PROCEEDINGS OF SPIE

SPIEDigitalLibrary.org/conference-proceedings-of-spie

The Argus Array Technology Demonstrator: rapid prototyping of core technologies for an all-sky multiplexed survey telescope

Hank Corbett, Alan Vasquez Soto, Lawrence Machia, Nathan Galliher, Ramses Gonzalez, et al.

Hank Corbett IV, Alan Vasquez Soto, Lawrence Machia, Nathan Galliher, Ramses Gonzalez, Glenn Walters, Nicholas M. Law, "The Argus Array Technology Demonstrator: rapid prototyping of core technologies for an all-sky multiplexed survey telescope," Proc. SPIE 12182, Ground-based and Airborne Telescopes IX, 121824D (29 August 2022); doi: 10.1117/12.2629489

Event: SPIE Astronomical Telescopes + Instrumentation, 2022, Montréal, Québec, Canada

The Argus Array Technology Demonstrator: Rapid prototyping of core technologies for an all-sky multiplexed survey telescope

Hank Corbett[a], Alan Vasquez Soto[a], Lawrence Machia[a], Nathan Galliher[a], Ramses Gonzalez[a], Glenn Walters[b], and Nicholas M. Law[a]

[a]Department of Physics and Astronomy, University of North Carolina at Chapel Hill, Chapel Hill, NC 27599-3255, USA

[b]Department of Applied Physical Sciences, University of North Carolina at Chapel Hill, Chapel Hill, NC 27599-3255, USA

ABSTRACT

The Argus Optical Array is a synoptic survey instrument that will use 900 commercial off-the-shelf telescopes to cover a composite all-sky of view with a total collecting area equivalent to a 5-meter telescope. We are currently carrying out a staged development process, leading up to the construction of the 38-telescope Argus Pathfinder system, which will observe the entire Northern sky between $-20° < \delta < 72°$ each night for 15 minutes per field. Argus Pathfinder is currently scheduled for a Q3 2022 deployment to the Pisgah Astronomical Research Institute in Rosman, NC. The Argus Array Technology Demonstrator (A2TD) is the first in this series of prototype instruments, and consists of 9-telescopes in a fiberglass enclosure on a tracking platform. The A2TD is a tool for rapid development, testing, and performance validation of the essential subsystems of the Argus Array design, including a custom-developed tracking drive and polar alignment system, thermal environment control, optical windows, and observatory control. The A2TD is also used for on-sky validation of telescope and camera pairs that have been bench-aligned, and for development of observatory automation and control software that are either directly transferable or scalable to later development stages, including the Argus Pathfinder. In this paper, we present the development process and design of the Argus Technology Demonstrator, and highlight early results from on-sky testing with the instrument.

Keywords: Argus Optical Array, array telescopes, transient surveys, observatory automation

1. INTRODUCTION: OVERVIEW OF THE ARGUS OPTICAL ARRAY

The Argus Optical Array will be a new type of deep synoptic survey instrument, leveraging the economy of scale for small optical telescopes and low-noise CMOS image sensors to image the entire sky above an airmass of ∼2 with arcsecond resolution. Relative to monolithic survey instruments, this approach has previously been demonstrated to provide competitive information grasp and survey speed per unit time and cost,[1] and is an evolution of previous array telescope designs using DSLR camera lenses, including the Evryscopes,[2,3] SuperWASP,[4] HATNet,[5] and MASCARA.[6] To minimize maintenance requirements, arrays of telescopes (O(1000) for full-sky coverage) can be mounted on a shared tracking mount assembly and housed in a climate-controlled enclosure. This approach minimizes the number of moving parts overall, and constrains the thermal environment for the optics, promoting long-term stability.

We are currently progressing through a staged protoyping and science deployment program for the Argus Optical Array. Funding has been secured to build Argus Pathfinder, a 38-telescope system capable of observing the entire Northern sky for 15 minutes per night, to a depth of $m_g = 19$ at 30 second cadence and $m_g = 16.1$ at 1 second cadence. Argus Pathfinder is on track to achieve first light during Q3 of 2022, with an initial science

Further author information: (Send correspondence to H. Corbett)
H. Corbett: E-mail: htc@unc.edu

Ground-based and Airborne Telescopes IX, edited by Heather K. Marshall, Jason Spyromilio, Tomonori Usuda,
Proc. of SPIE Vol. 12182, 121824D · © 2022 SPIE · 0277-786X
doi: 10.1117/12.2629489

deployment to the Pisgah Astronomical Research Institute, an educational center and observatory in western North Carolina.

