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How to pamper your optics: environment control for the Argus Optical Array

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ABSTRACT

Wide-field surveys using small-aperture, mass-produced telescopes have the potential to lower instrument hardware costs by orders of magnitude. The Argus Array series of instruments will open new pathways into the study of optical transients via high-cadence, all-sky imaging. The first prototype, the nine-telescope Argus Technology Demonstrator, is already on-sky and validates novel concepts in tracking and high-speed data reduction. Next, the fully funded Argus Pathfinder consists of 38 telescopes on a single mount, and will observe the sky between -20° and +72° declination over the course of each night. The project is planned to culminate with the Argus Optical Array observing 20% of the entire sky simultaneously with 900 telescopes at cadences as fast as 1 second. As the number of telescopes increases, so do the maintenance requirements. For a standard open-air array on many mounts, this could result in operations costs far in excess of those of an equivalent monolithic telescope and lead to inconsistent sky coverage while parts of the array are offline. To limit wear and the need for cleaning, re-alignment and focusing, we seal our telescopes in a filtered and air-conditioned environment. This enclosure will be heavily insulated and maintained within a temperature range small enough to prevent measurable changes in telescope focus. Cameras and other power sources in the enclosure are water-cooled and the heat is removed to an isolated service module containing the array's HVAC and support equipment. From there, the system temperature is maintained at a few seasonally changed set-points. This paper presents the design of the Pathfinder enclosure and environmental control system.

Keywords: Argus, Evryscope, Pathfinder, HVAC, climate control, enclosure

1. INTRODUCTION

The Astro2020 Decadal Survey[1] called for new midscale time-domain astrophysics surveys. Argus Pathfinder and the Argus Optical Array[2-8] are new wide-field, high-cadence optical surveys designed to meet this call with key projects in the study of optical transients, multi-messenger time-domain astronomy, exoplanet systems and habitability, stellar astrophysics, and solar system science. Building on the accomplishments of Evryscope in hardware[9-10], software[11], and research[12-16], Pathfinder and the Argus Optical Array aim to produce low-cost, high-etendue surveys capable of complementing, in pixel scale and depth, other existing[17-23] and planned[24] time-domain surveys.

The Argus Optical Array, planned in the next five years, will be a two-color optical survey of the northern hemisphere, monitoring, every minute, 20% of the entire sky to a depth of $m_g = 19.6$. Over five nights that will increase to 48% of the sky down to $m_g = 23.6$. The entire array will feature 900 8-inch-aperture Planewave Argus-8 telescopes with the combined etendue of a 5m-class monolithic telescope. All the telescopes are mounted on a single 40-foot diameter tracking structure and sealed in a climate-controlled enclosure ≈60 feet in diameter.

A prototype for the Argus Array design, Argus Pathfinder, is currently under construction with first light expected in August 2022, after which it will be deployed to the Pisgah Astronomical Research Institute in western North Carolina. Pathfinder will observe a 92° stripe in declination using 38 Argus-8 telescopes on a single tracking mount. The system will operate in two insulated and climate-controlled 20-foot shipping containers. The "Optics Module" occupies one full container and houses the optical array itself, which observes through a 28-inch window. The second container is split evenly between the "ArgusSpec[25] Module" and the "Service Module," which houses Pathfinder's control and support systems.

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With such large numbers of telescopes, these arrays will be among the more complex astronomical instruments yet built. A standard many-mount open-air array design would involve thousands of exposed moving parts and optical elements, all of which would require cleaning and regular maintenance. This could result in operations costs far in excess of those of an equivalent monolithic telescope, and lead to constantly-changing survey hardware while parts of the array are offline for maintenance. This problem can be ameliorated by enclosing the array in a climate-controlled and air-filtered environment. Climate control protects the array from rapid changes in temperature and humidity which can degrade image quality and increase wear on the system. Filtration protects the system from airborne particulates such as pollen, dust, or ash, which can accumulate on (and sometimes destroy) sensitive optics. Together, the Argus enclosure and climate control systems will result in a reliable, stable instrument requiring manageable levels of maintenance. This paper presents the design of Argus Pathfinder's enclosure and climate control system.

