameras. We will design the motor driver board with edge control, so that the high-frequency switching components will be greatly attenuated before leaving the controller.

Encoders

Positioning errors due to wind gusts, bearing cogging, and other external torques are removed via the servo control system. The error is sensed by comparing the desired position with the actual position, and is removed by the application of a counteracting torque. To do so, the telescope must first move very slightly, and this slight movement must be sensed before the correcting torque can be applied by the control system. Typically, several encoder resolution units (ticks) must be sensed as the correction is being applied. Thus for sub-arc second tracking accuracy, an encoder resolution of roughly 0.1 arc seconds is required (about 10 million ticks / telescope revolution).

We considered two basic approaches to obtaining the requisite encoder resolu-

tion. The first was to mechanically step up, via a large friction disk drive, a medium resolution encoder such as the Gurley 230,000 ticks/revolution encoder. One of us (Gray) has tried this encoder on his 14-inch alt-az telescope. One problem with this approach, which has not been resolved, is the periodic error induced by the run-out of the gearing and encoder. Other issues with this approach are reliability (slipping and dirt) and the requirement for the large mechanical step up.

The second approach is to place high resolution encoders directly on the telescope's axes. An good encoder for this is the Mercury II made by MicroE Systems. It uses a high degree of interpolation to achieve the required resolution.

Somewhat lower in cost are striped tapes with their associated read heads, such as those made by Heidenhain and Renishaw. Adhesive-backed stainless steel tapes with closely spaced lines can be adhered to the outer edge of a disk and read by an optical read head. The disk can have a large diameter (approximately 12 inches in our case, as we have plenty of room). This naturally provides a high angular resolution.

One difficulty of using a tape in azimuth is the break in the tape. The telescope cannot maintain precise tracking when it passes over a break. There are at least two solutions. One is to purchase a continuous tape (somewhat expensive, and requires placement on an exact diameter wheel). The other is to allow the telescope's OTA to rotate in altitude 180 degrees instead of just 90 degrees, i.e., allow the OTA to rotate nearly horizon-to-horizon, completely passing through the forks. With this capability and a simple software algorithm, the telescope can be pre-positioned such that any object can be tracked across the sky without encountering the azimuth break, thus avoiding the alt-az equivalent of a GEM's meridian flip. We plan to take this latter course for our telescope even though it places an additional requirement on the mirror cell.

We have chosen to use a Renishaw tape and read head on our first experimental motor/encoder/controller test setup. Heidenhain or Renishaw linear encoders with 100-nm resolution on 12-inch diameter disks will be used on the prototype telescope. Such encoders will have approximately 10 million counts per rotation-a resolution of about 0.125 arc seconds.

Instrument Derotator and Off-Axis Guider

For imaging, photometry, and spectroscopy, the focal plane of an alt-az telescope requires de-rotation. For our purposes it is sufficient to simply calculate the desired angular position as a function of time and drive the instrument platform to that position. We plan to use a simple geared servo motor for driving the rotator.

The instrument rotator can be used to pre-position an off-axis guider's (OAG's) pickoff mirror or prism on a bright guide star. By providing a large, well-corrected field of view (FOV), our telescope optics can support both a large format main camera and a large pickoff region for a sizeable guide camera.

Guide-star position information can be used for low rate corrections via the telescope's drive system. If the guide star is bright enough, the integration time can be reduced to a fraction of a second, and

high-frequency corrections can be fed to a low-inertia deviator plate to counter the effects of wind gusts and drive irregularities not handled by the telescope's basic control system. Our optical design has sufficient back focus to allow both an autoguider pick off and a deviator plate in the optical path.

If the autoguiding camera's FOV is small, or if the available annulus around the main camera's FOV is large, it may be worthwhile to place the autoguiding camera and its pickoff on a motorized radial slide, allowing the autoguiding camera to be moved in two dimensions, radially and rotationally. We plan on implementing an OAG system employing both of these motions.