At all stages of the prototype series, the Argus Array uses a unique observing strategy; rather than building sky coverage by observing a sequence of tiles, Argus (and the predecessor Evryscope system) tracks a large contiguous field of view in short intervals, "ratcheting" through the accessible right ascension range each night. This approach builds up sky coverage while minimizing the average airmass across the field of view. Each ratchet concludes with a slew back to the next field position, defined by the pointing of the meridian of the array. Two observing cadences will be used for Argus Pathfinder and for the full Argus Optical Array; a standard survey with either 30- or 60-second exposures, and a secondary fast survey at 1 second cadence.

Despite the design's usage of commercial off-the-shelf optical components, building the Argus Optical Array will require development and evaluation of several enabling technologies. The primary technological readiness areas and their evaluation goals are:

1. Motion control systems: Sidereal tracking around the axis of Earth's rotation with negligible impact on the instrument PSF (i.e., less than atmospheric seeing).
2. Camera and telescope control systems: Scalability to hundreds of telescopes at up to 1-second cadence.
3. COTS 200 mm, f/2 telescopes: Usable image quality across a $>$ 45-mm diameter image circle
4. 35-mm format CMOS image sensors: Long-term stability and evaluation of noise characteristics on sky.
5. Analysis Pipeline: Scalable operations and data product generation within the observing cadence.

In this paper, we present the Argus Array Technology Demonstrator (A2TD), a 9-telescope test bench for rapid development and testing of the core enabling technologies of the Argus Optical Array. The system design for A2TD is illustrated in Figure 1. The A2TD seeks to meet the needs of the Argus Array instrument team to iterate through designs addressing the four technological readiness areas listed above within the following constraints:

1. **Timescale:** We targeted a 6-month process for on-sky operations, beginning May 2021.
2. **Modularity:** Flexibility for swapping out camera systems, operating with a partial array, and upgrading components as new designs are available.
3. **Size:** The telescope array should be sufficiently large to be representative, while fitting within an 8-foot commercially-available fiberglass dome during operations and a standard box truck for transport.
4. **Budget:** Not including optical and camera hardware included in the NSF-funded Argus Array, the A2TD budget was $18,000.

We initially planned the A2TD instrument to be a rapidly deployable proof-of-concept observatory, intended for installation at a dark sky site in North Carolina; however, a project retrospective several months into system design determined that the development of the robotic observatory components necessary for a full deployment of the system would retire no additional risks given the years-long performance of such systems to support the existing Evryscope instruments built by our team. Further, our early experience with a maintenance shutdown of the EvryArgus system (see Section 5.1 in Ref. 7), and the continuing unsure nature of travel during the pandemic, incentivized us to convert the 400 kg A2TD instrument into a form that could be set up in a few hours at our local build facility in Chapel Hill, NC to perform human-supervised on-sky testing, but not necessarily undergo a full robotic deployment to a potentially unreachable remote site.

In Section 2, we describe the telescopes, cameras, and other optical components evaluated on the A2TD. In Section 3, we provide an overview of the mechanical design of the system. In Section 4, we outline the compute architecture used for the A2TD and the differences between the test bed model and the architecture selected for the Argus Array Pathfinder. In Section 5, we present a brief overview of the on-sky results from the A2TD system and its components. In Section 6, we summarize the instrument design and status.