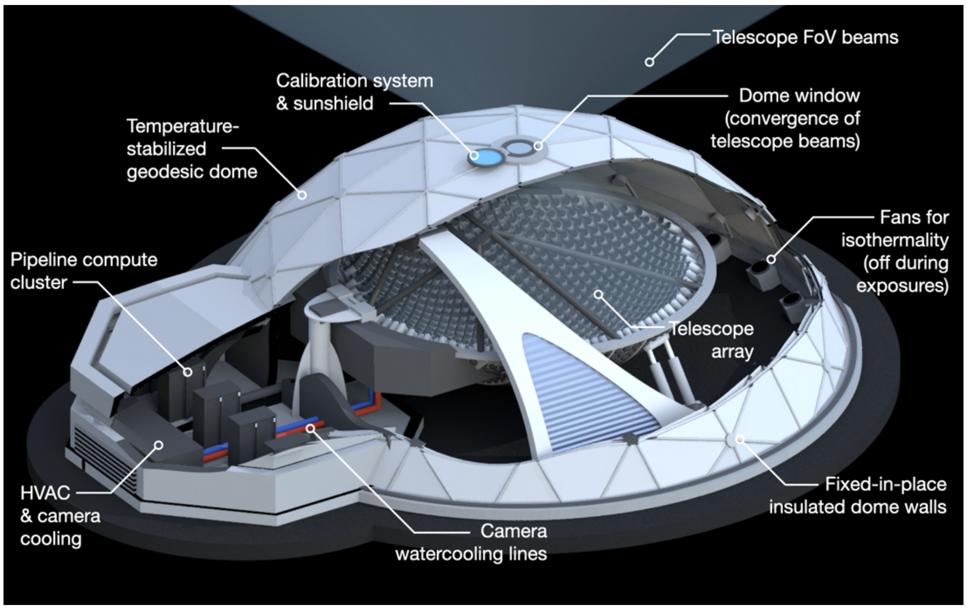

Figure 1: Model of the Argus Optical Array in its ≈ 60-foot diameter enclosure. With over 900 8-inch aperture telescopes sharing a single mount and enclosure, the Argus Optical Array will have the etendue of a 5-m-class telescope and image 20% of the sky instantaneously. Thousands of moving parts and optical elements are protected within a stable environment.[3]

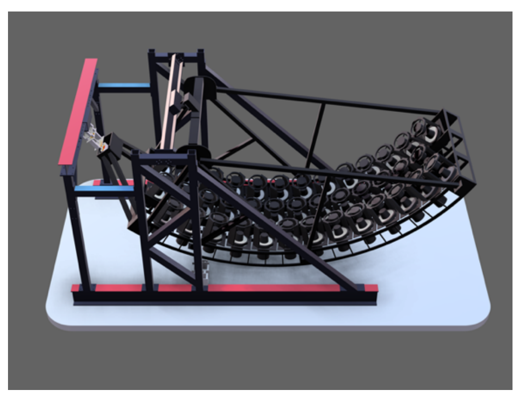

Figure 2: *Left*: The Pathfinder mount under construction with team members (left to right): Alan Vasquez Soto, Jon Carney, Hank Corbett. The array will fit inside a 20-foot shipping container with a separate container for support equipment. *Right:* Model of the completed Pathfinder array structure. Thirty-eight Argus-8 telescopes are mounted on a curved "cradle" and observe a segment, 92° long in declination, of the full Argus Array field of view.

2. CLIMATE-CONTROL (HVAC) SYSTEM AND ENCLOSURE DESIGN

There are three major design constraints on Pathfinder's enclosure and HVAC system: a) negative influences on image quality in the environment in and around the Optics Module must be removed; b) thermal expansion/contraction of the telescopes must be kept within limits that do not cause loss of image focus; c) the HVAC system must operate under expected loads while preventing large or sudden uncontrolled swings in temperature or humidity.

2.1 Mitigating Negative Influences in the Optics Module Environment

Internal Vibration and Convection: Within the Optics Module, vibration, convection currents from cameras and other power sources, and turbulence from the mixing of hot and cold air can degrade image quality. Therefore, we isolate virtually all of Pathfinder's heat production and mechanical vibration in the Service Module, which contains the control servers and the primary HVAC system components: heat pump, dehumidifier, circulation fans, and water-cooling system. All heat-producing equipment inside the Optics Module (most notably the science cameras) are cooled by an insulated water-cooling system which removes heat from the enclosure without causing significant temperature gradients. Other electrical components such as network switches are located within cabinets cooled by the same system. This greatly limits hot-spots and gradients that could lead to convective turnover and allows the temperature in the Optics Module to be held more stably. It also transports the electronics' heat to the Service Module where it is managed by the air-cooling system in an environment mechanically, thermally and electrically isolated from the science instruments.

