A New Breed of Medium-Aperture Robotic Telescopes

for

Free-Space Laser Communications and Space Situational Awareness

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Abstract A new breed of medium aperture telescopes has captured the key features of large, expensive, one-off mountaintop telescopes and incorporated these features into their design and low-cost quantity production. These features include wide fields-of-view, lightweight mirrors, compact and stiff alt-az mounts, and direct drive control with very precise pointing and high-speed slewing and tracking capabilities. These are the very features that make telescopes used for Free-Space Laser Communications and Space Situational Awareness highly cost-effective; maximizing on-target time by minimizing the time required to acquire targets and slew between them.

Introduction

A new breed of medium aperture, fully robotic telescopes is now being produced in quantity, and will be increasingly used for wide-band Free-Space Laser Communications (lasercom) with a rapidly growing number of satellites that require a higher data throughput and host their own lasercom space terminals. These telescopes can also be utilized for Space Situational Awareness (SSA) to identify and keep track of current Resident Space Objects (RSOs) and new satellites.

Ground-based telescopes can be divided into two broad classes:

- A very large number of low-cost, small-aperture, mass-produced telescopes, made by Celestron, Meade, and others, that are primarily used for recreation and education by the general public, amateur astronomers, and undergraduate and high school students. Typical instrumentation is either an eyepiece or small camera. These numerous small telescopes are usually located in the relatively benign environments of private backyards and school campuses.
- A few expensive, large-aperture, custom-built (one-off) telescopes used by professional astronomers and their graduate students for astronomical research. These telescopes are usually equipped with a number of different, often heavy, instruments. These large, environmentally rugged research telescopes are often located on remote mountaintop sites with dark skies and excellent "seeing" (steady atmospheres).

A new breed of telescopes has recently emerged, thanks to the Alt-Az Initiative—a voluntary group of engineers and astronomers—and a few commercial firms which have been working together for a decade to incorporate the key features of large, expensive one-off mountaintop telescopes into medium-sized telescopes. These telescopes are now being produced in quantity, making the highly desirable features of large telescopes affordable for a broad range of applications, including the commercial ground stations used for wide band lasercom with satellites and SSA.

This paper reviews the fundamentals of telescope optical, structural, and control system design, and the key large-telescope features that have been incorporated into this new class of medium-aperture production telescopes. Technical details are provided, as an illustrative example, for one of these telescopes, the PlaneWave Instrument PW-1000 1.0-m telescope. Finally, the paper describes how these telescopes can be formed into arrays and networks of robotic observatories for lasercom and SSA.

Optical Designs

Astronomical telescopes, starting with Galileo's in 1609, used a single lens, called the *objective* lens, as the primary light-gathering element. These telescopes suffered from serious chromatic aberration as different wavelengths of light were bent differing amounts by the objective. Sir Isaac Newton's 1668 reflecting telescope featured a parabolic primary mirror and a small flat secondary mirror that reflected light off the top end of the telescope to an eyepiece on the side for viewing. By replacing the objective lens with a parabolic mirror, Newton had solved the chromatic aberration problem.

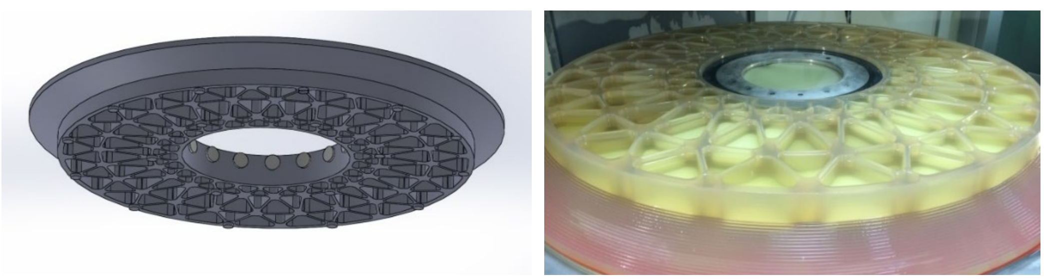
However, the top-end viewing location of Newtonian telescopes was inconvenient (even dangerous) for the increasingly large reflectors, a problem that was solved by a design attributed to Laurent Cassegrain. As with Newtonian telescopes, the primary mirror of Cassegrain telescopes was parabolic, but the secondary mirror, instead of being a small mirror reflecting the light off to the side, was a small convex hyperbolic mirror that reflected the light straight back down through a hole in the middle of the primary mirror to the focal plane behind the mirror.