Structure

Our 0.7-meter portable telescope requires an especially high ratio of stiffness to weight. Along with the usual considerations of precise and repeatable motion, weight and stiffness are primary considerations in our structural design. The requirement for light weight is more stringent than that of a typical mountain-top alt-az telescope, because most large telescopes are under a dome or other structure that gives them significant protection against the wind-typically reducing wind gusts by an order of magnitude. Our 0.7-meter telescope, on the other hand, is designed for portable or roll-off observatory operation out in the open where telescopes are exposed to the wind.

In order to be portable, our telescope needs to be lightweight. Yet to achieve precise pointing and tracking the telescope structure must also be very stiff. The stiffness requirement is manifest in two ways. First, the structure must not bend enough to significantly degrade image quality when subjected to disturbances such as wind gusts. Deflections of the optical tube and fork cannot be sensed and compensated for by the control system (unless autoguiding is being performed by sensing guide star position). It is our goal to have the telescope precisely track for 5 minutes without autoguiding. Second, the structure must be stiff enough to force all mechanical vibration frequencies to be out of the servo control bandwidth, otherwise coupling instabilities may result. Preliminary goals are to design a struc-

ture: (1) that will hold the telescope pointing angle to within 1 arcsecond RMS for wind gusts from 0 to 10 knots, (2) where all vibration frequencies are greater than 10 Hz, and (3) that will allow unguided exposures of 5 minutes with 1 arc second accuracy.

The tolerances for the structure can be divided into two categories: those which cause repeatable errors and those which cause non-repeatable errors. We can relax our tolerances with respect to the former somewhat, as the tracking software can be programmed to compensate for repeatable errors such as the flexure of the optical tube as a function of altitude. Non-repeatable errors, such as the slipping of bolted joints or run-out in bearings, must be designed out of the system and will receive close attention.

Although the details of the telescope's optical and control system designs are firming up, the structural design is just beginning. At this point in time, we expect that the top ring of the OTA and the truss tubes will be made from carbon fiber composite, which has the highest stiffness-to-weight ratio of any readily available material. The OTA midsection and forks will likely be made from either welded metal plate or carbon fiber composite. The choice will be a tradeoff between the lower cost and easier fabrication of metal, or the higher stiffness per weight of a carbon fiber composite structure.

Instrumentation

Our multi-use telescope must be designed to accommodate a variety

of instruments. In typical applications envisioned for this telescope, we expect that one of the Nasmyth ports will be utilized for CCD cameras and eyepiece, while the other port will host larger instruments such as spectrographs.

Specialized instruments are often quite bulky and heavy-one reason we went with a Nasmyth optical configuration-but their complexity and requirement for precise adjustment preclude them from being repeatedly installed and removed from the telescope, hence the requirement for two Nasmyth ports.

Visual Application

Newtonian optics have long been the mainstay of amateur Dobsonians, but the height of the eyepiece discourages some observers. In contrast, folded Cassegrain designs offer an eyepiece position that allows seated observing at the Nasmyth focus. Perhaps its only drawback is a small loss of light by the third reflection from the tertiary mirror, but the increased comfort of seated observing should make this a good trade-off.

Portability

We are currently evaluating three ways to design the telescope to be portable: Our requirement for the 0.7-meter alt-az telescope is easy setup and takedown by two people using a pickup truck, van, or trailer for transportation.

1.) Break down the telescope into small, lightweight parts that are easily carried and readily assembled. In this approach the maximum weight for a single unit