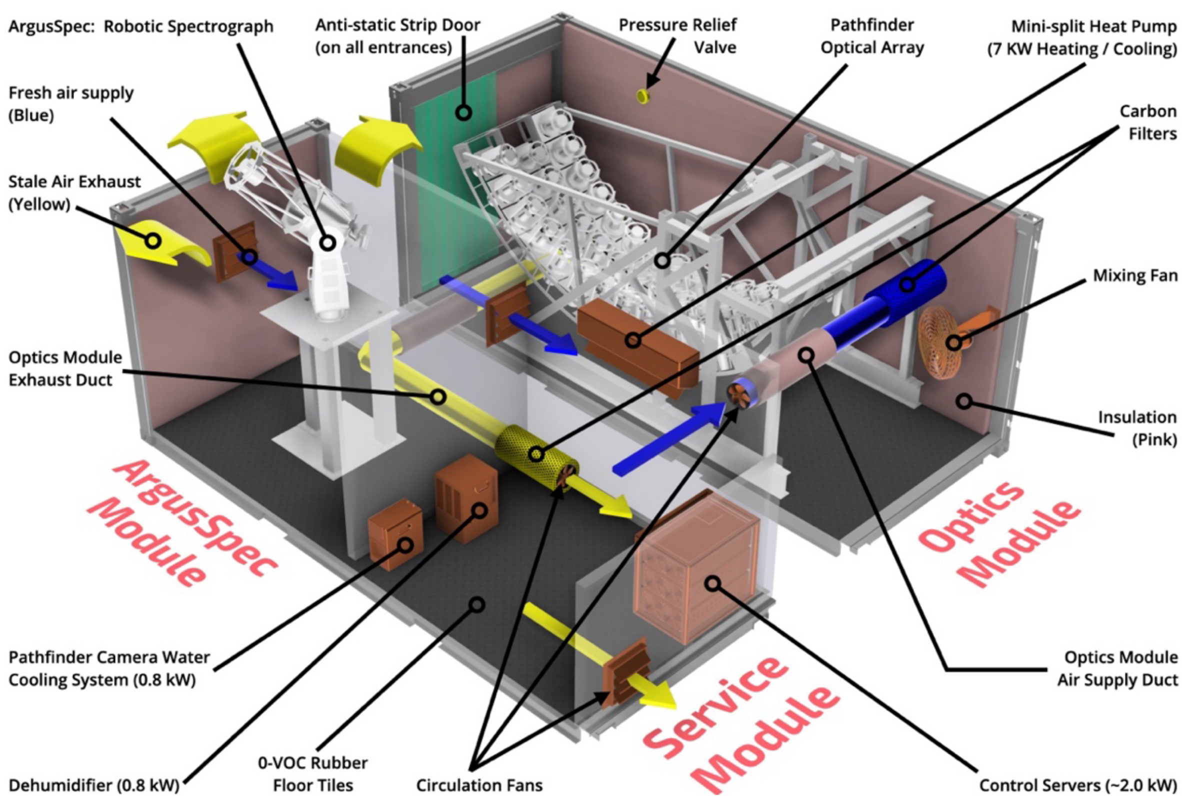

Figure 3: Cutaway model of the complete Argus Pathfinder system with airflow denoted by arrows. Blue represents fresh air supply, yellow indicates stale air exhaust. Brown indicates sources of heat or vibration. Fresh air enters through ArgusSpec and displaces stale air through the unsealed retractable roof. Commercial allergen filters together with carbon filters help remove VOCs and other potential optical-surface contaminants from the sealed system. Heat and vibration sources are isolated in the Service Module; the fans in the ArgusSpec and Optics Modules (one fan each) run only while science exposures are not being taken.

Turbulence: Turbulence in the Optics Module from hot and cold air mixing during ventilation will also degrade image quality. To avoid this, we take advantage of Pathfinder's tracking design, which requires a ≈1 minute downtime to reset the tracking drive every 14 minutes. During that reset no observations take place, and we may ventilate the enclosure freely. Filtered and conditioned air from the Service Module is cycled into the Optics Module while stale air is simultaneously returned to the Service Module. Meanwhile a circulation fan in the Optics Module, which runs only when observations are not occurring, ensures the air is well-mixed. A few seconds before observing resumes the fans shut down to allow turbulence and vibrations to die away, leaving an isothermal environment. We rely on the container's insulation to hold the temperature within acceptable limits during the 14-minute observing run.