Both Newtonian and Cassegrain telescopes suffered from an off-axis distortion called *coma.* George Ritchey and Henri Chretien's 24-inch 1927 "RC" telescope used both hyperbolic primary and secondary mirrors that, at least in theory, eliminated coma, but only on a curved focal plane with perfectly positioned optics. In practice, corrective lenses had to be introduced near the focal plane to flatten the field, as most cameras have a flat surface. Furthermore, maintaining perfect mirror alignment was not possible.

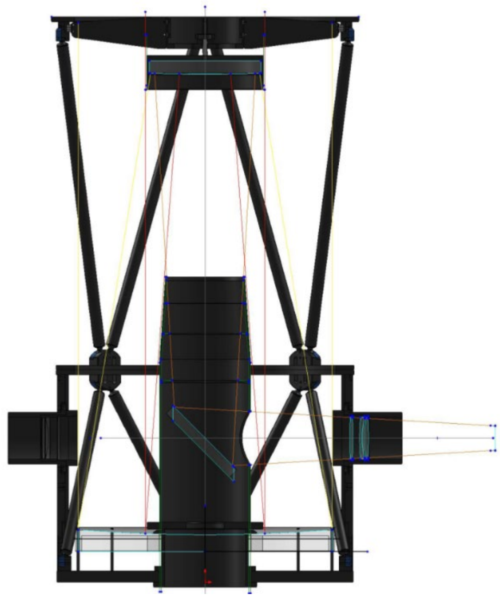
Given that corrective lenses are required for high-performance reflecting telescopes, Corrected Dall-Kirkham (CDK) telescopes, with elliptical primary and spherical secondary mirrors, provide equivalent or better optical performance than corrected (field-flattened) Ritchey-Chretien (RC) telescopes. Furthermore, the CDK optical configuration has three important advantages over the RC configuration that are making the CDK increasingly popular:

- The CDK's secondary is much easier to collimate because, unlike the RC's hyperbolic secondary, the CDK's spherical secondary has no preferred axis; any line that runs through the center of a sphere can be an axis.
- The CDK's spherical secondary is much easier to figure since it does not require deviation from a sphere, the natural shape that occurs when polishing a mirror.
- The CDK's spherical secondaries are much easier to test because they can be fringe tested against a spherical concave master.

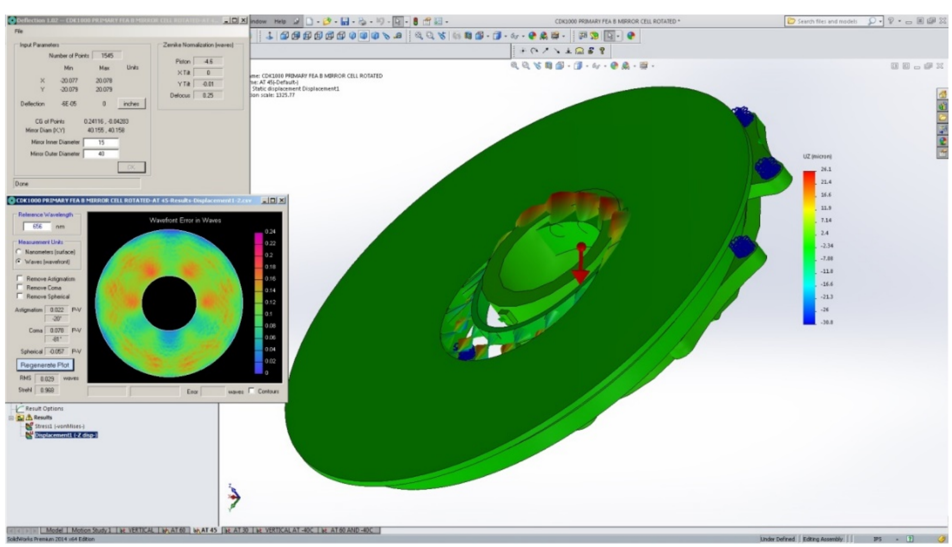
If the primary mirror is not at the same temperature as the air, its shape may be distorted. By using materials with nearly zero coefficients of thermal expansion and making the mirrors lightweight but stiff (cellular designs), this issue can be mitigated. It might be noted that since laser communication ground telescopes must operate both day and night, with a corresponding large change in air temperature, this is an important design issue for this application.