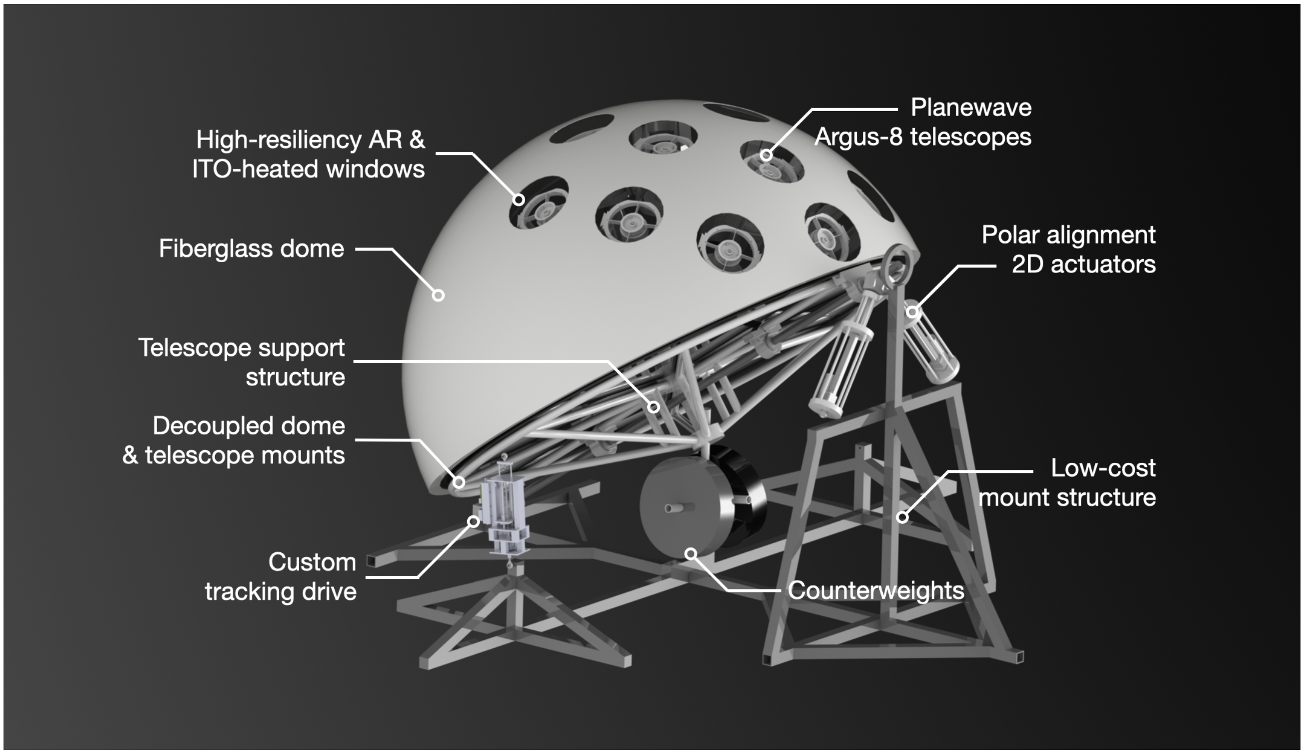

Figure 1. The Argus Array Technology Demonstrator concept design with its major components.

2. OPTICAL DESIGN

The system optics for A2TD consist of nine independent telescopes, paired with back-illuminated CMOS detectors, which observe through anti-reflective optical windows when the instrument is in a weather-safe configuration.

2.1 Telescopes

The initial reference design and early on-sky testing used the f/2.0, 8-inch Rowe-Ackermann Shmidt Astrograph (RASA) commercially available from Celestron*. These telescopes are low-cost ($2079 USD at the time of writing), and provide excellent image quality (RMS spot size $\leq 4.55\mu$m with $\leq 10\%$ vignetting) within their advertised 32-mm corrected image circle; however, this range does not fully include 35-mm format sensors, like those discussed in Section 2.3, which are necessary to meet our field-of-view requirements with $\sim$1000 telescopes.† For a full description of the RASA optical design, see Ref. 8. An additional telescope, a custom design (the Argus-8 in Ref. 7) developed by Planewave Instruments‡ will be integrated into A2TD for on-sky testing leading up to the construction of the Argus Pathfinder instrument. The Argus-8 provides a 33% improvement in pixel scale, and produces a stable PSF across the full sensor plane.