Block Diagram of Servo Controller
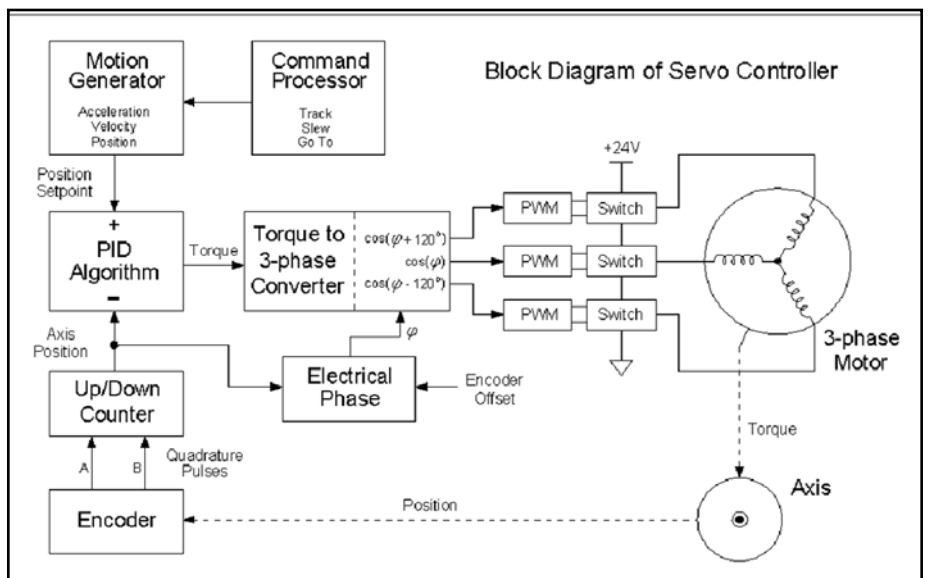
would be about 100 pounds. Although this implies that a large scope could be transported in a relatively small vehicle, it would also require the most assembly and disassembly time. In addition, the structure of the connection points would need to stand up to repeated use. Users who are well versed in putting together and taking apart the scope could make this a viable option, but it may be the least attractive way to make it truly portable.

2.) Keep the largest and heaviest parts together and move this assembly on deployable casters. In this scenario, only the upper cage and truss tubes would be assembled and disassembled, much like large Dobsonian telescopes. Deployment would either need two people or a winch or Tommy Gate to mechanize the lifting. One of the benefits of this method would be that the optics are moved while horizontal, and thus are well supported and protected by their respective cells. Noting that Dobsonians up to 1 meter have been moved this way, a feasible upper weight limit is perhaps 500 pounds. Using a wheelbarrow-like approach has a manageable upper limit of about 300 pounds if two people are available for setup and breakdown.

3.) Transport the fully assembled telescope in one piece. This option requires a large trailer with an excellent suspension and lift, but is certainly achievable today. In this approach the OTA would likely be pointed horizontally for transportation, which could place uncomfortably large edge stresses and vibration on mirrors and their cells.

Taking portability into account during the design of the telescope is vital. Whether a large telescope is moved a few times or many hardly matters because when portability and ease of setup is required, it becomes one of the most important attributes of the telescope.

The Future

Over the next six months we plan to fabricate and test the key components of the azimuth subsystem: the azimuth bearing, direct drive motor, and high resolution disk-tape encoder. Rowe is building the motor, while Gray is fabricating the driver. The completed unit, including the azimuth bearing from Impact Bearings, will be tested first at

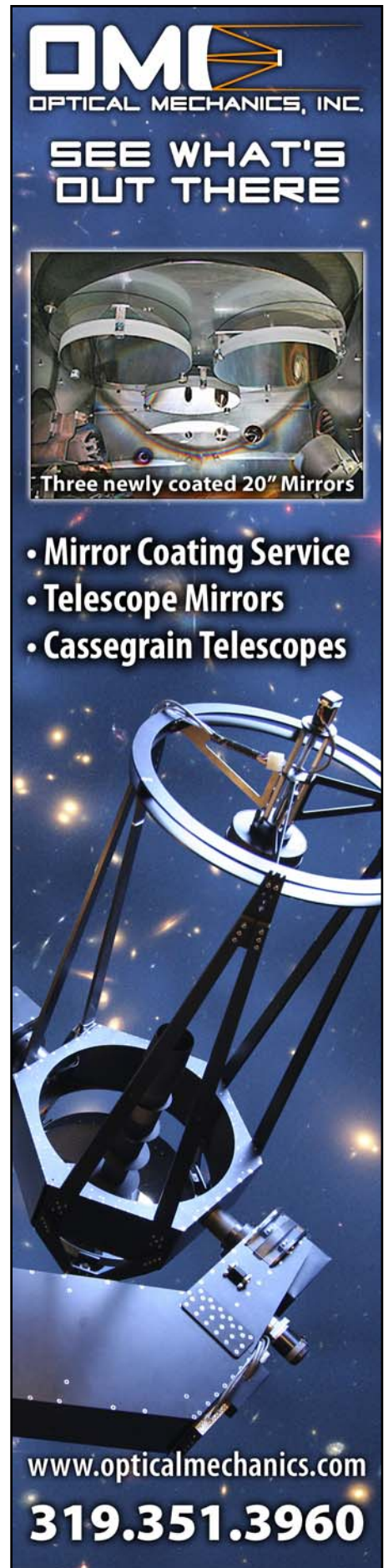Sidereal Technology and then at Trust Automation.