Left: *A Solidworks model of the one-meter fused Silica lightweight primary mirror used in the PlaneWave Instruments 1.0-m telescope and used as an example in this paper.* ***Right:*** *A photograph of the mirror being* *back-side ground on a machine that has been customized for this work. Advanced diamond tooling is used to rapidly remove the material prior to grinding and polishing.*



The optical tube assembly (OTA) of the one-meter PW 1000 telescope showing the primary mirror at the bottom (M1), the secondary mirror at the top (M2), and the tertiary flat mirror (M3) reflecting the light to the left through the three-element corrector. All optical components are made from fused silica. M3 rotates so that the beam can be directed toward either Nasmyth port. Carefully engineered and simulated support structures are used for all the optical components to assure that the performance of the telescope is maintained over temperature, time, and pointing direction. The CDK design uses a three-element fused silica corrector to achieve diffraction-limited performance across the full 100 mm diameter (1 degree) aperture over the full band from 375 nm to 1000 nm.



The finite element analysis (FEA) of the light-weighted one-meter primary mirror on its 18-point support structure is shown. In this example, the mirror is modeled with the telescope tipped at a 45-degree angle *from the vertical. Extensive analysis was used in the design to assure excellent performance over all environmental and pointing conditions.*

Structural Designs

Telescope structures (mounts) hold the optics and instruments in place and allow them to be pointed at and track objects in the sky. Early telescopes optical tube assemblies (OTAs) were placed on altitude-azimuth (alt-az) mounts. Naval guns are a good example of an altitude (move up and down 90 degrees from the horizon to the zenith) and azimuth (swing around 360 degrees horizontally) mount. While alt-az mounts were simple and compact, tracking a star across the sky required constantly change speeds in both altitude and azimuth. Furthermore, the field (image) rotated over time.

Joseph von Fraunhofer's 1824 equatorial mount tipped one of the telescope's axis of rotation over so it was parallel with the earth's axis. A constant-speed flyball-governor "clock" on this axis counteracted the earth's rotation, causing objects to appear stationary with no field rotation.

For over a century and a half, all large telescopes employed equatorial mounts. The 200-inch Hale Telescope on Palomar Mountain was the largest equatorial telescope ever built because, once reliable computer-controlled motors became available, all new, even larger telescopes switched back to using alt-az mounts for two, primarily financial, reasons:

- Alt-az telescopes are much more compact than equatorial telescopes. Larger equatorial telescopes, and the larger domes required to enclose them, are much more expensive.
- Structures that are all horizontal and vertical, such as alt-az telescopes, are easier (and hence lower in cost) to design and build, than ones canted at an angle such as equatorial telescopes.