2.2 Optical Window

Each telescope within the A2TD observes the sky through an independent optical window when the dome enclosure is in place, as shown in the reference design in Figure 1. Though the A2TD instrument is rarely operated in this configuration, we evaluated multiple options for exterior-facing windows, including the indium-tin oxide coatings named in Figure 1. However, conventionally specified optical glass is not typically suited for

*https://www.celestron.com

†We note that an alternate design route exists, using smaller (4/3-inch) format sensors fully-illuminated by the RASA8; however, to achieve all-sky coverage with these sensors requires 3-4× as many telescopes.

‡https://planewave.com

the demands of exterior use, which can involve hail, regular rainfall, consistent wind loading, and daily thermal cycling. Custom windows at the size and scale of the telescope apertures can cost thousands of dollars per unit, which is not scalable for to the full Argus Optical Array. We found anti-reflective architectural glass (Schott AMIRAN) to be the best match for our price and performance needs, and measured no detectable changes in the PSF FWHM above a 5% seeing-induced noise floor during on-sky testing. This includes measurements at a variety of angles of incidence out to 35 degrees from normal, relevant for the pseudo-focal Argus Optical Array design described elsewhere in the Proceedings,[9] which requires only a single exterior-facing window.

2.3 Camera Specifications and Evaluation

The A2TD instrument supports multiple camera manufacturers and models, primarily the QHY600M from QHYCCD and both air-cooled and a custom, liquid-cooled variant of the Atik Cameras Apx60 used in the Argus Pathfinder instrument. Both cameras use the 62 megapixel, Sony IMX455 back-illuminated CMOS sensor. This sensor provides 1.7 electron readout noise, 0.004 electron per pixel per second dark current at -10 °C, and has a peak quantum efficiency near 450 nm of ∼92%. The sensor is available in either a -K "industrial" or a -C "consumer" variant; advertised differences include a ceramic LGA, fewer pixel defects, and a higher MTBF for the industrial variant, at significantly higher cost. Both cameras will undergo long-term evaluation within the controlled environment of the Argus Pathfinder.

3. MECHANICAL DESIGN

The details of the mechanical design of A2TD, Argus Pathfinder, and Argus Optical Array can be found elsewhere in the Proceedings.[9] In this section, we will provide a general overview of the major components at the A2TD scale and their justification.

3.1 Hercules Mount Structure

The base of the A2TD system is the "Hercules" tube steel structure (see Figure 1), encompassing all stationary structural components of the instrument. The Hercules structure was designed to maximize transportability, and breaks down into six smaller components for shipping or storage. The assembled base structure, with the telescope support structure and tracking arms removed, will fit in a standard 12-foot trailer. The Hercules mount is described in full elsewhere in the Proceedings.[10]

3.2 Telescope Support Structure

The telescope support structure is a circular aluminum spoke platform that supports the dynamic components of the instrument, and is pictured in Figure 2. The tubing is connected to the axle of the Hercules mount via two pillow blocks, placed at the middle of the radius along the axle. Telescope mounts, made of 3D-printed dovetails and aluminum extrusion, are bolted to a plywood top secured to the tubing. The placement of the telescopes within A2TD does not produce a contiguous field-of-view; instead, the telescopes are distributed in airmass to produce data representative of an all-sky field of view. Additionally, modifying the system to provide a continuous field of view in declination would require a much larger structure, ultimately driving costs higher and compromising our size envelope goal. An overview of field of view packing techniques for array telescopes is provided elsewhere in the Proceedings.[11]

We fit the platform with a fiberglass dome and per-telescope viewing windows, as pictured in Figure 1. The dome is isolated from the platform and has an independent tracking drive to minimize image quality effects of wind buffeting. The dome is weather-sealed for robotic deployment using standard rubber gaskets around the windows, and a custom vinyl fabric skirt which runs between the edge of the dome and the bottom of the tracking platform. Because we determined that the robotic deployment of the A2TD was out of scope, the system has been operated primarily without the dome installed.

Figure 2. Telescope support platform, installed on the low-cost "Hercules" mount structure, during lab integration testing.