During the same time period, Liu at Hubble Optics will be fabricating and testing the complete optical system (primary, secondary, and tertiary mirrors, and the corrector lenses). Also, Ridgely, Widmann, and their students at California Polytechnic State University will be designing and fabricating portions of the telescope's structure.

At the Small Telescope & Astronomical Research (STAR) Conference, June 19-22, 2008, in San Luis Obispo, California, we will present a special session covering most aspects of the alt-az project and its 0.7-meter prototype (for details, see www.STARConference.org). Most of the talks from this special session will be included as chapters in the book-length conference proceedings. The STAR conference will be followed, seven months later, by a major conference in Hawaii, Galileo's Legacy: Small Telescope science 1609 and 2009 (www.GalileosLegacy.org).

Looking further into the future we foresee several possibilities. The first will be the completion and exhaustive testing and evaluation of the 0.7-meter prototype. We hope this will be followed with the manufacture, by one or more firms, of affordable systems and, hopefully, the increasing construction of such telescopes by amateur telescope makers.

With the 0.7-meter prototype under our belt, we are anticipating that we would then design, fabricate, and test a 1.0-meter prototype-a similar but scaled-up version of the 0.7-meter telescope. We are also contemplating a 0.5 meter Newtonian prototype with an f/4 hyperbolic primary and a two element corrector. It is our intent to provide useful information not only to manufacturers who may be able to afford off-the-shelf components, but to amateur telescope makers who, on a very tight budget, would prefer (and enjoy) making the components themselves.

Whatever the future might hold for our project, we feel that the time is ripe for the alt-az revolution that began with large mountaintop telescopes to be extended to modest aperture, lower elevation telescopes for research, astrophotography, and education. We plan to

place what we learn in the public domain and welcome others to join our informal developmental group or initiate their own projects.