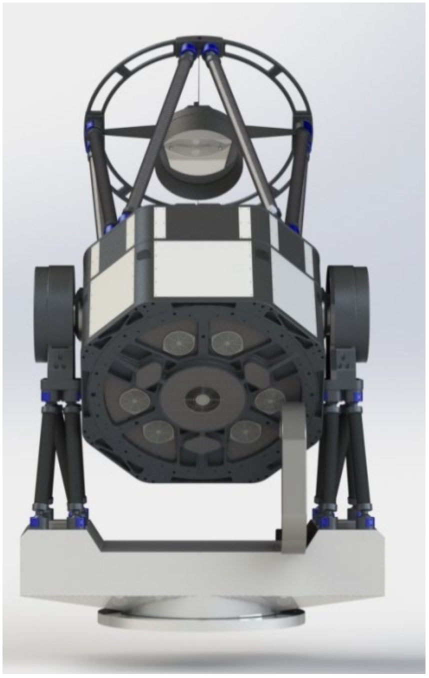
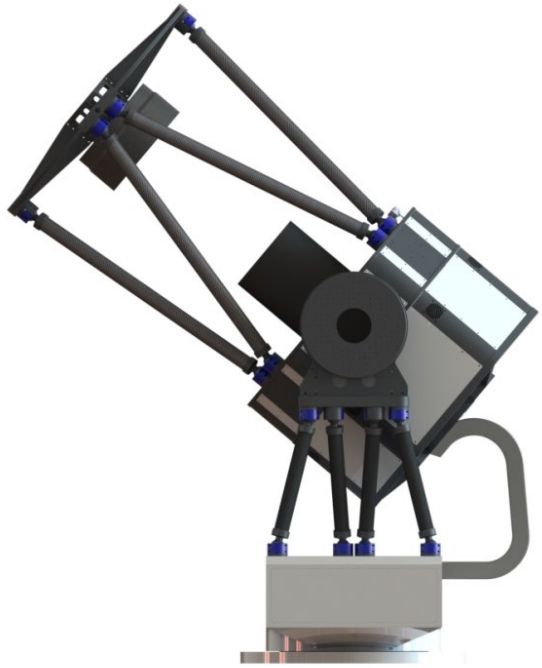
The problem of field rotation in alt-az telescopes was solved by mounting cameras (and other instruments) on a computer-controlled, motorized derotator.

Most large alt-az telescopes have a small, flat tertiary mirror that can be switched 180 degrees to deflect the light in either direction along the altitude (horizontal) axis through the center of an altitude bearing to instruments mounted on a derotator at either one of the Nasmyth foci (named after James Nasmyth).

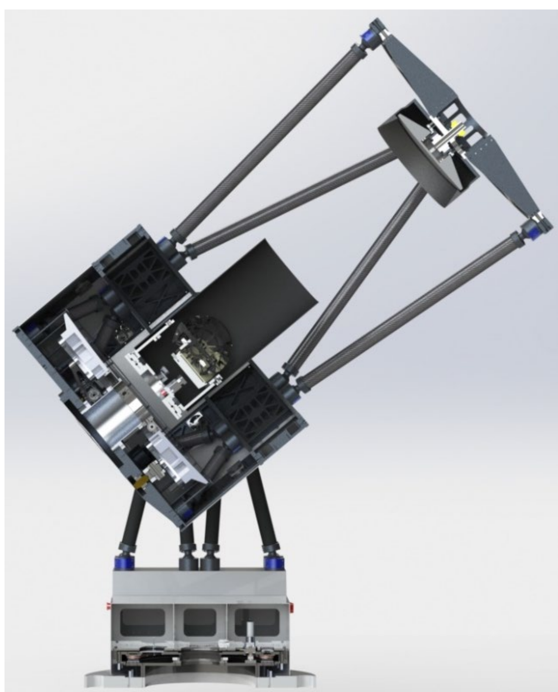
Nasmyth foci have four significant advantages:

- The instruments are located at the Nasmyth ports, which are along the alt-az telescope's altitude axis (and balance point), so the weight of the instruments (or changing them) does not affect the telescope's balance.
- Instruments can be large and heavy without having much effect on the performance or cost of the telescope.
- Instruments are not moving up and down as the telescope moves, so managing cables, coolant lines, and many other items are much simpler. Also, the gravitational load on an optical bench for lasercom, SSA, spectroscopic research, etc., is consistent, allowing for better conditions to keep the instruments and optical elements aligned.
- Having *two* Nasmyth ports is an improvement over having one Cassegrain port. Dual Nasmyth ports, when combined with four-port instrument selectors, allow a large number of instruments to be placed on a single telescope. Permanent placement of all the instruments that are likely to be regularly used reduces the wear and tear caused by the frequent changes of instruments (not to mention the expense, increased down-time, etc.)