"Dome" Seeing and Condensation: Significant differences between the surface temperature of the enclosure and the outside air temperature can result either in convection from the surface of the container (commonly known as "dome seeing") or excessive condensation. These problems are particularly acute at the observation window where the thermal resistance is lowest. Heat transfer through the container surfaces occurs even with insulation, so maintaining the enclosure at temperatures reasonably close to the outside can minimize condensation or convection. To avoid constantly changing temperatures, we will maintain seasonal setpoints.

2.2 Determining Delta-T Limits for the Optics Module

Given the large number of telescopes in Pathfinder and the Argus Optical Array, a robust design will minimize the need for refocusing. Temperature changes are the main source of focus issues. Therefore, we must determine what range of temperature variation our telescopes can tolerate without drifting out of focus, as measured by the mean point-spread-function (PSF) size in our images.

To test this, we constructed an insulated enclosure or "box" for a single telescope with a viewing window of similar glass as used for Pathfinder. The box contains a heater and vent connections for an external air conditioner, allowing the temperature to be raised and lowered at will. A Pathfinder-like telescope and camera are then mounted inside, and the entire assembly pointed at the North Celestial Pole (NCP). Near the NCP the angular speed is slow enough that with half-second exposures the images show little star-trailing, so tracking is not necessary. Before starting an image run, we removed the box sides to allow the telescope to reach the ambient air temperature, after which we focused the telescope and replaced the sides.

We took three consecutive image runs on the same night in early December 2021. For each run, the enclosure was gradually warmed 10 °C over the course of half an hour. This gentle heating ensured the telescope body remained as isothermal as possible. We took temperature readings every 30 seconds, and every 2 minutes we took a set of three 0.5-second exposures. Between runs, we used fans to accelerate the telescope's return to the ambient temperature.

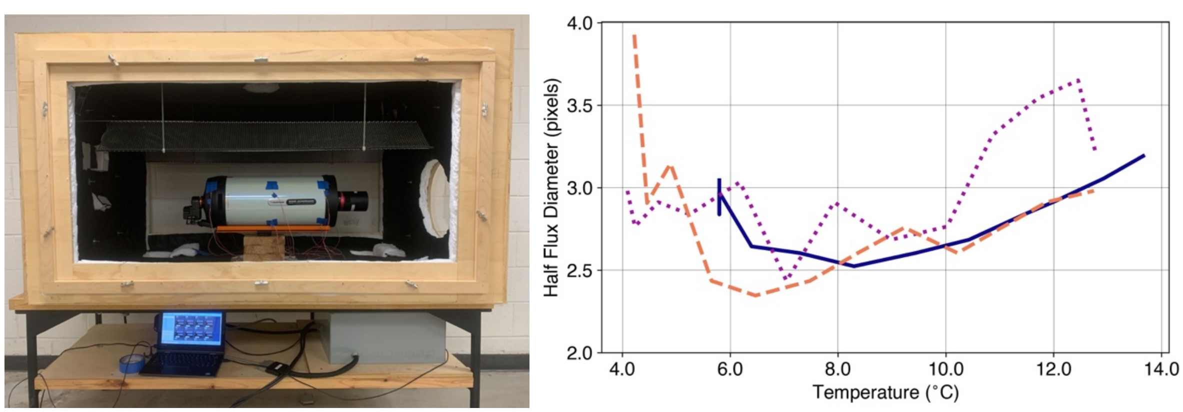

Figure 4: *Left:* The Delta-T Test Enclosure. A Celestron RASA-8 with a QHY600 camera is shown mounted on a block and centered on the round viewing window (right). The temperature is recorded with 11 RTD sensors distributed uniformly over the telescope body (covered in blue tape). The enclosure can be tilted to point at the NCP.
Right: Analysis results showing image quality as a function of temperature. Groups of three 0.5s exposures were taken every 2 minutes. The temperature was raised about 10 °C at a constant rate over ≈30 minutes. Three consecutive image runs show similar behavior where the optimal focus is achieved around 7 °C and varies by ≈10% within ± 3 °C of the optimal point. Much of the noise is likely due to poor seeing in urban Chapel Hill skies.

In analysis, we background subtract each image and measure the half-flux diameter (HFD) of every 5σ (or better) detection, yielding about 500 sources per image. We take the mean HFD over each image, and again the mean of each set of three images to average out any momentary spikes in seeing. We take the mean surface temperature (from 11 readings) of the telescope at each 30-second interval. The HFD measurements and temperature readings are then coordinated by their time stamps and each HFD is plotted against the temperature reading closest to it in time.