3.3 Tracking Drives

The tracking system for A2TD is a scaled-down variant of the tracking drive mechanism for the reference design of the full Argus Optical Array as described in Ref. 7 and the current pseudo-focus array design presented elsewhere in the Proceedings.[9] The AT2D dome and telescope platform track the sky independently using identical tracking drives, placed on opposite sides of the instrument. The dome tracking drive will be repurposed as the primary tracking drive for the Argus Pathfinder.

3.4 Polar Alignment

Precise tracking with a single-drive right-ascension instrument mount requires repeatable, accurate (few arcminute) alignment with Earth's rotation axis. For both A2TD and Argus Pathfinder, portability and ease of deployment with minimal site preparation are design goals. Differential settling of the ground underneath the instrument can shift the polar alignment out of specificiation over time, and a semi-automated procedure for re-alignment, potentially with no on-site support, is essential for recovery. To achieve this degree of pointing accuracy and resilience for the $\sim$400 kg A2TD instrument, we developed automated polar alignment system using a pair of linear actuators supporting the polar end of the instrument axle. This system is described fully elsewhere in the Proceedings.[12]

4. CONTROL SYSTEM ARCHITECTURE

The underlying architecture for the A2TD control system is a modular set of asynchronous HTTP web servers, implemented using FastAPI[§], running on a cluster of 13 Raspberry Pi 4 single-board computers. Of these, nine are "ocular" nodes, responsible for control of a single optical system, including a telescope, camera, and focuser. Three of the remaining nodes export motion control APIs for dome tracking, telescope platform tracking, and polar alignment. The final node is used for orchestration, communicating with each of the ocular and motion control nodes via their respective HTTP APIs. We also produced command-line clients for each of the subsystems, so that they can be manually addressed for debugging, and for subsystem testing independent of the full instrument. Figure 3 shows a single fully assembled ocular node, including the Raspberry Pi computer.

§https://github.com/tiangolo/fastapi

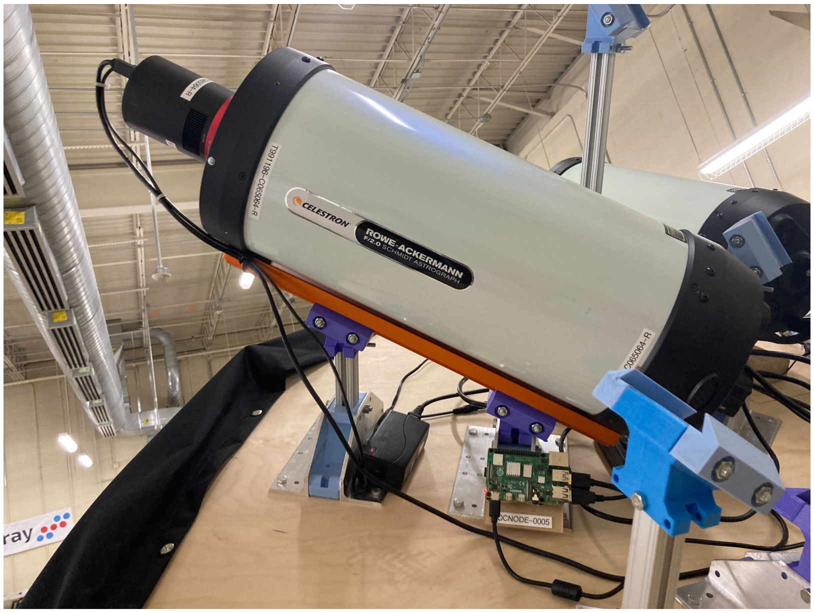

Figure 3. A modular telescope and camera assembly, with an attached "ocular node" control server (Raspberry Pi 4).

One notable issue with the Raspberry Pi-based architecture is scalability to the 1-second cadence observing mode. Due to the limited compute performance and the single-lane PCIe interface for the USB controllers on the single-board computers, readout times of several seconds are typical. This has motivated an alternate architecture for Argus Pathfinder and future project stages; rather than one node per camera, cameras are multiplexed into 48-telescope units which connect to a single x86 control and analysis server via high-speed PCIe 3.0 x16 interface cards. This configuration maintains the HTTP interface at the 48-telescope sub-array level, while providing higher transfer speeds (>90% duty cycle at 1 second cadence) and GPU-based data processing with no network latency. The hierarchical control and data analysis pipeline for Argus is described elsewhere in the Proceedings.[13]

5. OVERVIEW OF ON-SKY RESULTS

The A2TD and the standalone ocular node telescope assemblies have been used on-sky to support rapid design iteration and risk retirement. In this section, we provide a summary of the key findings and references to full results elsewhere in the Proceedings.