For these reasons, it is advantageous to include dual Nasmyth ports in medium-aperture production telescopes.

Instead of a heavy conventional fork, the PW 1000 uses an extremely lightweight and stiff space-frame structure made from steel tubing. This fork design minimizes the angular inertia of the telescope, making for a very accurate and responsive direct-drive servo system.



This Solidworks cross-sectional model of the telescope shows the double truss design of the OTA. The truss tubes are carbon fiber and they are connected through an internal altitude load-bearing ring. The entire telescope is designed and analyzed in Solidworks for minimum deflection. The vibrational modes of the telescope are also analyzed to assure that wind loading causes minimal disturbance to the system.

Control System Designs

For all but the simplest, least expensive telescopes, manual control is a thing of the past. Computer-controlled drives initially point telescopes at a specific location in the sky and then track objects to keep them centered within the field-of-view.

The tracking rate of traditional telescopes used to observe planets, stars, and galaxies is very slow (approximately one revolution per day), while motors turn very fast (many RPM); therefore, telescope drive systems, also known as a mount or gimbal, normally need several stages of reduction. Gear and belt reductions work, but they introduce backlash and periodic errors. Friction drive reduction eliminates the backlash but can introduce slippage.

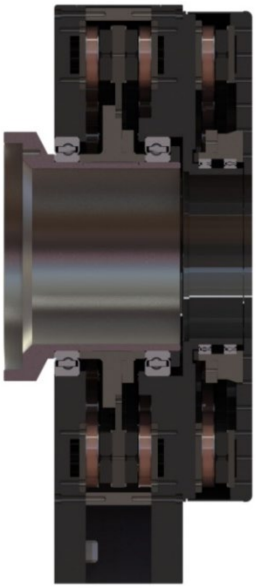
In a simple control system, the computer can issue “open loop” commands to the telescope drive system and assume that the commands will be followed precisely which, of course is unlikely, as there will be errors in the mechanical reduction system. Alternatively, high-precision rotational position encoders can be placed on each axis so the loop can be “closed” by having the control computer continuously check these encoders to make sure the telescope is actually positioned as desired.

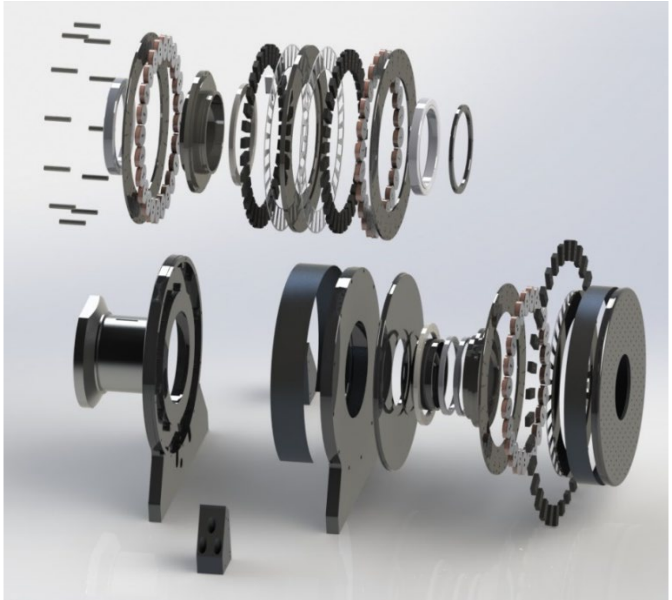
However, closing the loop on high-precision on-axis encoders can create a dynamic problem. Many telescopes have a low resonant frequency which introduces a time response lag in the control system loop. This can lead to control system oscillation (dog chasing his own tail). There are two solutions to this problem:

- Using a two-loop control system with a high-speed inner loop closed on the initial reduction stages, coupled with a slow speed (fine adjustment) outer loop closed on the high-resolution on-axis encoders. While this allows accurate pointing and tracking, the outer loop response has to be slow to avoid oscillation, so this is not a good solution for rapid slewing between objects, tracking fast-moving LEO satellites, and overcoming wind gusts; all which require a fast response.
- A single-loop, fast-response direct-drive system with high-resolution on-axis encoders.