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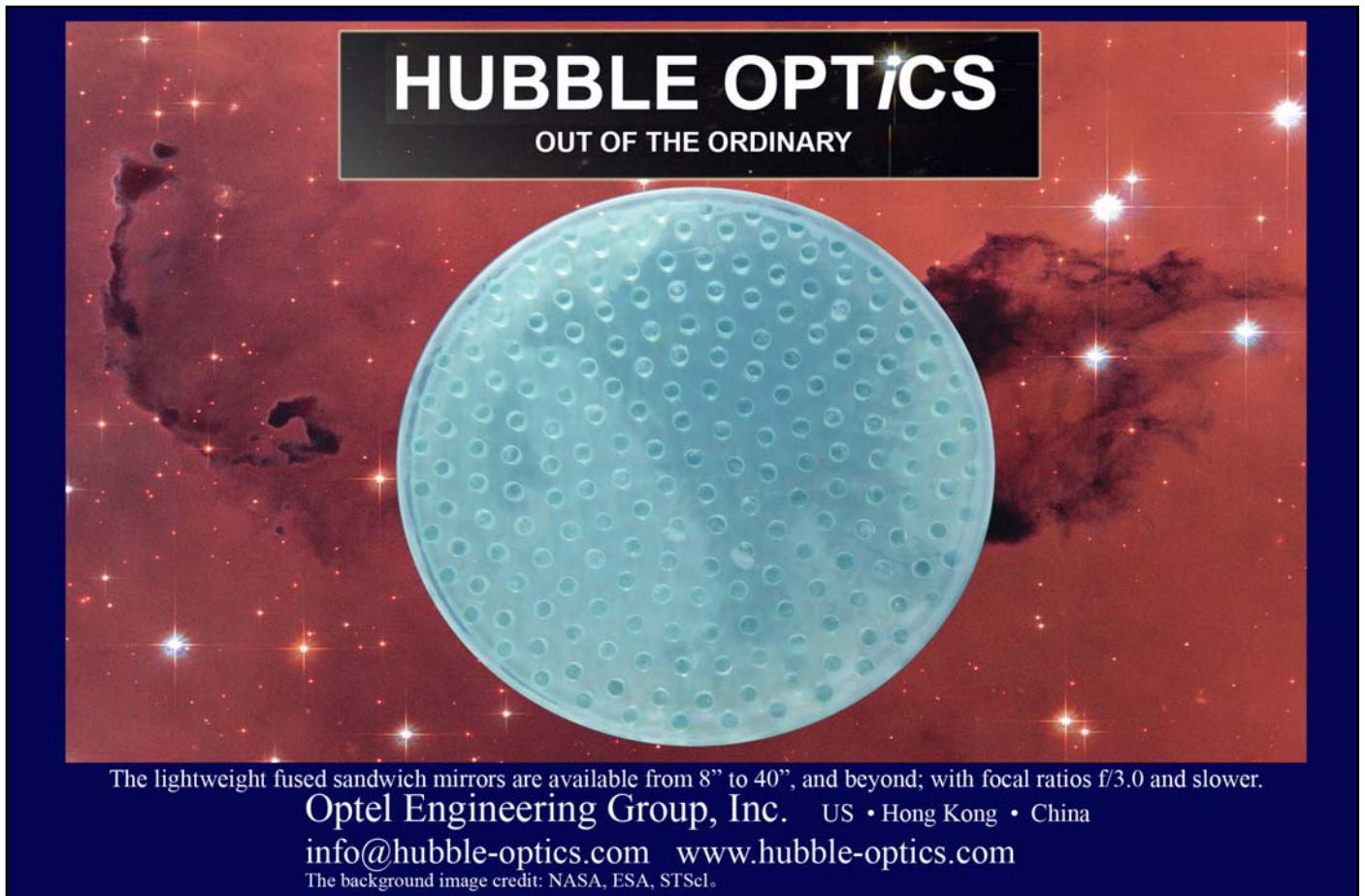## Acknowledgements

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Rick Hedrick is President of PlaneWave Instruments, which was founded in 2006 by Rick and Joseph Haberman. Rick has over 21 years of experience in telescope design. He worked for 11 years as the Chief Technology Officer and previous owner of Celestron where he was responsible for developing Celestron's award winning Schmidt-Cassegrain computerized telescopes. Getting a product like the CDK into the hands of serious imagers and amateur astronomers has been a

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Jim Widmann in an associate professor of mechanical engineering at California Polytechnic State University in San Luis Obispo, California. His areas of expertise are mechanical engineering design, mechanics, fluid power control, and design optimization. His industrial experience includes design engineering at L&F Industries, a world leader in the design and construction of larger research-grade optical telescope mounts. Jim organizes and teaches the Mechanical Engineering Design Project course at Cal Poly.

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Mel Bartels is a software architect and former musician and teacher. He ran the Amateur Telescope Makers listserv for six years, a worldwide group sharing the art of telescope making. In 1988 Mel began developing a freely distributed telescope control system that is in use worldwide. He has ground mir-

rors up to 30" in size, leads mirror making classes, and conducted a workshop where attendees figured 16" mirrors. His interest in innovative mounting designs led to popularizing ultra-lights with single upper rings in 1994 and inventing the TriDob in 2003. A speaker at astronomical conferences each year, his telescope walkabouts at the Oregon Star Party are a highlight that attract hundreds annually. The International Astronomical Union named asteroid 17823 Bartels for his contributions to amateur astronomy.

Richard Berry is the former editor-in-chief of Astronomy magazine, the founder and editor of Telescope Making magazine, and the author of a dozen or so books on amateur astronomy, including The Handbook of Astronomical Image Processing (with Jim Burnell), The Dobsonian Telescope: A Practical Manual for Building Large Aperture Telescopes (with David Kriege), and editor of Telescope Optics: A Comprehensive Manual for Amateur Astronomers by Harrie Rutten and Martin van Venroiij. www.wvi.com/~rberry.

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