1. **Optical Alignment**: We developed a routine for tilt aligning camera and telescope pairs, using bench test data of a near-field focus and shims. From on-sky testing, we measure up to a 50% improvement in edge of field FWHM for the corrected Celestron RASA-8s relative to pre-correction imaging.
2. **Thermal Stability Testing**: We installed an ocular node in a custom thermal enclosure to measure variability in the optical PSF as a function of temperature and constrain the stability necessary for the Argus Pathfinder and Argus Optical Array enclosures. We measure $< 10\%$ differences in the PSF half flux diameter (HFD) for temperature fluctuations of ± 6 °C around the optimal focus. This process and the climate control design for Argus Pathfinder are described in Ref. 14.
3. **Optical Window Testing**: We observed no changes in the PSF HFD above a 5% seeing-induced noise floor during on-sky testing through Schott AMIRAN architectural glass. We have also measured this glass to provide no degradation of the Strehl ratio of the PSF at up to 30-degree angle of incidence, and $< 5\%$ out to 55 degrees, beyond the operating parameters of the Argus Pathfinder window.

4. **Polar Alignment**: We have tested the automated polar alignment system described in Section 3.4, and achieved a sub-10-arcminute alignment with the pole, corresponding to a few-pixel drift over the course of a 15-minute ratchet and a negligible impact on PSF stability in single images. For a full description, see Ref. 12.

5. **Sidereal Tracking:** We have demonstrated tracking at the sidereal rate with sub-pixel RMS offsets over 15-minute pointings.

6. SUMMARY

In this paper, we have described the Argus Array Technology Demonstrator (A2TD), a platform for rapid, iterative development of core technologies for the Argus Optical Array, which is a new synoptic survey instrument able to observe the entire visible sky using O(1000) small telescopes arranged with a contiguous 8000 square degree field of view. The Argus Optical Array leverages newly available and cost-effective astrographic optics aimed at the amateur market, along with high-efficiency, low-noise CMOS image sensors, but has required the development of new technologies to minimize maintenance requirements for polar alignment and sidereal tracking, and for observatory operations that scale to one thousand optical systems and cameras. We addressed the needs of the development process for these new enabling technologies by building the A2TD, a modular demonstrator system for rapid iteration of motion control, optical, and software.

ACKNOWLEDGMENTS

This paper was supported by NSF MSIP (AST-2034381) and CAREER (AST-1555175) grants, and by the generosity of Eric and Wendy Schmidt by recommendation of the Schmidt Futures program. This research, and the con- struction of the Argus prototypes, is undertaken with the collaboration of the Be A Maker (BeAM) network of makerspaces at UNC Chapel Hill and the UNC BeAM Design Center. We thank the staff of the UNC Physics Instrument Shop, Phillip Thompson, Cliff Tysor, Will Harris, and David Norris, for fruitful discussions on the structural components of A2TD and for their assistance during fabrication.

REFERENCES

[1] Ofek, E. O. and Ben-Ami, S., "Seeing-limited Imaging Sky Surveys—Small versus Large Telescopes," *PASP* **132**, 125004 (Dec. 2020).

[2] Law, N. M., Fors, O., Ratzloff, J., Wulfken, P., Kavanaugh, D., Sitar, D. J., Pruett, Z., Birchard, M. N., Barlow, B. N., Cannon, K., Cenko, S. B., Dunlap, B., Kraus, A., and Maccarone, T. J., "Evryscope Science: Exploring the Potential of All-Sky Gigapixel-Scale Telescopes," *PASP* **127**, 234 (Mar. 2015).

[3] Ratzloff, J. K., Law, N. M., Fors, O., Corbett, H. T., Howard, W. S., del Ser, D., and Haislip, J., "Building the Evryscope: Hardware Design and Performance," *PASP* **131**, 075001 (Jul 2019).