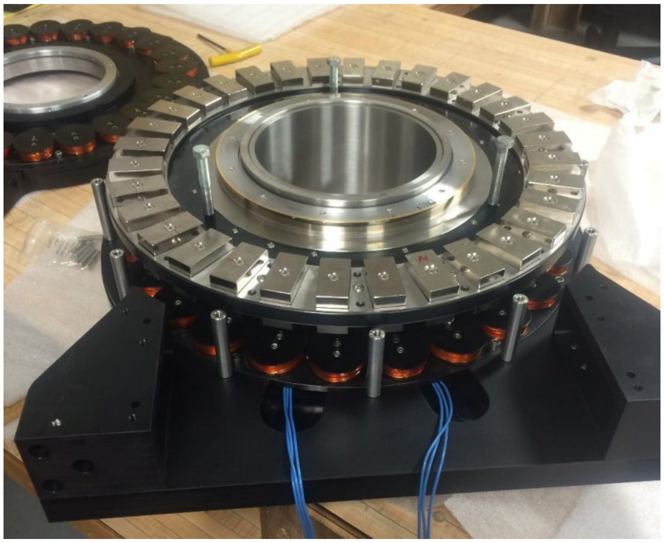
Direct-drive telescope mounts have no gears, belts, friction drives, or any reduction mechanism. The mount itself becomes the motor. A ring of powerful permanent magnets is opposed by another ring of energized coils. By varying the current through the coils, the mount can slew the telescope to a new target at very high speed, track a target at almost any rate, or hold completely still. Closed-loop feedback is provided by high resolution encoders on each axis. The high speed and complete silence of direct-drive telescopes have to be seen and heard to be fully appreciated.

There is a catch, however: the resonant frequency of direct-drive telescope structures must be high, and this requires a very stiff structure. Stiff telescopes require a lightweight design that uses high-stiffness, modern materials such as carbon fiber. In the example 1.0-m telescope described above, notice that the massive steel forks of traditional telescopes have been replaced with tube trusses. This significantly increases the mount’s resonant frequency.

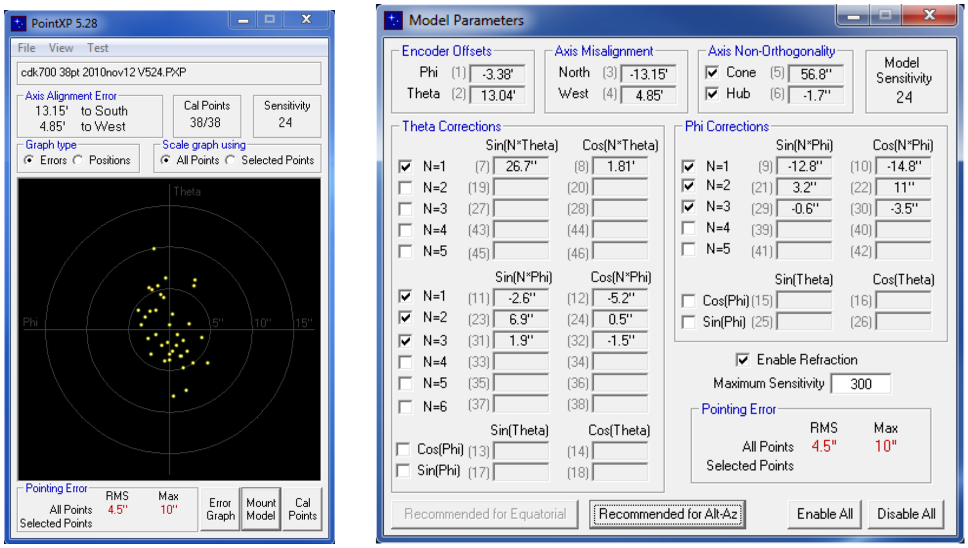




Left: *A cross-section view of the altitude drive and field derotation assembly for the PW 1000 telescope.* ***Right:*** *An exploded view of this assembly showing the direct drive motor magnets, coils and high-resolution on-axis encoder. The field derotation assembly uses the same direct-drive servo technology as the axis motor to achieve high rotational rates and very high accuracy.*



A direct-drive motor assembly showing the array of magnets and coils.