The three runs show an optimal focus around 7 °C. Past that point the HFD gradually increases, with some variation, until the end of the run. In a region ± 3 °C around the optimal focus, the image quality appears relatively stable for all three runs, within about a 10% variation that can be explained by atmospheric seeing. Given the consistent behavior over all three image runs, we conclude that the Celestron RASA-8 can tolerate changes in its body temperature up to ± 3 °C before loss of image quality becomes noticeable over atmospheric seeing variations. We expect similar performance for the Argus-8 telescopes; therefore, Pathfinder's HVAC system must maintain the Optics Module within this temperature range.

2.3 Specifying the HVAC System Components

The HVAC system is designed to make clean air at the correct temperature in the Service Module and send it to the Optics Module. To do this well, the HVAC system must be able both to deliver the necessary kilowattage of heating or cooling and to move the appropriate volumes of air at high enough rates. Correctly specifying the hardware means determining what these "necessary" quantities actually are.

For the fans, we consider the largest effect the HVAC system could make, theoretically, in the Optics Module. At approximately double the volume of the Service Module, the largest effect we could make at one time would be to cycle over all the conditioned air in the Service Module. Accounting for the static pressure added by duct lengths and filters, we chose circulation fans capable of moving at least 14 m^3 / min, which is equivalent to transferring the entire volume of the Service Module's air to the Optics Module during one Pathfinder Array reset period.

For heating and cooling, the appropriate kilowatt rating is determined by estimating maximal expected loads on the HVAC system. These loads depend on the surface area of the enclosure and its thermal resistance, the total heat generated within the enclosure, and the local weather conditions.

Pathfinder's containers are 20 ft long, 8 ft wide, and 8.5 ft high. Space constraints limit us to 4 inches of fire-resistant insulation on walls and ceiling with rubber tiling on the 1-inch-thick plywood floor. The average thermal resistance in RSI[1] (units Δ°C m^2 / W), weighted across all surfaces, is 3.3 in the Optics Module and 3.6 in the Service Module. The reason for the Service Module's slightly better thermal resistance is its much smaller floor area, as the floor could not be as heavily insulated as the walls and ceiling. Further, the Optics Module's window cupola is, for geometric reasons, slightly less insulated than its walls, contributing to the module's slightly lower overall thermal resistance.

The components dominating heat generation in the Service Module are the servers, dehumidifier, and water-cooling system (which transports heat from the Optics Module). From these together we estimate a maximum of ≈3.5 kW of heating. In practice, this much heating is unlikely, as the dehumidifier and cooler do not run continuously, and the servers do not always run at full power. However, it serves as a useful upper limit for estimating the internal power.

Local weather data[26] give summer day-time high temperatures around 28 °C and winter nighttime lows around -1 °C, although we may reasonably expect both these numbers to be lower for mountaintop conditions. To minimize solar heating the containers are painted white, and a sunshield shutters the window by day. We represent the often-windy mountain conditions in our heat-flow calculation by assuming the skin of the container to be the same temperature as the outside air.

To calculate the heat load from all the above estimates we use a simple conductive heat-flow model. As previously stated, some surfaces in the two enclosures are insulated differently, so we directly measure the areas of each surface from a CAD model and calculate the heat flow through each of those surfaces. The final estimate of Pathfinder's heat load is the sum of the flow through all the surfaces plus the total internally generated heat. In Figure 5 we plot the heat load as a function of the temperature difference (ΔT °C) between the outside air and the inside setpoint. Because of the internal heat production, most conditions actually require heat to be removed from the system. Therefore, we invert our results to show a "cooling" load.

[1] RSI is the metric equivalent of R-value, a standard measure of the thermal resistance of insulation in the construction industry.