[4] Pollacco, D. L., Skillen, I., Collier Cameron, A., Christian, D. J., Hellier, C., Irwin, J., Lister, T. A., Street, R. A., West, R. G., Anderson, D. R., Clarkson, W. I., Deeg, H., Enoch, B., Evans, A., Fitzsimmons, A., Haswell, C. A., Hodgkin, S., Horne, K., Kane, S. R., Keenan, F. P., Maxted, P. F. L., Norton, A. J., Osborne, J., Parley, N. R., Ryans, R. S. I., Smalley, B., Wheatley, P. J., and Wilson, D. M., "The WASP Project and the SuperWASP Cameras," *PASP* **118**, 1407–1418 (Oct. 2006).

[5] Bakos, G., Noyes, R. W., Kovács, G., Stanek, K. Z., Sasselov, D. D., and Domsa, I., "Wide-Field Millimagnitude Photometry with the HAT: A Tool for Extrasolar Planet Detection," *PASP* **116**, 266–277 (Mar. 2004).

[6] Talens, G. J. J., Spronck, J. F. P., Lesage, A. L., Otten, G. P. P. L., Stuik, R., Pollacco, D., and Snellen, I. A. G., "The Multi-site All-Sky CAmeRA (MASCARA). Finding transiting exoplanets around bright ($m_V < 8$) stars," *Astronomy & Astrophysics* **601**, A11 (May 2017).

[7] Law, N. M., Corbett, H., Galliher, N. W., Gonzalez, R., Vasquez, A., Walters, G., Machia, L., Ratzloff, J., Ackley, K., Bizon, C., Clemens, C., Cox, S., Eikenberry, S., Howard, W. S., Glazier, A., Mann, A. W., Quimby, R., Reichart, D., and Trilling, D., "Low-cost Access to the Deep, High-cadence Sky: the Argus Optical Array," *PASP* **134**, 035003 (Mar. 2022).

[8] Berry, R. and the Celestron Engineering Team, "Big! Fast! Wide! Sharp! The Story of the Rowe-Ackermann Schmidt Astrograph." https://celestron-site-support-files.s3.amazonaws.com/support_files/RASA_White_Paper_2020_Web.pdf (March 2020). (Accessed: 28 May 2022).

[9] Law, N., Vasquez Soto, A., Corbett, H., Galliher, N., Gonzalez, R., Machia, L., , and Walters, G., "The inside-out, upside-down telescope: the Argus Array's new pseudofocal design," in [*Ground-based and Airborne Telescopes IX*], *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **12182** (July 2022).

[10] Gonzalez, R., Corbett, H., Law, N., Galliher, N., Vasquez Soto, A., and Machia, L., "The Hercules Mount: Shouldering the Weight of the Argus Optical Array," in [*Ground-based and Airborne Telescopes IX*], *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **12182** (July 2022).

[11] Galliher, N., Law, N., Corbett, H., Gonzalez, R., Machia, L., and Vasquez Soto, A., "Packing the sky: coverage optimization and evaluation for large telescope arrays," in [*Ground-based and Airborne Telescopes IX*], *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **12182** (July 2022).

[12] Vasquez Soto, A., Law, N., Corbett, H., Galliher, N., Gonzalez, R., and Machia, L., "Argus Optical Array motion control: novel pointing and tracking solutions for large array telescopes," in [*Ground-based and Airborne Telescopes IX*], *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **12182** (July 2022).

[13] Corbett, H., Vasquez Soto, A., Machia, L., Galliher, N., Gonzalez, R., and Law, N., "The sky at 1 terabit per second: Architecture and implementation of the Argus Array Hierarchical Data Processing System," in [*Software and Cyberinfrastructure for Astronomy VII*], *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **12182** (July 2022).

[14] Machia, L., Law, N., Corbett, H., Galliher, N., Gonzalez, R., and Vasquez Soto, A., "How to pamper your optics: environment control for Argus Optical Array," in [*Ground-based and Airborne Telescopes IX*], *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **12182** (July 2022).