PlaneWave has developed software that automatically calibrates the telescope using all-sky imaging of star-fields. Such calibration does not take long, can be done any clear night, and usually does not need to be redone until there are instrument or other system changes. The pointing model can contain as many as 46 independent terms. In practice, 20 terms produce an excellent pointing model with better than 5 arcseconds RMS error over the entire sky and only takes a few minutes to perform.

Robotic Observatories

If a telescope, its instruments, and enclosure are all computer controlled, they can be combined with weather sensors and power backup to form a robotic observatory. In the 1980s, a sizeable group of engineers and astronomers, led by the Fairborn Observatory (and funded by the National Science Foundation, Smithsonian Institution, and others), computerized the operation of small-aperture telescopes, achieving totally automatic operation in 1983. The Fairborn Observatory's array of automatic telescopes began operation at a totally automated observatory on Mt. Hopkins in southern Arizona in 1985. Computer control of small telescopes became widespread in the 1990s, while fully robotic observatories with ever larger telescopes are becoming more numerous.

Robotic observatories can be highly cost-effective because:

- Operating costs are often lower as there are no on-site observers to be paid.
- Maintenance costs are also often lower as humans aren't disturbing the equipment, changing instruments, etc.
- The effectiveness of robotic observatories is often high as they can be placed at locations with good weather, dark skies, and steady atmospheres (low atmospheric jitter). Site locations can be based on historical weather data and atmospheric jitter tests. Since there are no observers to be paid, even very remote locations do not run up the observational cost.
- Computer selection of targets and control of the telescope and instruments can be faster and more efficient than human operation.
- Robotic telescopes, with their fast-slewing direct drives, can be programed to move more rapidly than would be safe with human operators, thus increasing time on target.

Robotic telescopes are often incorporated into arrays and networks. There are two common types of robotic telescope arrays:

- Independent telescope arrays that that are sited together and are installed and maintained as a group for reasons of economy, but are otherwise operated independently.

- Summative arrays that combine observations incoherently to improve the overall signal (S/N). If high optical resolution is not required, summative arrays of smaller robotic telescope can compete with large single telescopes in “photon hungry” applications, thanks to the cost-versus-aperture and cost-versus-production-quantity scaling laws which favor an array of telescopes with the same equivalent aperture over a single larger telescope. For instance, an array of four 1-m robotic telescopes costs considerably less than a single 2-m telescope. Such an array, with a single command, can be transformed from four independent 1-m telescopes to one summative 2-m telescope.

*MINERVA, the Miniature Exoplanet Radial Velocity Array, located on Mt. Hopkins in Arizona, consists of four 0.7-m PlaneWave Instruments CDK-700 telescopes housed in two flip-open enclosures. An optical fiber from each telescope are combined to feed a spectrograph with an equivalent single-telescope aperture of 1.4-m. Alternatively, the four telescopes can be operated independently when cameras are selected instead of the optical fiber feeds. The fifth CDK-700 in the dome is not part of the four-*telescope *array.*

Unlike arrays, networks of robotic observatories are distributed geographically. The advantages of networks of identical, robotic telescope/instrument systems (observatories) include:

- Continuous coverage over time as objects are passed from one telescope to another as the earth turns.
- Relative immunity to weather disruptions if there are sufficient telescopes in the network at weather-diverse locations.

Laser Communications and Space Situational Awareness Applications

The bandwidth requirements for communications around the planet are rapidly escalating. Besides ground-based optical fiber/cellular communications, increasing reliance is being placed on communication satellite constellations for more complete global coverage. The SpaceX Starlink, Telesat, Amazon’s Project Kuiper, and OneWeb constellations, for instance, will consist of thousands of satellites in low earth orbit (LEO) with the purpose of providing low-latency, high-speed broadband connectivity. Although the communication links will initially be via microwave, it is expected that, over time, lasercom links will predominate as microwave frequency allotments become scarce and the need for ever greater bandwidths and security increase.