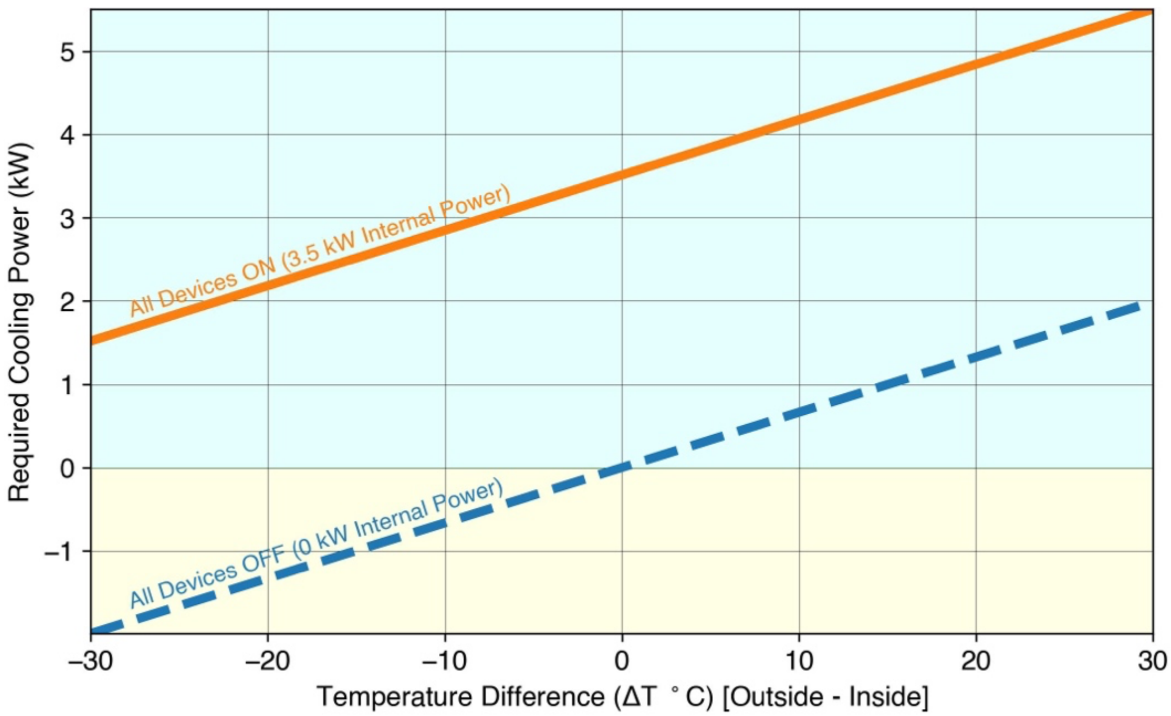

Figure 5: Cooling power required to maintain a given temperature difference between the outdoors and the enclosure. Positive ΔT values indicate where it is warmer outside than inside. Positive kW values represent heat removed from the system. The yellow region is where active heating is required. Internal heat levels could, theoretically, range between all the electronics being off at the same time (dashed blue line), and everything running at full power simultaneously (solid orange line. In most regimes the electronics produce enough heat to warm the system in excess. The most extreme case calls for ≈5.5 kW of cooling (upper right corner).

Our estimates suggest that, in the worst case, Pathfinder would require 5.5 kW of cooling capacity. As an engineering safety margin, we specified the system at least 20% in excess of this maximal expected load. This need was easily met with a commercially available heat pump capable of delivering 7 kW of cooling and heating. The heat pump can also provide cooling in low outside temperatures, a necessary feature when internal power generation demands cooling for most projected conditions – even when it is cool outside. This allows us to cool Pathfinder without constantly introducing outside air, although a short daily fresh-air exchange cycle is planned to help remove build-up of VOCs and other contaminants from the sealed system.

3. SUMMARY AND FUTURE PLANS

Argus Pathfinder and the Argus Optical Array are wide-field, high-cadence optical surveys utilizing tens to hundreds of individual telescopes to image the entire accessible sky simultaneously. Climate-control systems and sealed enclosures will keep these systems consistently working long-term with operations costs manageable by a small research team. Pathfinder's climate control system isolates virtually all heat and vibration from the Optics Module in a separate Service Module and is designed to maintain the system within, at most, ± 3 °C of a seasonal temperature set point. Both the enclosure and HVAC system are built from easily obtained, commercially available products. The HVAC system is a 1/2.5 scale version of the Argus Optical Array's and will thoroughly test our approach in realistic mountaintop conditions.

Construction of the Argus Pathfinder assembly is expected to conclude in August 2022. First light and initial testing of the entire system will take place in Chapel Hill, NC, after which Pathfinder will be remotely deployed to the Pisgah Astronomical Research Institute in western North Carolina.

Figure 6: *Left*: The Pathfinder enclosure under construction in Chapel Hill, NC as of June 2022. The Service Module is in the foreground and the ArgusSpec Module sports a retractable roof. The Optics Module is beneath the tent.
Right: Exterior view of the completed Pathfinder enclosure in similar perspective as the left image. ArgusSpec is visible with roof retracted. The Optics Module is in the background showing the window cupola. Sunshield not shown.

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