With the advancements of telescope system capabilities described in this paper, these systems can be turned into lasercom ground stations, commonly known as optical ground stations (OGSs). The main OGS components consist of the telescope (optics and mount) and an optical bench that enables the system to receive and transmit data to a lasercom space terminal that is hosted on the end-user's satellite. Since satellites with lasercom space terminals are expected to be located in different orbits from low earth orbit (LEO) to geostationary orbit (GEO), different telescope apertures can be used depending on link communication budgets.

The OGSs that are to be built and integrated with the network provider's infrastructures are expected to operate within the Short-Wave Infrared (SWIR) waveband. Collaboration between the network providers, the space terminal supplier, and the OGS supplier are required to build a reliable communication network.

Keeping track of the rapidly increasing number of satellites and their changing orbits—SSA—will be a major challenge. Existing space surveillance networks rely on radars to track RSOs, as well as a few optical observatories designed for the acquisition of new objects. The goal is to augment existing optical and radar capabilities with these new robotic telescopes. Radar and optical can work together by utilizing radar data to queue optical systems to track RSOs and record their parameters. Using multiple low-cost telescopes with the combination of different sensors can help provide more accurate orbital parameters and also identify and characterize the RSOs.

The fast-slewing and the precise pointing and tracking capabilities of the new breed of medium-aperture production telescopes maximize the time spent on target as opposed to moving to or acquiring the targets. The relatively low cost and high reliability of these telescopes increases their cost-effectiveness. Formed into arrays and networks, they can provide assured, continuous coverage of many satellites.

Conclusions

The new breed of medium-aperture telescopes has successfully captured the key features of large, expensive, one-off mountaintop telescopes and incorporated them into the design and quantity production of relatively low-cost, medium-aperture telescopes. These features are:

- An optical design with a wide, flat field, and optics that are relatively easy to manufacture and adjust.
- Light-weight mirrors made of low coefficient of temperature expansion material.
- Alt-az mounts for their compact size, vertical/horizontal structure, and lower cost.
- Dual Nasmyth ports with instrument derotators to accommodate large instrument payloads at these two ideal, fixed-height, natural balance-point positions.
- A very stiff, lightweight structure using modern materials that would result in a high resonant frequency, thus allowing trouble-free direct-drive operation.
- Direct-drive, closed-loop telescope control for high precision pointing, smooth and silent operation, fast slewing and tracking speeds, and the total elimination of any periodic errors, backlash, or slippage.
- Environmentally ruggedness, including resistance to wind gusts.

Thanks to their very precise pointing and high-speed slewing and tracking rates, these telescopes maximize on-target time by minimizing the slewing and acquisition times between targets. Incorporating these robotic telescopes into fully automated observatory arrays and networks will provide the continuous, all-weather, ground-station capabilities needed for lasercom and SSA.

The Authors

Russell Genet, an astronomer and Research Scholar in Residence at California Polytechnic State University, was a research supervisor at government laboratories for many years. He founded and Directed the Fairborn Observatory for many years, and was one of the pioneering developers of robotic telescopes.

David Rowe, a physicist and Chief Technical Officer of PlaneWave Instruments, was the Chief Technical Officer of Sierra Monolithics for many years. He developed a number of unique optical designs for telescopes and directed the design of the CDK-700 and PW-1000 telescope examples in this paper. David and Russell, as charter members of the Alt-Az Initiative, collaborated on the "Cal Poly 18" telescope which, a decade ago, implemented direct drive control in a modest-aperture alt-az telescope. Recently, they have been working on the instrumentation and software for speckle interferometry observations of close double stars.

Ruben Nunez is a high-tech business development executive with 10+ years of experience in the space industry. He has developed and executed strategic roadmaps to secure customers within the Free-space Laser Communication, Space Situational Awareness, DoD Engineering Services, and Lunar markets. He was also a leader and founder of a formal Google Lunar XPRIZE team that collaborated with multiple firms worldwide. Ruben is also a STEM advocate and implementer of inquiry-based learning methodologies.